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CONTENTS

Section 1

PAPERS AND DISCUSSIONS

OF GENERAL INTEREST

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ENGINEERING AND CONSTRUCTION FEATURES OF THE TENNESSEE RIVER VALLEY SYSTEM

By HARRY A. HAGEMAN *

(Presented at a meeting of the Boston Society of Civil Engineers held on September 22, 1937)

THIS is an unexpected privilege and pleasure for me to speak to the members of this Society in part on a well-known subject, namely, the Tennessee Valley Authority. Having lived in the vicinity of Boston for many years it is only natural that I should come back to New England to spend my vacation, and to renew acquaintance with my friends of former years, especially those of the engineering fraternity.

Shortly after my arrival here recently I received a telephone call from Mr. Carl A. Bock, assistant chief engineer of the Authority, asking me to represent Dr. Arthur E. Morgan, chairman of the Authority Board, who was unable to address you tonight, and to speak on certain phases of the Authority's work in the Tennessee River Valley. I was very glad to accept this assignment, and propose to discuss briefly some general engineering and construction features of the hydroelectric plants that have been planned, some of which are completed or are under construction.

The Tennessee Valley Authority was authorized by an act of Congress in 1933. This act is administered by a board of three, Messrs. Arthur E. Morgan, chairman; Harcourt A. Morgan, assistant chairman, and David E. Lilienthal, director. The primary purpose of the act is to

* Chief hydraulic engineer, Tennessee Valley Authority.

unify the development of the Tennessee River system by constructing dams and reservoirs to aid and stimulate navigation on the main river and its tributaries and control the destructive floods originating in the watershed. The act also directs the Authority to provide facilities at any dam, as may be consistent with the regulation of the stream flow, to generate hydroelectric power, — such power to be transmitted and marketed as provided by the act, to aid in liquidating the costs or the maintenance of the projects.

The tributary streams which form the Tennessee River have their source in the mountains of eastern Tennessee, western Virginia, North Carolina and northern Georgia. The drainage area from the source to its mouth at Paducah, Kentucky, where it empties into the Ohio River, is approximately 40,600 square miles. This drainage area, especially in the mountains, is productive of a high rainfall with a quick run-off, thereby creating large floods, with the consequent damage to the cities and towns in the valley and the land in the watershed.

The river from Knoxville, Tennessee, to Paducah, Kentucky, falls about 500 feet in 650 miles. In this stretch of river will be located the principal structures, such as dams to form the reservoirs for controlling the floods, locks to aid navigation in reaching the higher levels, and power plants to produce hydroelectric energy. In the higher elevations dams will be constructed on the most important tributaries to create flood storage reservoirs, the water from these reservoirs being released at certain seasons of the year, through the dams and water wheels of the power plants, to augment the low summer flow to aid navigation and to generate large blocks of power to supply any deficiency in the transmission system.

The plan contemplates the construction of eight main river developments and three tributary river developments. Commencing farthest downstream and coming up the river, the developments proposed or under construction and those existing are as follows:

1. Gilbertsville (proposed).
2. Pickwick Landing (under construction).
3. Wilson (generally known as Muscle Shoals, constructed during the World War period).
4. Joe Wheeler (completed and dedicated this month).
5. Guntersville (under construction).
6. Hales Bar (existing and owned by the Tennessee Electric Power Company).
7. Chickamauga (under construction).

8. Watts Bar (site now being explored).
9. Coulter Shoals (proposed).

On the tributary rivers the following developments are either existing, under construction or proposed:

1. Norris (completed).
2. Hiwassee (under construction).
3. Fontana (proposed).

The main river plants are practically all of the low head type, the average heads being from 40 to 92 feet. Of the tributary river plants, the Norris development, near the former junction of the Clinch and Powell rivers, has a head varying from 129 to 194 feet. The Hiwassee Dam will be nearly 300 feet high, and the proposed Fontana Dam will develop a maximum head of about 382 feet.

This system of hydroelectric developments will create large reservoirs for flood control storage, having a capacity of six million acre-feet on the main river and two million acre-feet on the tributaries. Of this storage capacity the proposed Gilbertsville reservoir will contribute three and one-half million acre-feet. The operation of these reservoirs under a plan of unified control will substantially aid in checking the Mississippi River floods and provide at least two feet additional freeboard to its levees.

The system will also provide for the future installation of power-generating equipment at the several dams totaling about 2,000,000 kilowatts. Of this capacity about 1,650,000 kilowatts would be in the main river plants, and about 350,000 kilowatts would be supplied by the plants on the tributaries.

The geological formation of the Tennessee River and its tributaries has been investigated with great care and reports have been issued on over one hundred dam sites. The age and type of rocks differ materially. The river bed in eastern Tennessee and northern Alabama consists largely of dolomite, limestone, sandstone and shale. In some cases these materials are fairly soluble, and sinks and caves are not unusual; in other cases these rocks are satisfactory for dam foundations. From the southern to the northern boundary of Tennessee the right bank of the river is bordered by limestone of good quality, while the left bank consists of sands and clays, and does not show rock except at considerable depths. Through Kentucky to its junction with the Oh o River the present Tennessee is flowing over ancient river channels of sand, gravel and clay material from 100 to 300 feet thick. However, at the Gilbertsville site, in this stretch, the rock is at a reasonable depth below the river bed.

At most of the main river developments the foundation problems are extremely difficult and costly to solve for water tightness.

The structures for the main river developments are similar in character. In general they all contain or will have a navigation lock, an intake and power house section, a gate-controlled spillway, and in most cases an earth dam connecting the concrete structures with the river shores.

The distance across the structures comprising a project, from shore to shore, varies from a few thousand feet up to 9,000 feet. The spillways will have ample capacity to discharge safely the largest flood flows which may occur. The maximum recorded flood of 450,000 cubic feet per second occurred in 1897 at the Gilbertsville site. The spillway for this project will be designed to discharge safely 960,000 cubic feet per second.

These spillways will be controlled by steel gates. The gates, for most developments, will be mounted on rolled steel flanged wheels equipped with heavy-duty roller bearings and run on tracks in the gate slots. The gates will be provided with water seals of moulded rubber for water tightness. There will be two gates in each spillway opening, each 20 feet high by 40 feet long, placed one above the other and operated by an electrically driven traveling gantry crane of 80 tons capacity. Two cranes will be provided for each spillway. These cranes run on tracks over the entire length of the spillway and power house intake sections. There are some exceptions to the type of spillway gates just described; these are as follows: the spillway gates for the Wheeler development are of the radial type, mechanically operated; those for the Norris development are of the drum type, hydraulically operated; and those on the Wilson Dam are of the sliding type, hydraulically operated.

The water flowing over the spillways will fall into a water cushion of variable depth, depending on the river stage, on to the heavily reinforced concrete apron connected with the spillway. This apron, in most cases, will be about 85 feet long and 900 feet wide, depending upon conditions at the site, and will have a suitable weir at its downstream end to insure that the hydraulic jump will take place on the apron rather than on the river bed below it.

The Authority has constructed a well-equipped hydraulic laboratory at Norris, Tennessee, where extensive model tests have been made for all hydraulic structures. The information obtained from these tests has been invaluable in working out an economical design of the structure in question. The intake structure will have in general a three-channel waterway to supply the scroll case of each water wheel unit. Each intake will have the customary trash screen, the bars having a 9-inch spacing to keep out the heavy débris floating in the reservoir. Means will be provided to remove large floating material and not pass it on to the next downstream plant. The trash handling problem will have careful attention.

All intakes will have the usual gates to provide a means for inspection or maintenance of the waterways supplying the turbines. The trash racks and intake gates will be operated by the gantry cranes referred to above.

The water wheel units for the low head plants will be of the vertical-shaft, high-speed-propeller Kaplan type. Each water wheel unit will have a runner about 25 feet in diameter and be directly connected to a 60-cycle, 3-phase, 13,800-volt generator. This voltage will be stepped up in most cases to 154 kilowatts for long distance transmission.

Much thought has been given to the selection of the speed of the units. The specific speed chosen for the water wheels has been determined from extensive model tests and experience records of existing units to minimize cavitation. Considerable investigation has been made regarding the lengths, sizes and shapes of the water passages to and from the turbines in the interest of high efficiency, low maintenance and smooth operation. The generating units will each be from about 25,000 to 36,000 kilowatt capacity, depending on the plant. On account of the relatively low head and large capacity of the units, the principal component parts will be of large physical dimensions. For example, the Pickwick Landing wheels, now nearly completed, have a speed ring 37 feet in outside diameter and weighing about 240,000 pounds. The main shaft is 36 inches in diameter. The outside diameter of the generator housing is over 40 feet. These large capacity units require steel castings and forgings of large dimensions, which only comparatively few companies in the country can furnish. These companies at present are extremely busy; and it is not only difficult to obtain proposals from them, but the delivery time is long. The so-called high head plants will have vertical-shaft, Francis-type water wheel units of large capacity. For example, the Norris plant has two 50,000 kilowatt units in operation since last year, and it is proposed to install two 60,000 kilowatt units in the Hiwassee plant. These two plants will probably operate on about a 20 per cent annual load factor basis and can supply large blocks of power to the entire system, if necessary, during the low flow season.

The power plants which the Authority has built so far are of reinforced concrete. It is now proposed to build the power house superstructures for the Chickamauga and Guntersville plants of brick, above the high tail water level; and studies are now in progress on this basis.

It is believed that a more pleasing effect can be obtained with the superstructure of brick construction, and there is a material saving over concrete.

Much is being done on standardization of design, especially on the Chickamauga and Guntersville developments. The head difference in these developments varies by only a few feet, making it possible to use the same design for the spillway and intake sections and the power house, modified as to reinforcement to suit the small difference in head of the two plants. The deck girders spanning the spillway openings and supporting the traveling gantry cranes for operating the gates are alike in both cases. The spillway gates and gantry cranes will be alike, also the power house cranes. Trash screens, intake gates and draft tube gates will have the same design for each type of equipment. The design for the power houses will generally be the same. A cross section of the power houses shows that the distance from the intake gates to the center of the water wheel units and the length of draft tubes are the same. The reinforcing design has been standardized to a large extent by making loading and stress diagrams for both developments, from which a typical design is made showing the spacing, sizes and arrangement of the reinforcing steel. There are many other items, including oil, water and air systems, railings, lighting fixtures, etc., which are being standardized for both jobs. It is impossible to make both developments exactly alike since there are minor differences which must be taken into account, but enough standardization has been done to conclude that large money savings will be made in design and the purchase of equipment.

The area covered by the structures has been extensively explored by core borings, and the site selected largely from this information. Generally each development on the main river is built in three stages. A sheet-pile, cellular-type cofferdam is used in the river area, the earth embankment being constructed on the dry land prior to making the closure in the river section.

An interesting core-boring machine is being used, making it possible to take out rock cores from 36 inches in diameter, and larger if necessary. While most of the information regarding the foundation is obtained from small rock cores, say 3 to 4 inches in diameter, the 36-inch diameter core holes enable one to descend into the hole and observe the character of the rock at close range below the foundation surface. The area within the cofferdam having been unwatered, the foundation is carefully prepared and inspected prior to placing the reinforcement and pouring the concrete.

The preparation of the foundation for the earth embankments is done with equal care. The foundations for all structures must be practically water-tight by sealing them, and thereby preventing water from flowing through the structure and endangering the stability.

In general, two lines of holes are drilled close to the upstream face of the concrete structures, the holes being 10 feet on centers and inclined about 20 degrees from the vertical. The second line of holes is drilled 5 feet downstream from the first line, the hole spacing being the same but staggered with the first line and inclined in the opposite direction. The hole depth depends upon conditions, but usually varies from 20 to 30 feet.

After the holes are cleaned and tested they are grouted at about 15 pounds pressure per square inch, care being taken to watch the pressure and check the foundation for movement. Another line of holes much deeper is drilled about 10 feet downstream from the second line, these holes being tested and grouted at much higher pressure after the concrete dam has been poured. This grout curtain is the first line of defense against serious leakage under the structure, and the indications are that it will be entirely satisfactory. For the earth embankments, the excavation for the concrete core wall foundation is taken down to solid rock. Holes for grout are then drilled at about 4-foot centers, and after being cleaned and tested the grouting is done under variable pressure, as required. If the rock is not water-tight, the 4-foot spacing is cut in two and the grouting done as before. Usually this is effective, although in many instances the spacing has been reduced to 1-foot centers before the rock could be made tight. Where caverns have been encountered it has been necessary to resort, in some cases, to mining operations; that is, sinking a shaft and driving a smaller tunnel to the affected area. These caverns usually contain sand and gravel. After all loose material has been removed, the hole is cleaned and sealed with concrete.

Each job is equipped with a concrete testing laboratory, in charge of a technician who determines the concrete mixture and does the necessary testing. There is also a geologist on the job to study the rock structure of the foundation and advise the engineering and construction forces accordingly.

The construction plant has been carefully designed to meet the conditions. All equipment is thoroughly modern and of large capacity. Much thought has been given to the design of the plant and the selection of the equipment for manufacturing, transporting and placing concrete. This is equally true as regards the handling and placing the fill in the earth embankments. The results obtained indicate that both the concrete and the earth fill have been built into the structures in a satisfactory and workmanlike manner. Much of the equipment, such as concrete mixing plants, storage bins, tractors, bulldozers, pile drivers, cable-ways, etc., is being used from job to job until worn out or otherwise disposed of.

Four of the developments above mentioned, including the privately owned Hales Bar plant, have been completed and are in operation. The Wilson plant has been operating for many years. The Norris development was completed and put into operation early in 1936. The Joe Wheeler development was finished this year and dedicated this month. The Hales Bar plant has been operating for about thirty years. There are under construction at present the following major developments: Pickwick Landing, Guntersville, Chickamauga and Hiwassee. These will be completed in the order given. The first named will go into operation next summer; the other three at about one-year intervals thereafter.

When the program outlined above is completed there will be available about 5,800,000,000 kilowatt hours of primary energy and about 1,000,000,000 kilowatt hours of secondary energy 80 per cent of the time in an average year.

The 1936 report to Congress, as submitted by the Board of Directors, states in regard to expenditures substantially as follows:

> The suggested program of dam construction now under way and recommended by the Tennessee Valley Authority for the unified development of the Tennessee River system, which would be most efficient from an engineering standpoint, would require an appropriation of about $35,000,000 a year for between seven and eight years, in addition to investment which may be necessary for generating electric power at other than the Norris, Wheeler and Pickwick Landing Dams.

In closing let me say that the unified development of the Tennessee River system as proposed will, when completed, accomplish at least these three important things:

1. It will greatly assist navigation throughout the year by providing an adequate channel with an ample water supply from Knoxville to Paducah, thereby promoting commerce by water transportation between the ports on the Tennessee River and those on the Ohio and Mississippi rivers.

2. It will contribute in a large way in assisting to control the floods on the lower Ohio and Mississippi rivers.

3. Lastly, it will provide a large amount of electrical energy at a low cost to a great population within the valley and several hundred miles from it.

ENGINEERING GEOLOGY OF THE PASSAMAQUODDY PROJECT

BY IRVING B. CROSBY, MEMBER *

(Presented at a meeting of the Designers Section of the Boston Society of Civil Engineers held on October 14, 1936)

The Passamaquoddy Tidal Power Project has been before engineers in one form or another for many years, and although the project was abandoned in the summer of 1936 it seems desirable to place on record the results of the extensive geological and foundation investigation made for this project. Interest in this record is increased by the fact that the dam sites have certain similarities and certain strong contrasts with dam sites elsewhere in New England. — EDITOR

INTRODUCTION

THE peculiar features of the many dam sites of the Passamaquoddy tidal power project are due to the fact that these dam sites, unlike most dam sites, have been under the sea in post-glacial times. This project, near Eastport, Maine, has been before engineers in various forms for over ten years, but it was not until 1935 that any work beyond the most preliminary investigating was done on the project.

This paper will be entirely confined to the technical aspects of this problem and largely to the relation of geology to design and construction. Before taking up the geology, some of the engineering features of the project will be considered briefly.†

The original scheme of Dexter P. Cooper comprised two tidal basins: Passamaquoddy Bay, largely in Canada, and Cobscook Bay, in the United States. The power house would have been between these and continuous power would have been possible. (Fig. 1.) This international scheme was temporarily abandoned some years ago on account of opposition of the Canadian government. Several schemes entirely

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* Consulting Geologist, 6 Beacon Street, Boston, Mass.

† For a more detailed description of the engineering, plan of operation, and purpose of the project, see "Construction of Rock-Filled Dams in Flowing Water on the Passamaquoddy Tidal Power Project," by Hugh J. Casey, Second Congress on Large Dams, Communication No. 3, Washington, 1936.

in the United States were then proposed and the project was adopted by the United States government in May, 1935, and assigned to the Corps of Engineers, United States Army, for construction.* The writer was appointed consulting geologist of the project.

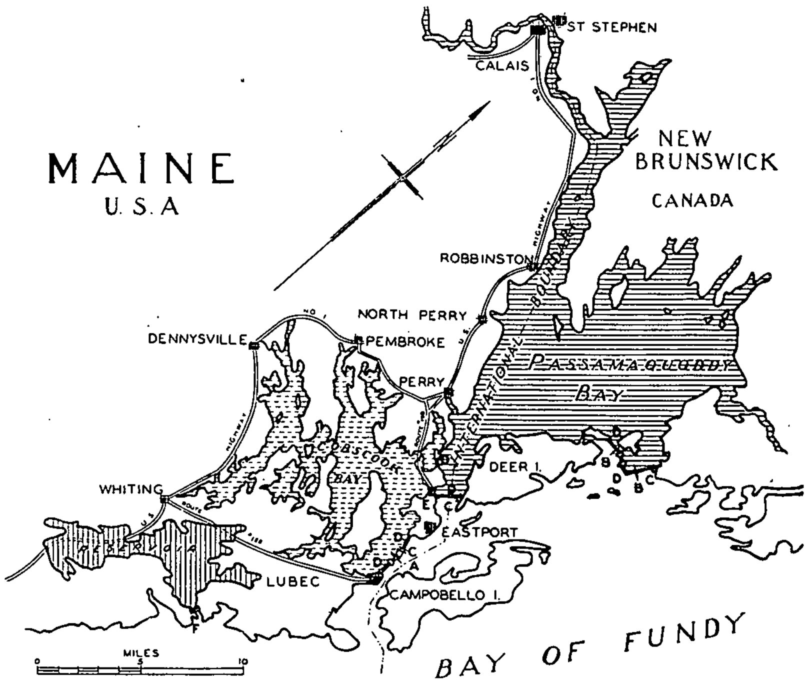

FIG. 1. — LAYOUT MAP OF PASSAMAQUODDY TIDAL POWER PROJECT, INTERNATIONAL PLAN

A. Filling gate structure	D. Dam
B. Emptying gate structure	E. Power house
C. Navigation lock	F. Pumped storage station

(From Communication No. 3, Second Congress on Large Dams, Washington, D. C., 1936. Paper by Hugh S. Casey, Captain, Corps of Engineers, United States)

The plan, as now modified from Cooper's original scheme, is to enclose Cobscook Bay from the Bay of Fundy and from Passamaquoddy Bay, by a series of dams, gate structures, navigation lock, and power house, and provide for intermittent power generation between the high-tide level of Cobscook Bay and the fluctuating level of the Bay

* Lieut.-Col. Philip B. Fleming was District Engineer and Capt. Hugh J. Casey was Chief of the Engineering Division.

of Fundy. The tides at Eastport have a mean range of 18.1 feet, ranging for extreme perigean spring tides up to almost 27 feet, and for apogean neap tides to less than 13 feet. The cycle of operation would be as follows: At and near high tide the filling gates would be opened, permitting the pool to fill to near high-tide level. As the tide begins to fall below the pool level, the gates would be closed. When the tide falls to 5½ feet below the pool level the turbines would be started and power generated during the ensuing falling and rising tide until a head of 5½ feet was again reached. The power station would then be shut down due to insufficient head. As the rising tide reaches the level of the interior pool, the gates would again be opened to restore the draw-down in the pool to near high-tide level.

Such operation would provide only intermittent power, about 7¼ hours out of each 12-hour and 25-minute tidal cycle. Cooper's plan for the priming of this power was by provision of a pumped storage reservoir (known as the Haycock Harbor Reservoir), about sixteen miles distant, where energy would be stored during peak output and drawn on during shut-down periods. This and another reservoir site were extensively investigated, but due to a 45 per cent loss of power and a large duplication of pumping and generating facilities the pump storage reservoir was very costly. The Army Engineers, therefore, recommended provision for priming by (*a*) interchange of power with existing hydro-electric facilities, (*b*) construction of supplemental hydro-electric facilities, or (*c*) stand-by steam or Diesel electric plant.

The initial development contemplated 10 units developing 15,000 kilowatts each at 23-foot head. The power house could be expanded to provide for 20 such units, or a total of 300,000 kilowatts. The power house is located near a neck of land between Cobscook and Passamaquoddy bays. It therefore fits into a potential international two-basin development providing for a continuous power development.

Under the latter arrangement, Passamaquoddy Bay would also be cut off from the Bay of Fundy by a series of dams, navigation lock, and gate structure, but Passamaquoddy Bay would be maintained as a low-level basin, its gates being opened at and near low tide. Power could thus be generated continuously through the interconnecting power house, head being maintained by restoration of draw-down in the high-level Cobscook Bay pool at high tide, and by draining off the rise in tail-water from the low-level Passamaquoddy Bay pool at low tides.

When work on the project was stopped a year ago extensive investigations and surveys had been made for the tidal dams and power house, gate structures and lock, and for two alternate pump storage reservoir sites. Geological investigations had been made of sixty dam sites. No actual construction work had been done on either of the two pump storage reservoir sites when this feature of the project was withdrawn from consideration. Three small tidal dams had been built and the site of the lock and gate structures had been cleared when construction ceased.

General Geology

The geology of the Passamaquoddy area is extremely complicated. Volcanic lava flows and tuffs and sedimentary beds were folded and cut by faults and intruded by igneous rocks, producing a very intricate pattern. This was subjected to stream erosion for a long period and then glaciated, following which the area was submerged beneath the sea to about 200 feet above present sea level and marine deposits were laid down. Each chapter of this long, complex history had its influence upon the engineering project, but the effects of glaciation and marine submergence are of the greatest importance.

Deposition of the rocks of this area began in the Silurian age, several hundred million years ago. The sedimentary rocks were deposited in a sea as muds, sands and gravels, from which shale, slate, sandstone, quartzite conglomerate and limestone were found, and the lavas were poured out from volcanoes. The igneous rocks include diabase (traprock) flows, tuffs and intrusions, and rhyolite (felsite) flows and tuffs and some andesite. Subsequent to their formation the rocks were folded and faulted in an intricate manner, with the result that the geologic map is extremely complex. Faults are very numerous, and evidence of shearing is often found where there is no distinct fault. As a result much of the diabase and rhyolite is very badly fractured.

After the formation of these rocks the region was raised above the sea and stream erosion worked upon this complex mass for a long time. The resulting topography was partly controlled by the rock structure. The streams took advantage of zones of faulting and of belts of soft shales, leaving the harder rocks as ridges. Where the belts of the various formations were curved the resulting valleys were curved. This curving of the topography is very pronounced in Cobscook Bay.

The great ice sheet modified this topography, bevelling off some of the hills and widening and possibly deepening some of the valleys, but its greatest effect was by partially blanketing the hard rocks with glacial deposits, filling many of the old valleys and greatly changing the appearance of the topography. The glacial deposits consist of boulder clay, clay, silt, sand and gravel.

During the glacial period the weight of the ice depressed the surface of the earth under it several hundred feet, also the level of the seas of the entire earth were lowered some 300 feet, due to the great amount of water locked up in the ice sheets. As the ice melted the sea rose and the surface of the earth in the glaciated regions was tilted, the uplift being greatest to the north where the weight of the ice and the resulting depression had been greatest. As a result of these movements we find elevated beaches about 200 feet above the present level of the sea in the vicinity of Eastport, Maine, but the highest elevated beaches in Massachusetts are a hundred feet or more lower.* While this area was submerged marine deposits of clay and sand were laid down upon the glacial deposits and upon the hard rocks partially concealing them.

The submergence beneath the sea at the close of the glacial period resulted in an intricate shore line. The sea invaded valleys and interior low areas producing Cobscook and Passamaquoddy bays and the innumerable small bays and inlets which indent the shore. Due to complete disarrangement of the preglacial drainage by the glacial deposits, the present irregular drainage has little relation to the old drainage. Streams have often cut down upon buried rock ridges while near by are deep valleys buried beneath the glacial drift.

The peculiar conditions which permit the development of tidal power here are the existence of the funnel-shaped Bay of Fundy, which is the cause of the high tides, and the existence of two large, landlocked bays, Passamaquoddy and Cobscook, which serve as basins for the tidal power scheme. The Bay of Fundy is probably due in part to faulting, in part to stream erosion and glacial erosion. Passamaquoddy and Cobscook bays are due principally to stream erosion modified by glacial erosion, but the shape of the bays was controlled by the complex structure of the rocks.

This is practically the only place on the east coast of the United States where this peculiar combination of high tides and landlocked bays makes the development of tidal power possible. Higher tides occur farther up the Bay of Fundy in Canada, but not in the United States.

Tidal Dams

To close off Cobscook Bay from Passamaquoddy Bay and the Bay of Fundy requires six dams, two large and four small ones. (Fig. 2.)

* Ernst Antevs, "Late Quaternary Changes of Level in Maine." American Journal of Science, 5th Series, Vol. 15, pp. 319–336, April, 1926. Irving B. Crosby and Richard Lougee, "Glacial Marginal Shores and Marine Limit in Massachusetts." Bulletin of the Geological Society of America, Vol. 45, pp. 441–462, 1934.

FIG. 2. — MAP OF COBSCOOK BAY AND VICINITY, SHOWING TIDAL DAMS AND HAYCOCK HARBOR PUMPED STORAGE RESERVOIR

Eastport is on Moose Island which separates Cobscook and Passamaquoddy bays, and which is connected with the mainland by highway and railroad bridges. The railroad crosses from the mainland by two small islands, and three small dams are planned across the openings. These are known as the Carlow Island Dam and the Pleasant Point Dams. They have been built as rock fills and would be made tight by an impervious blanket on the Cobscook Bay side.

The other three dams will connect the southern point of Moose Island with Lubec Neck. In between are Treat and Dudley islands, and the Eastport Dam, 3,400 feet long, would extend from Moose Island to Treat Island, the short Treat–Dudley Dam, already built, would connect these two islands, and the Lubec Dam, 3,500 feet long, would extend from Dudley Island to the mainland at Lubec. The principal problems are concerned with the two large dams. The lock would be in the north end of Treat Island and the filling gates in the south end of this island.

The basins now occupied by Cobscook and Passamaquoddy bays were made by preglacial streams at a time when the land stood several hundred feet higher than now. The Passamaquoddy basin was drained through a deep valley which extended southerly along the International Boundary to the vicinity of Eastport and then apparently turned northeasterly and emptied into the Bay of Fundy valley. The Cobscook Basin was drained through a valley which passed south of the Eastport hills then turned northeast and joined the Passamaquoddy valley. The preglacial Cobscook and Passamaquoddy streams not only eroded the basins which made this project possible, but they also eroded the gorges draining these basins, and thus made the most serious problem for the construction of this project. The gorge draining the Passamaquoddy basin is very deep; one sounding showed 390 feet of water, and it is not known how much farther it is to bedrock. It is possible that this gorge was deepened by glacial erosion. If the International project were carried out it would be necessary to close this gorge with a rock-fill dam.

The gorge leading from the Cobscook Basin was made by a smaller stream, has probably not been deepened by glacial erosion, and is not so deep. The deepest water at the site of the Eastport Dam is 115 feet, but one boring showed 283 feet to rock, and it may be a little deeper. (Fig. 3.) The maximum thickness of overburden is about 170 feet, of which the upper 110 feet consist of silty clay with scattered thin beds of fine sand, and the lower 60 feet consist of clay with more numerous and thicker beds of sand.

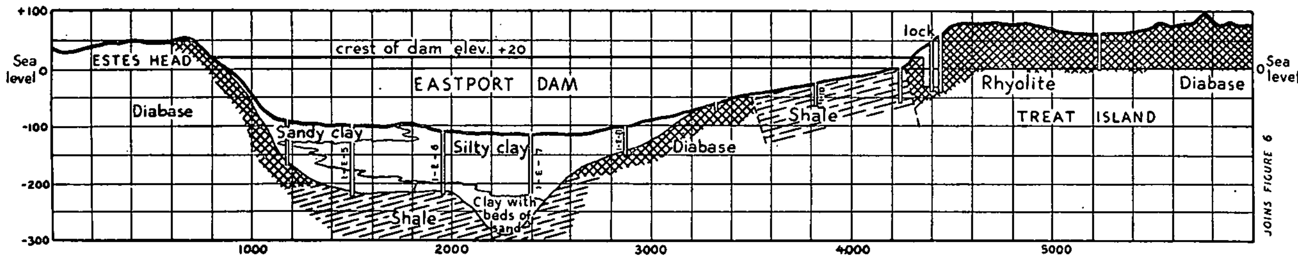

FIG. 3. — GEOLOGIC SECTION OF EASTPORT DAM SITE ALONG AXIS OF DAM

Deep water borings were made from two large lighters, each of which was anchored to six 7-ton anchors by lines to winches which permitted movement of about 1,500 feet in any direction without shifting the anchors. (Fig. 4.) Each boat had an outrigger on the side for the support of a huge spud which consisted of a steel casing $21\frac{1}{2}$ inches in diameter. This spud had a pad 7 feet in diameter at the bottom and a removable platform at the upper end. The spud was kept vertical by tackles from the outrigger. Six-inch casing was driven inside the spud to rock, and a core boring was made in rock. Five-inch samples were taken of the overburden. These borings were made in currents as great as 6 knots, and with a maximum tidal range of 26 feet.

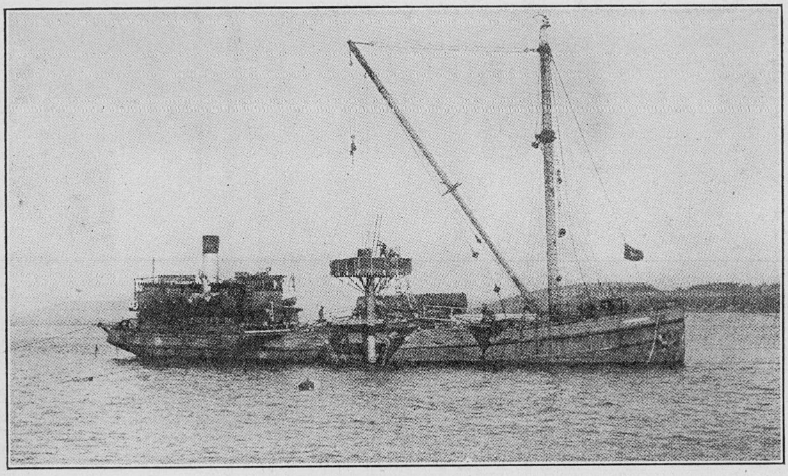

FIG. 4. — DEEP WATER BORING RIG

(From Communication No. 3, Second Congress on Large Dams, Washington, D. C., 1936)

Geologic sections were prepared from the scanty borings, using geologic principles of the erosion of these valleys, and the mode of deposition of these deposits to interpolate between the borings. The soil samples were tested in the soil mechanics laboratory for consolidation, shear, water content, grain size, etc. The shearing strength of the clay samples generally ranged from a little less than 0.2 ton per square foot, and the water content varied from 25 to 35 per cent of the solids. From the geological and laboratory information, estimates were made of the probable settlement of the dam.

On account of hydraulic conditions it was decided to make the dam 225 feet wide at elevation —30 mean sea level. The necessary

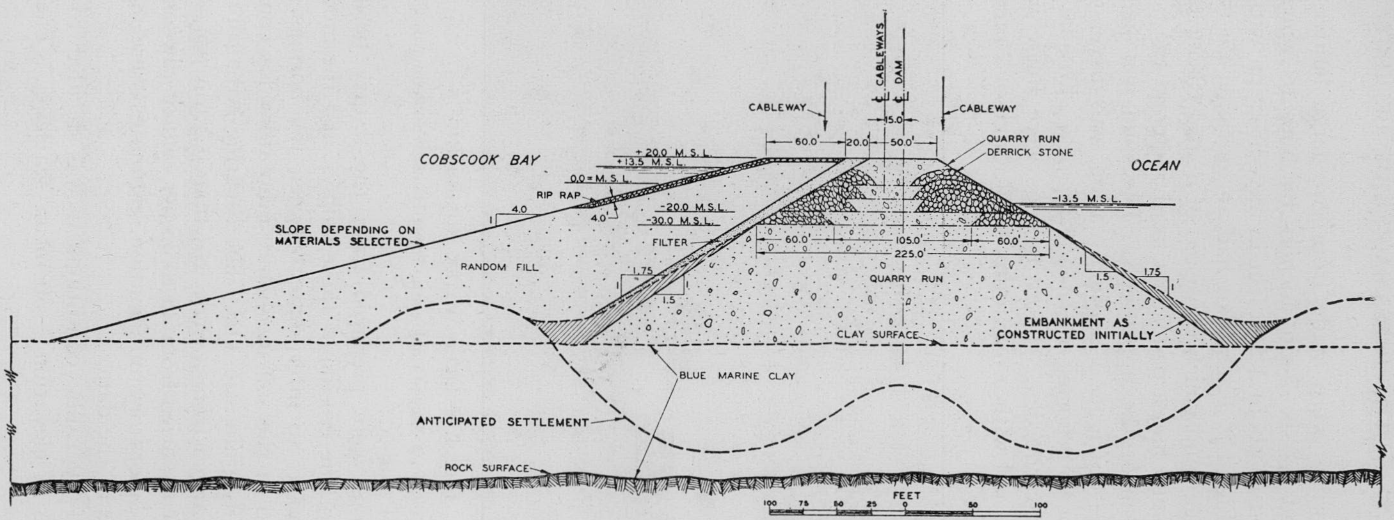

FIG. 5. — SECTION OF ROCK-FILL DAM SHOWING ANTICIPATED SETTLEMENT

(From Communication No. 3, Second Congress on Large Dams, Washington, D. C., 1936. Paper by Hugh S. Casey, Captain, Corps of Engineers, United States) slopes of 1 on 1½ to 1 on 1¾ resulted in a base width up to 500 feet for the rock-fill dam. (Fig. 5.) In order to determine the nature and extent of stress in the plastic clay under such loading, photo-elastic gelatin tests were run in the soils laboratory, and these were confirmed by model tests on clay. These tests indicated an outward flow of the clay with settlement of nearly 100 per cent under both toes and approximately 50 per cent under the center of the dam.* It would have been possible to design the dams with flat slopes, 1 on 5 to 1 on 10, but this would have required much more rock than would be necessary for 100 per cent settlement. Therefore, contrary to normal practice, the design contemplates failure of the plastic clay foundation as the most economic solution.

At the site of the Lubec Dam the water is not so deep and the thickness of the overburden is not so great. (Fig. 6.) Geologic studies indicated that there was a depression in the bedrock surface near the northern end of this dam which was not found by the borings. This depression is due to a fault zone which crosses the line of the dam. It was found that by moving the dam a short distance to the east a better bedrock profile with less thickness of overburden could be obtained. The maximum thickness of overburden is about 135 feet, of which the upper 90 feet are silty clay with the scattered thin beds of fine sand, and the lower part is clay with more numerous and thicker beds of sand. The conditions here are, therefore, similar to those at the Eastport Dam, but are not quite so severe. The Lubec and Eastport dams will together require approximately 7,000,000 cubic yards of rock.

The power house is located at a narrow neck connecting the two parts of Moose Island. The neck is composed of clay, silt and sand. Numerous borings and jettings were made on the site of the power house and the headrace and tailrace channels. From this data and from geologic studies a contour map of the bedrock surface was prepared. This showed that but little rock excavation would be necessary for the headrace and tailrace channels. The rocks upon which the power house would rest are shale, slate, sandstone and rhyolite (felsite). The shale is thick bedded and is amply strong to sustain the load of the power house, and the other rocks are still stronger.

It would seem at first that rock for the rock-fill dams could be obtained almost anywhere from the numerous diabase and rhyolite ledges, but careful observation shows that much of the rock is so closely cut by fractures and incipient fractures that it is not possible to obtain

* Hugh J. Casey, "Construction of Rock-Filled Dams in Flowing Water on the Passamaquoddy Tidal Power Project." Second Congress on Large Dams, Communication No. 3, 1936.

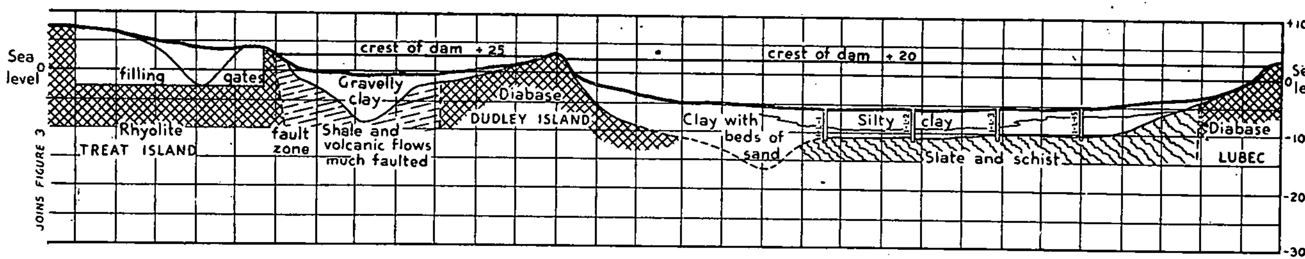

FIG. 6. — GEOLOGIC SECTION OF LUBEC DAM SITE ALONG AXIS OF DAM

large blocks. Shackford Head offered a very convenient quarry site, but here the rock was unusually badly fractured. Rock from here would, however, be suitable for the bulk of the rock fill and for aggregate, and it was planned to open a quarry here. Excavations for the lock and filling gates on Treat Island would provide a large amount of rock suitable for rock fill except where large blocks were needed. At Black Head, on a branch of Cobscook Bay, the diabase is more massive, and it is probable that 4-foot blocks could be obtained. If blocks of the necessary size were not available at any of these places they could be obtained about twenty miles north of Eastport, where there are numerous ledges of massive granite near the shore of Passamaquoddy Bay. Here large blocks of any desired size could be quarried and transported by water to the dams.

Haycock Harbor Pumped Storage Reservoir

The site of the Haycock Harbor Pumped Storage Reservoir is located among low hills about twelve miles south of Eastport and on the south side of Cobscook Bay. (Fig. 2.) The reservoir is planned for a flow line at an elevation of 120 feet, and would occupy parts of the drainage basins of three small streams. The natural drainage into this basin would be negligible, and it would be operated as a pumped storage plant, using excess power at the peak of the tidal power cycle to pump ocean water up into this reservoir. When the tidal power plant was not running this stored water would be used in the power house of the pumped storage plant to generate power, thus maintaining a steady supply of power from the Quoddy project.

It was at first planned to have the pumping and power plant at Haycock Harbor and pump directly from the ocean into the reservoir. When the Haycock Harbor site was first chosen by Cooper it was expected to use Cobscook Bay as a low-level pool. Since then it was decided to make the bay a high-level pool, and it was also found that the necessary layout of dams to obtain a power house in a satisfactory location on Haycock Harbor would be more expensive than expected, and therefore a study was made for a power house location on the Whiting–Lubec road, with the pumping plant taking water from Cobscook Bay at near high-tide level which would result in an operating economy. It was also found that this power house location with the resulting dams had advantages over the original location on Haycock Harbor, and this was the preferred plan at the time investigation of this part of the project was stopped. Haycock Harbor Reservoir would require twelve dams, large and small, but the study of this project involved investigation of ten additional dam sites.

These dam sites are of two types: (1) those across old stream valleys, now partly filled with glacial and marine deposits, and (2) those across saddles and along ridges. Each type has practical problems peculiar to it, and recognition of the type to which a particular site belongs aids in understanding the problems of the site. As regards the valley type dam site the valleys are partially filled with glacial deposits in every place known. Even where the stream is now flowing over ledge a buried valley is believed to exist near by. The buried valley may not be indicated by any surface stream. The filling of these buried valleys is often pervious and may allow seepage under or around the dam. Where dams cross clay-filled valleys the possibility of settlement must be studied. Buried valleys are known to lead from the reservoir in four places and four of the dam sites chosen and several of the alternate sites are of the valley type. The saddle-type dam sites cross saddles between rock hills, and in places follow ridges. Rock is often at or near the surface, and the overburden is generally not clay, but there are some exceptions. In at least two cases the saddles are deeply buried, and there is a seepage problem at one and a settlement problem at the other. In the case of dams on rock ridges the tightness of the rock becomes a factor.

Buried valleys are very common throughout New England and the adjacent glaciated regions, and the valley type of dam site is most common. There is, however, a very important difference between the dam sites on this project and dam sites in other parts of New England, in that this area has been submerged beneath the sea in post glacial time, and the rocks and glacial deposits are partially blanketed by marine deposits, largely clay. This increases the difficulty of investigating the sites and increases the problems of the sites. Saddle type dam sites are less common elsewhere but exist in connection with some reservoirs. The dams at such places are usually small earth dikes, and it is seldom that they have the problems of some of the saddle type dam sites of the Passamaquoddy project.

The Haycock Harbor Reservoir may be divided geologically along its northeast-southwest axis. The rocks to the northwest are rhyolite tuffs and flows, with some small areas of diabase tuffs and flows and of shale. To the southeast is an extensive mass of intrusive diabase in which are elongated areas of the Quoddy formation. This last is the oldest formation of the Eastport region, and consists of shale, quartzose shale, slate and quartzite, with occasional flows or tuff beds of rhyolite or diabase. It is an extremely variable formation formed of sediments, lava flows and volcanic ash, and is less resistant to erosion than the diabase. As a result, valleys tend to lie in the Quoddy formation, and it is of greater practical importance in relation to the dams than its area would indicate. Three shear zones cross the reservoir, one of which separates the rhyolite from the intrusive diabase. One of these zones intersects a dam site, but only a small earth dike was planned here, and the presence of the shear zone would have no effect on the plans.

The most interesting problems were concerned with the location of the power house and necessary dams at Haycock Harbor, and with the dam which took the place of these when the power house location was removed to the Cobscook Bay side of the reservoir. Haycock Harbor is a long narrow inlet eroded by a stream in a belt of shale of the Quoddy formation at a time when the sea stood at a lower level. This inlet is bordered north and south, and at its head by diabase, which is a much more resistant rock. Wiggins Brook flows into the head of the inlet falling over diabase ledges. The original plan for a dam at Haycock Harbor contemplated crossing the valley of Wiggins Brook, between two rock hills. Early in the geological study of this site, before any borings had been made, evidence was found of a buried valley north of the present channel of the brook. The fact that the brook valley was wider above the place where it crossed the diabase ledges into tidewater, and that just north of this a belt of less resistant shale of the Quoddy formation leads to tidewater, indicated the probable existence of a buried valley in the bedrock surface north of the present stream and north of Haycock Harbor. Other evidence indicated that this valley was probably filled with clay; therefore two borings were located in the probable location of this valley. One of these borings reached rock near sea level, the other did not encounter rock until an elevation of 34 feet below mean sea level was reached. It is not certain that this boring was in the deepest part of the valley, but it was evident from the study of the surface outcrops that the buried valley was narrow and gorge-like. It was also found that the filling of this buried valley was soft clay which would require a broader base and flatter slopes than would otherwise be used for the earth dam.

Three different sites for the power house and six different dam sites were studied, but it was found that whatever arrangement of power house and dams was chosen it would be necessary to cross this buried clay-filled valley. There were, however, no other serious problems here, and there would be little seepage under or around the dams.

When it was decided to locate the power house on the Cobscook Bay side of the reservoir, a dam site was chosen northwest of Haycock Harbor which took the place of those in the vicinity of the harbor and had certain advantages. This new site, known as Site F, also crossed the valley of Wiggins Brook and the inland extension of the buried valley. The geological indications were that the buried valley would be much less deep at this point, due to the fact that the belt of shale did not extend so far inland, and that the preglacial stream had not eroded so deeply in the more resistant diabase. This indication was borne out by the borings. There is less clay at this site and less probability of settlement of the dam. This dam would be the largest in the Haycock Harbor Reservoir project, and would require approximately 2,670,000 cubic yards of earth.

Dam site 7, on the northwest side of the reservoir, extends across saddles and along ridges for a distance of 6,300 feet. The southern part of the site is across a broad saddle where rock is buried 50 feet deep. The overburden is sand, and an impervious blanket on the reservoir side of the dam would be necessary to reduce seepage under the dam. This dam would require approximately 1,082,000 cubic yards of earth. Part of this dam would be on a narrow rock ridge of rhyolite. The tightness of this rock was tested by water pressure in an inclined boring. It was satisfactorily tight, and a masonry structure on the rock ridge would probably have been used here.

Dam site 8 is at the power house site on the west side of the reservoir. It crosses two small buried valleys in which there is sand buried beneath a layer of clay. The clay will effectively prevent seepage under the dam. However, the power house site would be on diabase near a contact with shale. Some of the rock is deeply weathered, and treatment of the foundations would probably be necessary. This is practically the only place on the reservoir project where the condition of the rock is an important factor, and it is not a serious difficulty here.

Dam 12 would be a long low dam across a broad sandy saddle between two sluggish streams. There was physiographic evidence of a buried valley under this saddle, and its existence was proved by a boring which failed to reach rock at a depth of 90 feet.

The twelve dams would require approximately 5,700,000 cubic yards of earth, and the location of suitable deposits was a difficult problem. Generally in a glaciated region suitable materials for earth dams are not lacking, but, due to the submergence of the glacial deposits here, much of the boulder clay was washed by the sea which removed the fines and left sand and gravel. In addition much of the area was covered by a blanket of marine clay which probably conceals many of the remaining deposits of boulder clay.

A careful physiographic study of the area was made, both by map and in the field, and a number of likely looking places were located, many of which proved to have usable material. The investigation for borrow material was not complete when this part of the project was stopped, but it appeared that sufficient material could be obtained, though it would be necessary to use many small deposits.

The proposed Haycock Harbor Reservoir encountered no very serious difficulties, but there were several factors which tended to increase the cost. Several of the dams would cross valleys filled with marine clay, and flatter slopes with greater yardage would be necessary. Probably the most serious factor is the scarcity of large deposits of suitable embankment material which could be worked economically. These factors caused the investigation of another reservoir site nineteen miles north of the tidal power house site at Eastport and just south of Calais.

Before leaving consideration of the Haycock Harbor Reservoir it should be added that there is no danger of contamination of public water supplies by salt water from the reservoir. The Lubec supply is several miles distant, and is separated by several valleys and rock hills from the reservoir.

The Calais Pumped Storage Reservoir

The Calais Pumped Storage Reservoir would utilize natural basins in the hills southeast of Calais, Maine. (Fig. 7.) These basins are now occupied by several lakes and ponds, the three larger of which had been raised by small dams years ago when the granite industry was active here. The reservoir could be of greater or lesser size, as required. The southern lake basin was separated by a low ridge through which it was planned to cut a canal if this additional storage were needed. There were many alternate dam sites, and arrangements were possible which would give greater or less storage, but final choice had not been made when this investigation was stopped. Four locations of the power house were possible, three of which would require tunnels, but final selection had not been made. A flow line of 198 feet was considered, but a flow line a little higher or considerably lower was feasible. A minimum of seven dams would be necessary if the southern basin were not used, but twenty-eight dam sites were studied.

The rocks of this area are all granitic and include true granites, norite and quartz diorite. The granites are gray, pink and red, and the last two are very beautiful stones. The red granite takes a high polish and is excellent for ornamental work. The gray granite is a very

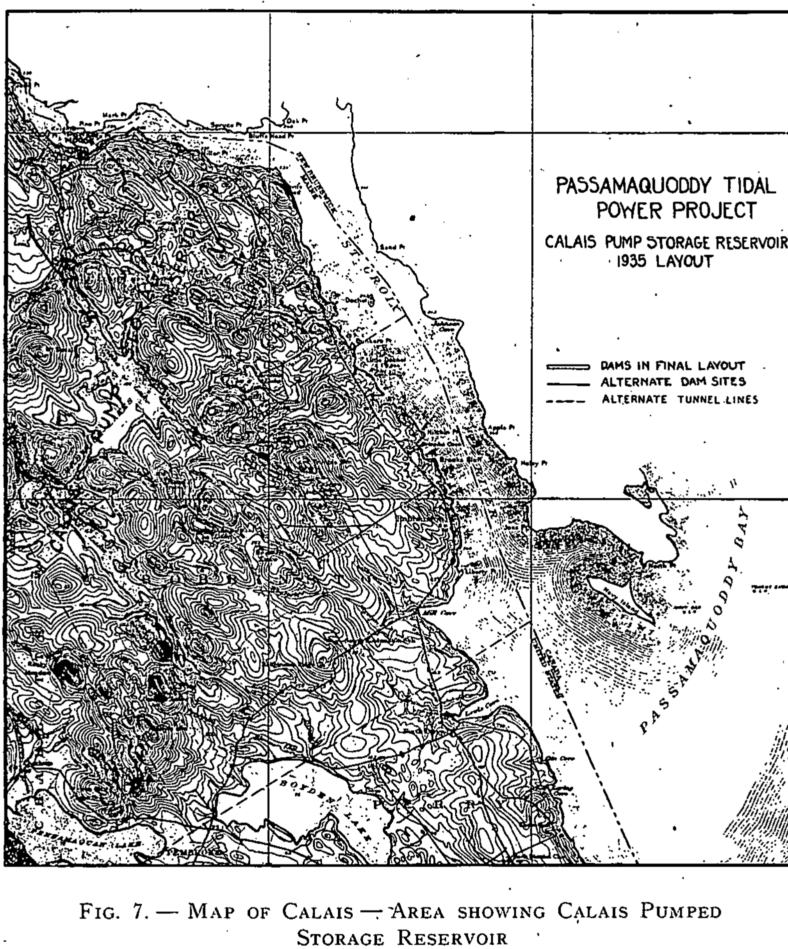

FIG. 7. — MAP OF CALAIS — AREA SHOWING CALAIS PUMPED STORAGE RESERVOIR

massive rock and huge blocks can be obtained from it. The norite and quartz diorite are very dark gray, almost black, and are quarried as "black granite." This stone takes a very high polish, but cut surfaces are very light in comparison to the very dark polished surface. It is excellent monumental stone for inscriptions, and is still quarried in a crude way on a small scale. The decadence of this granite industry appears to be partly due to lack of initiative. There are few places where such a variety of beautiful granites can be obtained. All of these granites are excellent foundation rocks, and cause no problems for this project.

Although the lower part of this area was covered by the late glacial sea, the effects of the submergence are not as pronounced as in the Haycock Harbor area. Much less of the boulder clay was removed by wave action and much less marine clay blankets the glacial deposits. Therefore the dam sites have more favorable conditions, and large deposits of boulder clay suitable for earth dam construction are available.

These dam sites are of two types: valley sites and saddle sites, as in the Haycock Harbor area. The stream valleys are partly filled with glacial deposits, but so far as is known these are nowhere as thick as at some of the Haycock Harbor sites. Some of the buried valleys are not now followed by streams, and the possibility of seepage from the reservoir through these was studied but did not appear to be serious. Five dam sites are certainly of the valley type, but most of the dam sites are of the saddle type and many of these have excellent foundation conditions. At some of these sites the basin on the inner side is filled with bog material, and the bog overflows, giving the appearance of a valley type dam site, but there is the important difference that there is no buried valley, and rock is near the surface.

The largest dam would be 6A, at the northern end of the reservoir. The height from the brook would be 126 feet and the length 3,500 feet. From the dam short penstocks would lead to the power house on tidewater. It would be possible to avoid this large dam by building several small ones, but this would necessitate a long tunnel to the power house. Final choice between these alternatives had not been made when this part of the project was stopped. This site is of the valley type, but the valley filling is only 30 feet thick, is impervious, and is partly boulder clay, which provides good foundation conditions for an earth dam.

Dam site 13A is a typical example of the valley type. (Fig. 8.) Physiographic considerations caused me to suspect a buried valley here, and a boring on the bank of the stream found rock 48 feet below the level of the stream. The overburden consisted of 26 feet of peat over 22 feet of clay and sand. Removal of the peat would be necessary here, and although there would be no seepage problem there might be some settlement.

Dam site 6C crosses a bog where the depth to rock is not great, passes over a low rock ridge, and crosses a saddle between rock hills. It appears at first to be a saddle type dam site, but physiographic study shows that the buried valley which was proved at dam site 13A must pass under this saddle. A boring reached rock at 32 feet, but it is probable that there is a narrow gorge some 20 feet deeper, and another boring was recommended but had not yet been drilled when work was stopped.

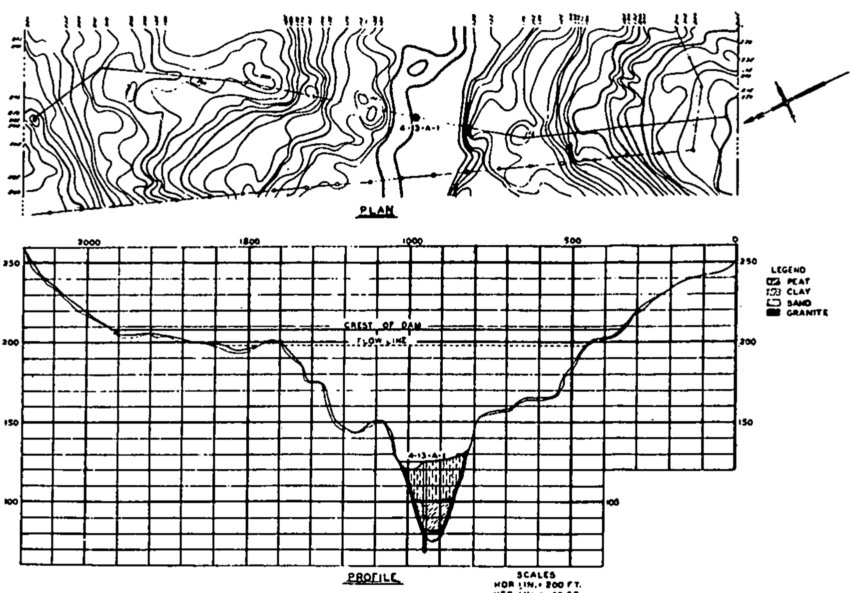

FIG. 8. — MAP AND GEOLOGIC SECTION OF DAM SITE 13A
A typical valley type dam site

Dam site 5 is a typical saddle type site with satisfactory conditions for an earth dam. (Fig. 9.) At the surface in the bottom of the saddle are about 6 feet of silty clay beneath which are some 20 feet of boulder clay and then granitic bedrock.

Several of the possible arrangements of dams and power house would require tunnels to the power house. In every case the rock is excellent for tunnelling.

In respect to embankment material this project is especially fortunate. Northwest of dam site 6A is a broad, flat-topped hill capped with a thick deposit of boulder clay. This is believed to contain at least 5,000,000 cubic yards of usable material. Just west of this is a similar hill on which over a million cubic yards of boulder clay was proved and which probably has much more. In addition, smaller deposits of boulder clay are scattered about the reservoir area, and there are deposits of sandy material suitable for the outer sections of the dams. It would therefore be possible to obtain suitable embankment material very economically.

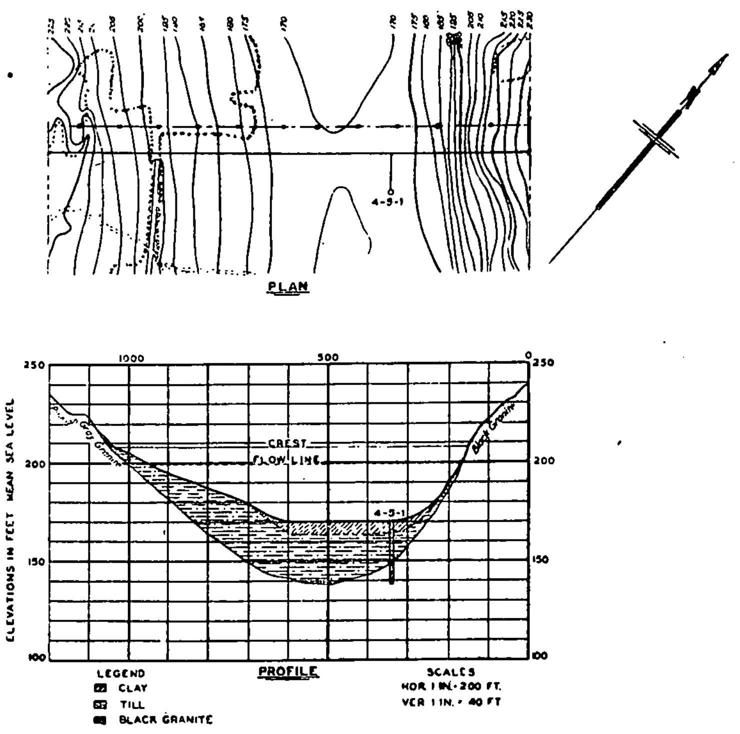

FIG. 9. — MAP AND GEOLOGIC SECTION OF DAM SITE 5
A typical saddle type dam site

Although the Calais Storage Reservoir project is not ideal in every way, it has no serious geological difficulties and is superior to the Haycock Harbor Reservoir project as regards settlement of dams, seepage under dams, and availability of embankment material. This reservoir project has no serious geological difficulties and has many advantages. An unusually tight reservoir could be obtained and conditions are conducive to economical construction.

MODEL ANALYSIS OF STRUCTURES

BY DR. JOHN B. WILBUR, MEMBER *

(Presented at a meeting of the Designers Section of the Boston Society of Civil Engineers held on December 8, 1937)

INTRODUCTION

THE investigation of structural action by means of models presents a method of attack which under some circumstances may be of considerable value to structural engineers. This by no means implies that model testing is in general preferable to analytical methods, nor that the model approach is one easily carried out by those untrained in the theory of stresses or unskilled in the technique of laboratory procedure. The proper sphere of problems to which the model analysis approach should be considered is difficult to define, and is a function, among other things, of our knowledge of model procedure. Structural analysis by means of model studies is a comparatively new development, and one in which there is every reason to believe that rapid strides will be made. New developments will open up new fields of application.

It is, however, possible to outline in a general way the types of problems which at the present time may be suitably approached by model study. In complicated structures, particularly in rigid frame structures which are highly indeterminate, moments, shears, direct stresses and deflections may be determined. Under these circumstances the model analysis may be used to obtain an independent check of an analytical solution, or it may be counted upon to furnish by itself the data necessary for design, provided the methods and techniques used have been thoroughly tested in previous work. Even where the total direct stresses, moments and shears acting on a member may be easily determined by analytical methods, considerable uncertainty may exist as to the actual stress distribution in a member. Here the problem may become so theoretically complicated that a model study appears to be the only workable approach to a substantially correct solution. The study of the properties of materials, while necessarily interrelated with model analysis, does not strictly constitute a part of the field of model analysis.

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Stress analysis by means of models may be subdivided into two general approaches: direct methods and indirect methods. In the direct methods loads are applied to the model, which are comparable to the actual loads which would be applied to the structure reproduced, and the resulting deformations so interpreted that the stresses are determined. In the indirect methods, the applied loads bear no direct connection to actual loads which would be applied to the real structure, but they are, nevertheless, such that the structural action of the model may be interpreted to give the desired results.

Direct Methods of Model Analysis

The most obvious direct method of model analysis consists of measuring linear strains on a model with strain gages. The Berry

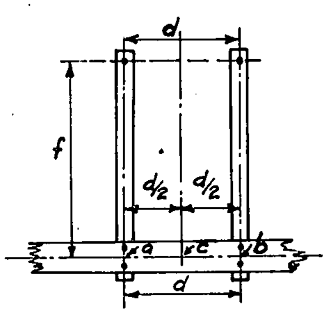

Fig. 1a
(Before Distortion)

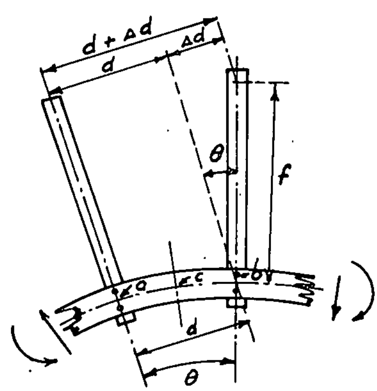

Fig. 1b
(After Distortion)

strain gage and the Huggenberger tensometer are two well-known gages which may be used for this purpose. With these and similar gages, direct stresses in members may be determined, and it is believed that methods might be developed whereby they could also be used in the determination of bending moments and shears.

The determination of bending moments in members of rigid frames is of particular interest in model analysis. Any number of direct approaches might be made in their determination, two of which will be discussed briefly. In theory, the simplest set-up would consist of measuring the change of slope between two points a and b as shown in Fig. 1.

Then $\theta = \frac{\Delta d}{f} =$ area under $\frac{M}{EI}$ curve between a and b by the first moment area theorem. Since shear between a and b is constant, the moment curve between the two points is a straight line. Hence, if I and E are constant, $\theta = \frac{\Delta d}{f} = \frac{1}{2}\left\{ \frac{M_a}{EI} + \frac{M_b}{EI} \right\} d = \frac{M_c}{EI} d$. From this expression, $M_c = \frac{EI\Delta d}{fd}$. The term Δd may be determined by reading the distance between points on the ends of the arms with a microscope before and after the distortion of the beam occurs; once Δd is known, M_c may be calculated, provided the E of the material used is also known. I, f and d are, of course, easily measured. By determining the moments at two points in a beam, the shear in the beam can be computed.

FIG. 2*a*
(Before Distortion)

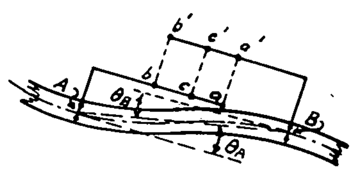

FIG. 2*b*
(After Distortion)

While simple in theory, various factors contribute to making accurate determinations of moments by the method just described extremely difficult. The M. I. T. moment indicator, developed in principle by Prof. A. C. Ruge, and adapted to the problem at hand by Mr. E. O. Schmidt, possesses inherent advantages which lead to a more accurate determination of moments. This indicator is based in theory upon the slope deflection equations, and may be explained by reference to Fig. 2.

From Fig. 2*b*, $bb' = d + \frac{L}{3}\,\theta_A + \frac{2L}{3}\,\theta_B$

$\therefore\ bb' - d =$ relative movement of points b and $b' = \underline{b} =$

$\frac{L}{3}\theta_A + \frac{2L}{3}\theta_b = \frac{L}{3}(2\theta_B + \theta_A)$; also $aa' = d + \frac{2L}{3}\theta_a + \frac{L}{3}\theta_B$

$\therefore$ $aa' - d =$ relative movement of points a and $a' = \underline{a} =$

$$\frac{2L}{3}\theta_A + \frac{L}{3}\theta_b = \frac{L}{3}(2\theta_A + \theta_B); \text{ also } cc' = d + \frac{L}{2}\theta_a + \frac{L}{2}\theta_b$$

$\therefore$ $cc' - d =$ relative movement of points c and $c' = \underline{c} =$

$$\frac{L}{2}\theta_a + \frac{L}{2}\theta_b = \frac{L}{2}(\theta_A + \theta_B)$$

By the slope deflection theorem —

$$M_{AB} = \frac{2EI}{L}(2\theta_A + \theta_B) = \frac{2EI}{L} \cdot \frac{3\underline{a}}{L} = \frac{6EI\underline{a}}{L^2}$$

$$M_{BA} = \frac{2EI}{L}(2\theta_B + \theta_A) = \frac{2EI}{L} \cdot \frac{3\underline{b}}{L} = \frac{6EI\underline{b}}{L^2}$$

$$V_{BA} = \frac{M_{AB} + M_{BA}}{L} = \frac{1}{L}\left[\frac{2EI}{L}(2\theta_A + \theta_B + \theta_A + 2\theta_B)\right] =$$

$$\frac{6EI}{L^2}(\theta_A + \theta_B) = \frac{6EI}{L^2} \cdot \frac{2\underline{c}}{L} = \frac{12EI\underline{c}}{L^3}$$

Hence, if $\underline{a}$, $\underline{b}$ and $\underline{c}$ are determined from the model study, by reading movements of points on the moment indicator with a microscope, and if E is known, the moments and shear in the member considered may be determined.

The material used in the model must behave elastically if correct results are to be obtained. It should have a relatively low value of E, so that the distortions will be large enough to be measured with a fair degree of accuracy. It should be easy to work with so that the construction of the model will not involve too much time and expense. Celluloid meets these requirements, and consequently is much used. Two difficulties of major importance are present, however, when celluloid is used. While celluloid has a definite value of E at a given instant, it changes appreciably from day to day, due to drying and consequent hardening and to changes in temperature. More serious still, celluloid creeps under load, that is, if a load is applied, while some 85 per cent of the deformation occurs within a few seconds, the remaining 15 per cent occurs more slowly. It would be necessary to wait an appreciable period — in the neighborhood of fifteen minutes — before motion would be essentially complete. Even then small movements would still be occurring. So many measurements must be made that to wait for the creep to occur on each measurement would be impractical. Fortunately the strains due to creep are proportional to the fiber stresses acting, as are also the strains due to the initial elastic character of the celluloid. It is therefore correct to say that the effect of creep corresponds to a lowering of the modulus of elasticity. At any instant, however, the effective E for the entire model is constant. Referring to Fig. 3*a*, if load P is applied at the end of the cantilever shown, the elastic curve will progressively assume different positions, and readings on a moment indicator would change correspondingly. Suppose, however, the end of the cantilever is subjected to a fixed deformation as shown in Fig. 3*b*. Then the cantilever end remains in a fixed position, and the elastic curve of the beam does likewise. Although E is changing with time, the shape of the elastic curve does not depend upon the

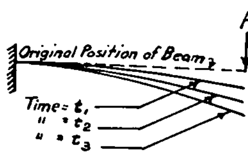

FIG. 3*a*

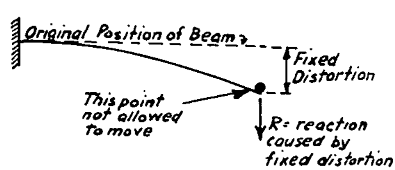

FIG. 3*b*

particular value of E at any instant, as long as that value is constant for the entire beam. A definite reading on the moment indicator may be made. The value of R decreases with time because of creep, but the reading on the moment indicator corresponds to that which would result if an unknown force, P, which remained constant, acted at the end of a cantilever beam of unknown but unchanging E. Under these conditions, values of moment read on the indicator for different points on the beam would be in the correct ratio to each other; in other words, relative values of moment at points along the beam due to a load P at the end may be determined.

For these results to be of use, the actual value of the moments in terms of P must be obtained. Under most circumstances this may be carried out by applying an equation of statics which involves a number of bending moments, the relative value of each being known. For example, referring to Fig. 4, suppose the relative values of the moments in the column ends A, B, C and D due to load P have been determined by the moment indicator. From these relative values the constants C_1, C_2 and C_3 are known in the equations —

$$M_{BA} = C_1 M_{AB}$$
$$M_{CD} = C_2 M_{AB}$$
$$M_{DC} = C_3 M_{AB}$$

Then by statics

$$Ph + M_{AB} + M_{BA} + M_{CD} + M_{DC} = 0$$
$$Ph + M_{AB}\,(1 + C_1 + C_2 + C_3) = 0$$
$$M_{AB} = \frac{-Ph}{1 + C_1 + C_2 + C_3}$$

This involves reading the indicator at four points in order to determine the value of one moment. As a rule, however, all the moments in the frame are required, and they may now all be easily evaluated, so

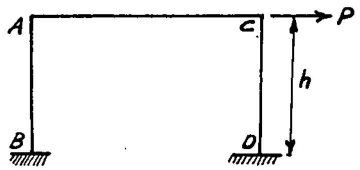

FIG. 4

that when an equation of statics is available, the fact that only relative values of moments can be determined by the method outlined is no great disadvantage.

In the determination of secondary moments in trusses, however, no equations of statics are available to convert relative values of moments to absolute values. Because of this difficulty, a method has been developed which can be used to obtain absolute values of moments directly with the moment indicator. Suppose on the cantilever beam shown in Fig. 5 a fixed deflection is imposed by moving B to B' and holding it there. The force required to impose this deflection is carried by the steel wire 1–2 to a celluloid spring balance 3–4–5–6 which is composed of two crossbeams 3–4 and 5–6 which are made from the same piece of celluloid as is the cantilever beam. The two crossbeams are connected by steel strips 3–5 and 4–6. From the crossbeam 5–6 the force is carried to the end of the cantilever beam by the steel wire 7–8. The moment indicator is clamped to the cantilever so that the movement of the points at D will measure the relative value of the moment at A, point A being at distance d from the point of application of the load at the end of the cantilever.

When the distortion BB' is imposed the relative movements of the points on the moment indicator are read at D, and this movement called e_1. The centers of the crossbars of the celluloid spring will also move relative to each other. This movement is read, and called e_2.

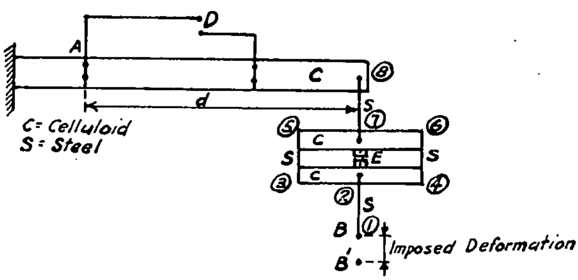

FIG. 5

Now $e_2 = K_2 \frac{P}{E}$ where K_2 is a constant depending on the geometry of the spring, P the tension in the wire at any instant, and E the modulus of elasticity of the celluloid at the same instant. From this relation, $E = \frac{K_2 P}{e_2}$.

Moreover, $M_a = \frac{6EI}{L^2} e_1 =$ where E has the same instantaneous value as in the foregoing equation, and M_a is known by statics to equal Pd, P also having the same instantaneous value as before.

Therefore $Pd = \frac{6I}{L^2} e_1 \frac{K_2 P}{e_2}$ and from this $K_2 = \frac{dL^2 e_2}{6Ie_1}$ and can be evaluated.

The determination of K_2 calibrates the celluloid spring. If it is now required to evaluate a moment in an indeterminate frame, a model is built, using the same kind of celluloid. The indicator is applied at the point where the moment is to be determined, and the load applied by imposing a fixed distortion, making use of the celluloid spring for which K_2 has been determined. Readings e_1 and e_2 are read as before. The following relations then hold, where M is the required moment:

$$M=\frac{EI}{L^2}e_1$$

$$E=\frac{K_2P}{e_2}$$

$$\therefore\ M=\frac{I}{L^2}\ \frac{K_2P}{e_2}e_1=K_3\frac{e_1}{e_2}P$$

In the foregoing expression K_3 is a constant which can be calculated, while e_1 and e_2 are relative movements read on the moment indicator and spring balance, respectively. Thus M becomes known as a direct function of P.

Another direct method of stress analysis with models is made possible by the use of polarized light, and is called the photo-elastic method. It is of particular importance in the solution of problems of stress distribution. It is mentioned in this paper for the sake of completeness, but will not be discussed further.

Indirect Methods of Model Analysis

The best known indirect method of model analysis in this country is that which was developed by Prof. George E. Beggs of Princeton. Referring to Fig. 6, let δ_{ab} be the downward deflection of point a due

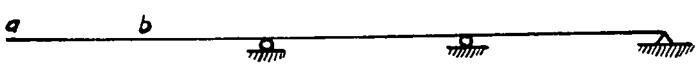

Fig. 6

to a unit downward load at b, and δ_{aa} be the downward deflection of point a due to a unit downward load at a.

If a reaction, R_a, existed at a, the deflection of a due to a unit downward load at b would equal zero. This fact could be mathematically expressed as follows:

$$\delta_{ab}+(-R_a)\ \delta_{aa}=0$$

from which —

$$R_a=\frac{\delta_{ab}}{\delta_{aa}}$$

Suppose that it is desired to obtain the influence line for the left vertical reaction of the continuous beam shown in Fig. 7*a*, and that a model is built as shown in Fig. 7*b*, to which a unit load is applied as shown at the left end. Let δ_{aa} and δ_{ba} be measured. δ_{ba} is the downward deflection of point b due to a unit downward load at point a. By Maxwell's theorem, $\delta_{ba}=\delta_{ab}$, where δ_{ab} is defined in discussing Fig. 6. It follows that —

$$\frac{\delta_{ba}}{\delta_{aa}} = \frac{\delta_{ab}}{\delta_{aa}} = R_a \text{ due to a unit load at } b.$$

If the model were made of celluloid, the creep of the model would preclude the application of a unit load as just suggested. It is possible, however, to impose a fixed distortion at a. To do this requires the original application of an unknown force, Q. As the celluloid creeps,

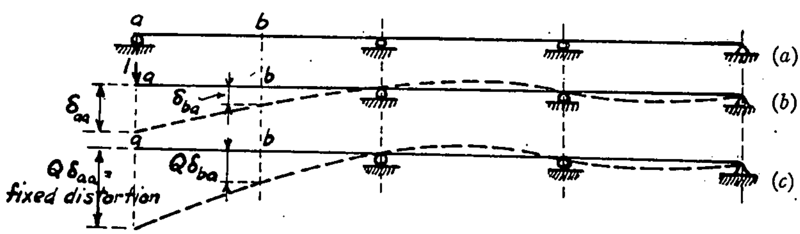

FIG. 7

the force Q changes, but the shape of the elastic curve does not, since the latter does not depend upon the particular value of E existing, as long as E is constant for the entire model; in other words, the model deflects exactly as it would if it had an unchanging although unknown value of E, and were acted upon by an unchanging but unknown force, Q. Under these circumstances the fixed distortion imposed at a may be interpreted as $Q\delta_{aa}$, and the distortion read at b as $Q\delta_{ba}$. It follows that the ratio of the distortion read at b to the distortion imposed at a is given by $\dfrac{Q\delta_{ba}}{Q\delta_{aa}} = \dfrac{\delta_{ba}}{\delta_{aa}} = \dfrac{\delta_{ab}}{\delta_{aa}} = R_a$, the reaction at a due to a unit load at b. Inasmuch as b is any point on the beam, it follows that the ordinates to the influence line for R_a vary directly with $\delta_{ab}=\delta_{ba}$. Thus when a vertical distortion is introduced at a, the model takes the shape of the influence line for R_a. The true values of the ordinates are obtained by dividing the resulting movements at various points by the magnitude of the imposed distortion.

The foregoing discussion has been limited to the special case of the determination of vertical reactions in order to simplify the presentation. The Beggs method is, however, applicable to the determination of any type of reaction or to internal stresses. If, for example, it is

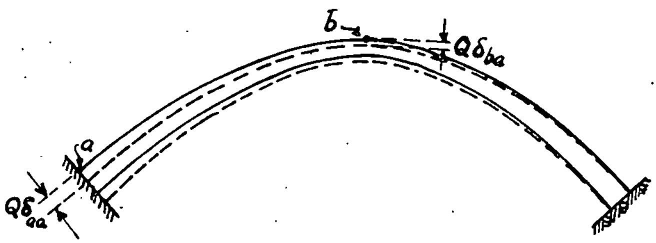

FIG. 8

desired to obtain values of the shear at the left reaction of the arch shown in Fig. 8, a displacement $Q\delta_{aa}$ is introduced at that point which is in the direction of the required shear, that is, normal to the axis of the arch at that point. No tangential movement or change of slope at a is permitted. The ratio $Q\delta_{ba}$ over $Q\delta_{aa}$ then equals the shear at a, due to a unit downward load at b.

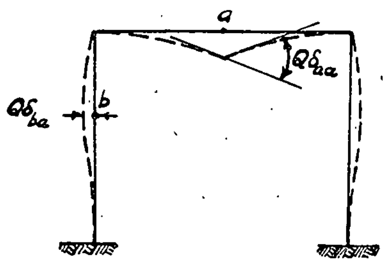

FIG. 9

When an internal stress is desired, it becomes necessary to cut the model in order that the deformation may be imposed. Suppose it is desired to obtain values of moment at the center of the girder of the building frame shown in Fig. 9. The model is cut at a and an angular distortion, $Q\delta_{aa}$, introduced. The two cut ends are not permitted any horizontal or vertical movement relative to each other. The ratio

$Q\delta_{ba}$ over $Q\delta_{aa}$ then equals the moment at a, due to a unit horizontal load at b, inasmuch as $Q\delta_{ba}$ is measured horizontally.

The necessity of cutting the model in order to obtain internal stresses seems to be a disadvantage of the Beggs method. The use of the moment indicator; which is simply clamped to the member where the moment is to be measured, has an advantage in this respect. The Beggs method has the advantage, however, that it gives stresses as a function of applied loads with the necessity of the spring balance.

Simultaneous Calculator

One of the major difficulties which is present in the analytical solutions for stresses in indeterminate structures is in the solution of simultaneous equations. In running tests on models, particularly in trying to develop new methods and techniques of model analysis, it is necessary to make analytical solutions as a check on the model work. For the solution of simultaneous equations there has been developed at Massachusetts Institute of Technology the simultaneous calculator, which under some conditions saves considerable time. The simultaneous calculator can, in a direct solution, solve nine or fewer linear simultaneous equations, and, by an indirect method, handle a greater number of unknowns. Arbitrary accuracy of results may be obtained by successive approximations. A description of this machine appeared in the December, 1936, issue of the Proceedings of the Journal of the Franklin Institute, which describes the theory upon which it is based.

Conclusion

This description of model analysis has of necessity covered only some of the high spots in the theory of model analysis. It is hoped, however, that it will serve to make the inspection of the laboratory of greater interest than would otherwise have been the case.

Of General Interest

PROCEEDINGS OF THE SOCIETY

MINUTES OF MEETINGS

Boston Society of Civil Engineers

NOVEMBER 17, 1937. — A regular meeting of the Boston Society of Civil Engineers was held this evening at Chipman Hall, Tremont Temple, and was called to order by the President, Arthur D. Weston, at 7 P.M.

This meeting was the annual joint meeting with the Student Chapters of the American Society of Civil Engineers at Harvard University, Massachusetts Institute of Technology, Tufts, Brown University, Rhode Island State College and the Northeastern University Section of the Boston Society of Civil Engineers. About 175 members and guests attended, and 152 persons attended the buffet supper.

The President extended a welcome to the students and expressed appreciation of the co-operation of all those who had co-operated in obtaining so large an attendance.

The Secretary reported the election of the following members on this date:

Grade of Member: Clinton C. Barker, Oral J. Calderara,* James N. De Serio,* Frank L. Heaney,* Waldo I. Kennerson, Oscar R. Lindgren,* Martin J. Markham,* Sabestino Volpe,* Charles A. White,* Julian H. White.*

Grade of Junior: James B. Gibbs,† Richard Halloran, William H. Mitchell,† Harry Samuel Perdikis,† Walter A. Randazzo, John F. Wiseman.†

Grade of Student: Chester L. Harris.

The President introduced Mr. John Elliott, who outlined briefly the campaign for associate membership in the Engineering Societies of New England.

The President then introduced the speaker of the evening, Dr. Miller McClintock, Director of Bureau for Street Traffic Research, Harvard University. He gave an extremely interesting talk on "New Types of Traffic Facilities." Descriptions were given of some of the modern super highways for the rapid and expeditious handling of large volumes of motor traffic, and the fundamental principles of design to prevent interruption to traffic flow and for providing safety as well as unimpeded movement. A question period followed the talk.

The President called upon Mr. Edgar F. Copell, Traffic Engineer, Massachusetts Department of Public Works, for discussion.

The meeting adjourned at 9.20 P.M.

EVERETT N. HUTCHINS, *Secretary.*

DECEMBER 15, 1937. — A regular meeting of the Boston Society of Civil Engineers was held this evening at the Engineers Club, and was called to order at 7 P.M. by the President, Arthur D. Weston. Fifty members and guests were present. Forty persons attended the buffet supper.

The President announced the death of the following members: Neal J. Holland,

* Transfer from Grade of Junior.

† Transfer from Grade of Student.

who died December 2, 1937, and had been a member since May 17, 1911; James A. McKenna, who died June 15, 1937, and had been a member since December 20, 1899; Edgar P. Sellew, who died October 20, 1937, and had been a member since October 17, 1888.

The Secretary reported that the following had been elected to membership on December 15, 1937:

Grade of Member: John H. Bowie.*

Grade of Student: Arnold B. James, Grant W. Joslin, Gordon A. Thomson.

Upon recommendation of the Board of Government it was —

Voted, That the Board of Government be authorized to use as much of the current income of the Permanent Fund as is necessary to meet the current expenses of the Society. The President stated that this matter will be presented at the January 26, 1938, meeting for final action.

The President then introduced the speaker of the evening, Mr. Lawrence Orton, Secretary and General Director, Regional Plan Association, Inc., New York City, who gave a very interesting talk on "Large Scale Planning," with particular reference to the developments in New York City, and he outlined the extensive powers and duties of the new planning commission for the city.

The meeting adjourned at 9 P.M.

EVERETT N. HUTCHINS, *Secretary.*

Sanitary Section

NOVEMBER 12, 1937. — A special meeting of the Sanitary Section was held this evening at the Massachusetts Institute of Technology, Cambridge. Preceding the meeting nineteen members gathered in the North Hall of the Walker Memorial for supper.

The meeting was called to order by the Chairman, Richard S. Holmgren, at 7.15 P.M. in the Eastman Lecture Hall, with thirty-eight members and guests present. Mr. A. B. Morrill, Associate Civil and Sanitary Engineer, city of Detroit, gave a very interesting talk on "Some Features of the New 420 M. G. D. Detroit Sewage Treatment Plant." The construction of this plant is now nearly completed, and the description of the various problems encountered during construction held the interest of all who attended. Following the discussion the meeting adjourned at 8.25 P.M.

RALPH M. SOULE, *Clerk.*

Designers Section

NOVEMBER 23, 1937. — The November meeting of the Designers Section was held jointly with the Highway Section at the Society Rooms.

The speaker was Mr. Donald W. Taylor, Research Associate in Soil Mechanics at the Massachusetts Institute of Technology. He spoke on the "Stability of Earth Slopes," discussing in detail the paper which appeared under this title in the July, 1937, JOURNAL of the Boston Society of Civil Engineers.

The talk was illustrated by lantern slides.

A question and discussion period followed the talk, and the meeting adjourned at 7.55 P.M.

The attendance was forty.

J. D. MITSCH, *Clerk.*

DECEMBER 8, 1937. — The December meeting of the Designers Section was held at the Massachusetts Institute of Technology on December 8, 1937, at 7 P.M.

The meeting consisted of a talk by Prof. John B. Wilbur, Associate Professor of Civil Engineering at Massachusetts Institute of Technology, and an inspection of the new structural model laboratory. In the talk Professor Wilbur discussed the instruments and materials used in the testing and building of structural models.

The inspection of the various problems being carried on in the laboratory proved interesting and instructive, and the meeting closed at 8.30 P.M.

The attendance was forty-five.

J. D. MITSCH, *Clerk.*

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* Transfer from Grade of Junior.

APPLICATIONS FOR MEMBERSHIP

[January 10, 1938]

THE By-Laws provide that the Board of Government shall consider applications for membership with reference to the eligibility of each candidate for admission and shall determine the proper grade of membership to which he is entitled.

The Board must depend largely upon the members of the Society for the information which will enable it to arrive at a just conclusion. Every member is therefore urged to communicate promptly any facts in relation to the personal character or professional reputation and experience of the candidates which will assist the Board in its consideration. Communications relating to applicants are considered by the Board as strictly confidential.

The fact that applicants give the names of certain members as reference does not necessarily mean that such members endorse the candidate.

The Board of Government will not consider applications until the expiration of fifteen (15) days from the date given.

For Admission

BECKER, ROBERT MAXWELL, Brighton, Mass. (Age 24, b. Boston, Mass.) Graduated, 1934, from Massachusetts Institute of Technology with S.B. degree in building engineering and construction; June, 1934, to April, 1935, laboratory assistant to Prof. W. C. Voss at Massachusetts Institute of Technology, on masonry materials research; May, 1935, to July, 1935, engineer and quantity clerk with Aberthaw Company, on Suffolk Downs grandstand; September, 1935, to March, 1936, architectural draftsman and specification writer with D. J. Abrahams, Boston, and assistant to T. F. McSweeney, consulting engineer, Boston, part time with each. March, 1936, to June, 1936, in charge of field engineering with Temple & Crane, Inc., first-class factory building, North Smithfield, R. I.; June, 1936, to January, 1937, superintendent and estimator with Arnold Hartmann, Newton Center (Oak Hill Village), building eight large residences. January, 1937, to date, with H. E. Cline Construction Company, Boston, as engineer and estimator, in charge of new apartment building, 1960–1980 Commonwealth Avenue, Brighton, and superintendent of construction of addition to W. T. Grant Building, Newport, R. I. Refers to *J. B. Babcock, J. G. Dietz, W. M. Fife, J. D. Mitsch, W. C. Voss.*

DAVIS, ERNEST LEWIS FREDERICK, Boston, Mass. (Age 55, b. Boston, Mass.) Graduated from Mechanics Arts High School, Boston, in 1902; then employed as draftsman in structural iron shop preparing detail plans for shop and erection use; April, 1904, to September, 1911, with Metropolitan Park Commission as rodman, transitman and resident engineer; September, 1911, to November, 1911, with Massachusetts Highway Commission as resident engineer; November, 1911, to May, 1913, with Massachusetts State Board of Health in charge of party on Neponset River improvement; May, 1913, to February, 1921, with Metropolitan Park Commission, as chief of party and resident engineer in charge of surveys and construction of Cottage Farm bridge and temporary Neponset River bridge; February, 1921, to the present time, first, in charge of drafting room, then office assistant to chief engineer, Massachusetts Department of Public Works; now associate civil engineer. Refers to *A. W. Dean, G. H. Delano, R. K. Hale, E. N. Hutchins.*

MAYER, DAVID, Cambridge, Mass. (Age 22, b. New York, N. Y.) Graduated, 1936, with degree of A.B., from Harvard College, and Harvard School of Engineering, with degree of M.S., in 1937; during summers of 1935 and 1936, with Bethlehem Steel Company, Fabricating Division, Pottstown, Pa., apprentice in drafting room; now engaged in building materials research, as research assistant at Massachusetts Institute of Technology. Refers to *Arthur Casagrande, G. M. Fair, A. Hartlein, H. M. Westergaard.*

RICH, EDWIN STAFFORD, Norwood, Mass. (Age 30, b. Boston, Mass.) 1926, graduated from Wentworth Institute, course in architectural construction; 1928, completed Lowell Institute course in buildings; 1926–28, structural detailer with New England Structural Company; 1928–31, structural detailer and estimator with Palmer Steel Company, Springfield, Mass.; 1931–32, estimator with A. O. Wilson Structural Company; 1932–33, sales engineer with Frigidaire Sales Corporation; 1933–34, timekeeper with West Construction Company; 1934–35, timekeeper and job engineer with Blakeslee, Rollins Corporation; 1935–37, New England District Construction Supervisor (Safety Engineering Department) of Liberty Mutual Insurance Company; 1937 to date, engineer with Blakeslee, Rollins Corporation. Refers to *M. F. Brown, C. A. Farwell, J. W. Howard, S. Huckins.*

For Transfer from Grade of Junior

CAVAZZONI, JOSEPH FRANCIS, Somerville, Mass. (Age 29, b. Bologna, Italy.) Graduated from Somerville, Mass., High School, 1926, and Northeastern University, 1930, with degree of B.C.E.; May, 1930, to July, 1934, with John Williams, contractor, as estimator and superintendent in various types of construction, including sewers, roads, drains and water mains in cities in Massachusetts; July, 1934, to January, 1937, with A. Singarella, contractor, as estimator on building sewers, water works, concrete and steel bridges, culverts. Since January, 1937, in private practice, making plans for various structures and surveying. Refers to *H. B. Alvord, S. O. Baird, Jr., J. J. Casey, A. E. Everett, Jr.*

For Transfer from Grade of Student

PERRY, LESTER S., Boston, Mass. (Age 24, b. Somerville, Mass.) Graduated from Northeastern University, 1937, with degree of B.S. in civil engineering. July to November, 1936, as co-operative student with Department of Interior National Park Service as a special enrollee in the Civilian Conservation Corps as rodman, transitman and draftsman; February to April, 1937, with W. W. Churchill, surveyor, Milton, Mass., as transitman and chief of party; September, 1937, to present time, draftsman with Water Bureau, Metropolitan District, Hartford, Conn. Refers to *H. B. Alvord, C. O. Baird, Jr., E. A. Everett, Jr., E. A. Gramstorff, H. A. Phillips.*

ADDITIONS

Members

CLINTON C. BARKER, 33 Crossman Avenue, Beach Bluff, Mass.

JOHN H. BOWIE, 36 Lantern Lane, Milton, Mass.

ORALL J. CALDERARA, Box A, Templeton, Mass.

GEORGE A. MACDONALD, 930 Summit Avenue, River Edge, N. J.

MARTIN J. MARKHAM, 35 Lincoln Street, Stoneham, Mass.

CHARLES A. WHITE, North Falmouth, Mass.

JULIAN H. WHITE, 84½ Washington Street, Brewer, Maine.

Juniors

RICHARD HALLORAN, 95 Dedham Street, Newton Highlands, Mass.

HARRY S. PERDIKIS, 419 Federal Building, Providence, R. I.

JOHN F. WISEMAN, 26 Clayton Street, Malden, Mass.

Students

CHESTER L. HARRIS, 922 Beacon Street, Boston, Mass.

ARNOLD B. JAMES, 923 Beacon Street, Boston, Mass.

GRANT W. JOSLIN, 33 Westminster Avenue, Arlington, Mass.

GORDON A. THOMSON, East Gay Street, Dedham, Mass.

DEATHS

NEAL J. HOLLAND . . . . Dec. 2, 1937
JAMES A. MCKENNA . . June 15, 1937
EDGAR P. SELLEW . . . Oct. 20, 1937

BOOK REVIEWS

*"Bridges in History and Legend," by Wilbur J. Watson and Sara R. Watson. 248 pages. Published by J. H. Jansen, Cleveland, Ohio. Price, $3.50.**

This is a non-technical book designed to show the significance of bridges in civilization, in the thought of man, and in his art. There are general descriptions of historical bridges and many pen and ink sketches illustrating these structures, but such material is only incidental to the main purpose. The principal emphasis is on legends and stories about bridges, and on events which have occurred on famous bridges. It seems that every famous bridge has had a poem written about it at some time or other. Many poets have used the bridge as a symbol in writing about life. Poetry is prominent throughout the volume, and comprises about ten per cent of the total number of printed lines in the book.

The earliest legendary references are to Rainbow Bridges, which have a religious symbolism and span from this to another world. These structures sustain the good and let fall the evil. There follow stories about Devil's Bridges, of which there are many existing specimens and whose construction was made possible only through the intervention of the devil, who has claimed a soul for his part in the deal. Later, the gods of both heaven and hell are concerned, and the bridge builders are church officials who construct Sacred Bridges to span streams which are identified with agents of Satan.

From very early times bridges have been important in military operations and, therefore, War Bridges are given their proper amount of space. This part of the book is not legendary but historical, and includes incidents from the building of the pontoon bridge over the Hellespont in 480 B.C. to the murder on the bridge at Sarajevo which precipitated the World War.

An entire chapter is devoted to the Old London Bridge, which was partly financed by a tax on wool. It is interesting to know that at one time tolls were collected from boats passing under this bridge as well as from traffic passing over it. Rentals from buildings on the bridge was another source of revenue. In medieval times a source of revenue for chapel or sacred bridges was the sale of indulgences.

In connection with Toll Bridges one learns that the Old Cambridge Bridge, built in 1786 on the site of the present Longfellow Bridge, paid principal, interest and about $7,000 surplus to each original share in forty years. This is a contrast to present-day toll bridges, which do not enjoy that kind of prosperity.

A chapter on Peace Bridges contains many stories of human interest. Medieval bridges were built for peaceful purposes, but had to be strongly fortified. The Karlsbrücke at Prague took one hundred and forty-six years to build. A bridge is involved in the origin of the card game "bridge whist" according to one story.

One chapter contains brief sketches of famous Bridge Builders. Another traces the development of bridge construction in the last century.

It is gratifying for an engineer to learn that bridges have participated to such an important degree in the history of civilization and that they have been found fit subjects by so many poets, artists and writers. While not technical, this book can be of value to an engineer in developing background.

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*"A Decade of Bridges," by Wilbur J. Watson. 125 pages. Published by J. H. Jansen, Cleveland, Ohio. Price, $4.50.**

In the design of bridges it is helpful to know what has been done previously in the projection of similar structures, what difficulties were encountered, and how they were met. This book provides answers to such questions by presenting a photographic record of the progress of bridge building in the decade 1926–1936, together with general descriptions and comments on engineering and architectural

* Reviewed by Eugene Mirabelli, Assistant Professor of Structural Design, Massachusetts Institute of Technology, Cambridge, Mass.

aspects of some one hundred notable bridges.

The illustrations are of both European and American structures, but only those are included which contain novel engineering or architectural features or serve to illustrate modern tendencies in bridge design. Reference is made to the more interesting points met in the design, financing, construction and operation of these bridges. Physical data appears throughout the volume, and occasionally there is a historical reference. Designers, consultants and contracting firms connected with each project are noted.

For more detailed information about the bridges included in the text the reader is referred to the appendix, which contains a selected index to descriptions in technical journals.

The principal feature of the book is probably its collection of excellent photographs. This volume, together with the author's previous volume on "Bridge Architecture," provides a continuous photographic history of the world's famous bridges from the earliest times to the year 1936.

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*"Theory of Statically Indeterminate Structures," by Walter Maxwell Fife and John Benson Wilbur, Associate Professors of Civil Engineering at Massachusetts Institute of Technology. 245 pages. Published by McGraw-Hill Book Company, New York, 1937. Price, $3.50.**

In their new text, "Theory of Statically Indeterminate Structures," Professors Fife and Wilbur of the Massachusetts Institute of Technology have for the first time made accessible to the average American engineer the rigorous structural thinking of the great German analyst, Dr. Heinrich Müller-Breslau. This is a mature, closely reasoned treatise which the beginner in the indeterminate field will find somewhat more difficult than those texts which approach the subject in the freer fashion usual in this country, — a difficulty which should be compensated for by increased competency and thoroughness of understanding. The graduate student, with the usual undergraduate preparation in indeterminate analysis, will traverse these pages with relative ease and pleasure, finding that they open up new relations and points of view which integrate "in a thorough and cohesive manner the principles which underlie the analysis of statically indeterminate structures." Throughout the book there is a generous use of numerical examples which give concreteness and clarity to the discussions.

The first chapter deals with the usual basic concepts and theorems presented in a very unusual and thorough manner. The general case of a three-dimensional frame with joints capable of resisting bending is considered, with six independent elements of stress at any section and six independent components of deflection for the end of any member. The unknowns accordingly number six times the sum of the joints and bars. For each joint six equations of equilibrium may be written, and for each member six geometric equations relating the conditions of end deflection. This manner of setting up basic relations is probably new to most American readers. The conditions for status as statically determinate, stable, unstable, statically indeterminate, are carefully investigated in detail from this general basis. The study of stability criteria is of especial interest, since their need was brought to our attention by Mr. Alfred Waidelich soon after the appearance of the Wickert truss.

The law of virtual work and those of Clapeyron and Betti are derived also with unusual thoroughness and generality. Maxwell's law of reciprocal deflections is stated briefly as a special case under Betti's law.

The second chapter is headed "Deflections," and considers the first portion of the general problem of analysis, the determination of the shape of the distorted loaded structure. The computation methods given comprise those by virtual work and by Castigliano's law, the Williot-Mohr graphical method, and Müller-Breslau's bar chain method. The basic theorems of moment-area and elastic weights are developed, having regard to shear as well as to bending strain.

* Reviewed by Hale Sutherland, Professor of Civil Engineering, Lehigh University.

The second half of the general problem of structural analysis, the determination of stress at any point in a structure, is considered in Chapter III, and the discussion probably conforms more closely to the usual methods of presentation than do the preceding chapters. Since only sixty-nine pages are given to the stress analysis of trusses and rigid frames, it is evident that only basic methods and the more common situations are discussed, omitting such topics as members of variable section, multiple story frames under lateral loading, and frames of multiple span, to mention three "headaches" of not uncommon appearance in structural offices.

The first method of analysis considered utilizes the familiar equations of consistent distortion given by application of the law of virtual work. When considering frames with moment-resisting joints shear distortion is included. The use of the elastic center is studied in connection with single-span, one-story frames, and it is demonstrated that this leads to the method of column analogy of Prof. Hardy Cross. A very fine development is given for the application of Castigliano's law to indeterminate trusses and frames, which, for the usual situation of unyielding supports, results in that essential basic — the familiar method of least work.

The standard equations for end moments for members with restrained ends are developed with exceptional clarity as to significance, and from these equations the methods of slope-deflection and the three-moment equation are derived. The last twelve pages of the chapter are given to Professor Cross' method of moment distribution as applied to continuous beams and to one and two story frames.

The fourth chapter (thirty-eight) pages is given to the practically important topic of influence lines for statically indeterminate structures. The possibilities of labor reduction by systematization of work are illustrated by the computation of an influence line by successive positions of the unit load. The use of the elastic curve and Maxwell's law in constructing influence lines for deflection, bar stresses and reactions is here illustrated for trussed structures, both singly and doubly indeterminate. The discussion of influence lines for fixed ended, restrained and continuous beams leads to a brief exposition of methods of mechanical analysis. The chapter concludes with a brief statement of the fixed-point method for continuous beams.

The fifth and concluding chapter deals with secondary stresses in trusses, giving the variation of the Manderla method suggested by Winkler, the Mohr semigraphical method, and Prof. Hardy Cross' method of moment distribution.

In their preface the authors point to the criticism currently leveled at the so-called classic methods of analysis, and state their conviction that the principles underlying these methods furnish "the best possible foundation for a knowledge of structural theory, and that familiarity with them is essential to an understanding of structural behavior." They do not decry nor neglect the great contributions of Professor Cross, but their major interest and effort is given to the classic methods, and they have accomplished a very fine piece of work in support of their thesis. It may be questioned, however, whether the situation is quite as this preface statement implies. In his method of moment distribution, Professor Cross introduced no new principles, but rather presented a revolutionary procedure which immensely facilitates both the application of basic principles and the visualization of structural action. Our authors emphasize the first point but not the second. The structural analyst should recognize that he deals with a compact body of basic principles involving several differing methods of mathematical application, whose relative values are to be judged on the basis of laboriousness and the degree of obscuration of the physical action of the loaded structure involved in the processes of computation. It is probable that this point of view would have led in no way to any change or curtailing of the treatment the authors have given the "classic" in this text, but rather to a more extensive and thorough study of moment distribution which by reason of its basic nature should henceforth rate as a truly *classic* method.

Vol. XXV
Sect. 1

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No. 1

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1848
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JANUARY - 1938

VOLUME XXV
TWO SECTIONS

NUMBER 1
SECTION 2

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Volume XXV
Two Sections

JANUARY, 1938

Number 1
Section 2

CONTENTS

Section 2

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REPRESENTATIVE HYDRAULIC LABORATORIES IN THE UNITED STATES AND CANADA

BY LESLIE J. HOOPER, MEMBER*

DURING the period 1934–36, the author was granted the John R. Freeman Scholarship of the Boston Society of Civil Engineers. This scholarship and a similar grant by the Alden Hydraulic Laboratory of Worcester Polytechnic Institute made it possible to inspect about 50 representative hydraulic laboratories in the United States and Canada. The following paper is a result of these inspections.

It is the purpose of this paper to describe a number of hydraulic laboratories in both countries in an effort to present a cross-sectional view of the development of such organizations. The descriptions have all been made correct for June, 1937, so as to present the information on a common basis as far as possible.

The expense of the inspection trips which supplied the material for these descriptions and of publishing this paper was borne jointly by the John R. Freeman Scholarship Fund of the Boston Society of Civil Engineers and by the Alden Hydraulic Laboratory of Worcester Polytechnic Institute.

* Instructor of hydraulic engineering, Worcester Polytechnic Institute, Worcester, Mass. John R. Freeman Scholar, 1934–1936.

CONTENTS

REPRESENTATIVE HYDRAULIC LABORATORIES IN THE UNITED STATES AND CANADA

Introduction

It was not possible for the author to visit all existing laboratories because both funds and time were limited, and the number of hydraulic laboratories at the present time exceeds 150. In addition, knowledge of the existence of some laboratories was not available at the start of the work.

Among those omitted that might be mentioned are the pump-testing laboratories of the Dominion Engineering Company, De Laval Company, and the Worthington Pump and Machinery Company. The pump and water wheel laboratory of the Allis Chalmers Company was not open for inspection. The present instructional laboratory of New York University was not installed at the time of the visit to that region. A number of college laboratories through the South and West were missed because of the time and expense involved in traveling back and forth over relatively great distances. For these reasons a number of excellent laboratories were not seen nor described in this paper. It is believed, however, that the original purpose of presenting a cross-sectional view of laboratory conditions has been realized within the limitations stated.

In order to show concisely the type of work being done at the present time, three tables have been prepared. The first comprises commercial and governmental laboratories and the types of work which they are equipped to perform. The second table comprises college laboratories which are also engaged in commercial work. The third and final table lists those colleges which are engaged primarily in staff research and student instruction.

TABLE 1. — COMMERCIAL AND GOVERNMENT LABORATORIES

	Water Wheels	Cavitation	Pumps	Calibration of Instruments	Fundamentals of Flow	Model Hydraulic Structures	River Laboratories	Transportivity	Towing Tanks
Baldwin Southwark Corporation, I. P. Morris Division	x	–	x	–	–	–	–	–	–
Byron Jackson Company	–	–	x	–	–	–	–	–	–
Bonneville Hydraulic Laboratory, Corps of Engineers	x	–	–	–	–	x	x	–	–
Holyoke Water Wheel Testing Flume	x	–	–	–	–	–	–	–	–
Langley Field	–	–	–	–	–	–	–	–	x
James Leffel Water Wheel Company	x	–	–	–	–	–	–	–	–
Lowell Locks and Canals	–	–	–	x	x	–	–	–	–
National Hydraulic Laboratory	–	–	–	x	x	x	–	x	–
Newport News Shipbuilding and Drydock Company	x	x	x	–	–	–	–	–	x
Pelton Water Wheel Company	x	–	x	–	–	–	–	–	–
Pennsylvania Water and Power Company, Holtwood Laboratory	x	x	–	–	–	–	–	–	–
Bureau of Reclamation:									
Denver Laboratory	–	–	–	–	–	x	–	x	–
Fort Collins Laboratory	–	–	–	–	–	x	–	–	–
Montrose Laboratory	–	–	–	–	–	x	x	x	–
Rodney Hunt Machine Company	x	–	–	–	–	–	–	–	–
Shawinigan Experimental Turbine Testing Plant	x	x	–	–	–	–	–	–	–
S. Morgan Smith Company	x	–	x	–	–	x	–	–	–
Tennessee Valley Authority	–	–	–	–	–	x	x	–	–
United States Waterways Experiment Station	–	–	–	–	–	x	x	x	–

TABLE 2. — COLLEGE LABORATORIES ENGAGED IN RESEARCH AND COMMERCIAL WORK

	Water Wheels	Cavitation	Pumps	Calibration of Instruments	Fundamentals of Flow	Model Hydraulic Structures	River Laboratories	Transportivity	Towing Tanks
California Institute of Technology	–	x	x	x	–	x	x	–	–
California, University of	–	–	x	x	x	x	x	x	x
Carnegie Institute of Technology	–	x	–	x	–	x	x	–	–
Case School of Applied Science	–	–	–	x	–	x	–	–	–
Cornell University:									
Mechanical Engineering Department	–	x	x	x	–	–	–	–	–
Civil Engineering Department	–	–	–	x	x	x	x	–	–
Iowa, University of	–	–	–	x	x	x	x	x	–
Maine, University of	–	–	–	x	x	x	–	–	–
Massachusetts Institute of Technology	–	x	–	x	x	x	x	x	–
Michigan, University of	–	–	x	x	–	–	–	–	x
Minnesota, University of	x	–	–	x	x	x	x	x	x
Ohio State University	–	–	x	x	–	–	–	–	–
Pennsylvania, University of	–	–	–	x	x	x	–	–	–
Stevens Institute of Technology	–	–	–	–	–	–	–	–	x
Wisconsin, University of	–	–	–	x	x	x	–	–	–
Worcester Polytechnic Institute	x	–	x	x	x	x	x	x	–

TABLE 3. — COLLEGE LABORATORIES USED FOR INSTRUCTION AND FOR SCIENTIFIC RESEARCH

Columbia University.
Illinois, University of.
Louisiana State University.
McGill University
Michigan State College.
Oregon State College.
The Pennsylvania State College.
Princeton University.
Purdue University.
Queen 's University.
Rensselaer Polytechnic Institute.
Stanford University.
Toronto University.
Tulane University.
Tufts College.
Washington, University of.
Yale University.

NOTE. — All college laboratories have equipment for the calibration of Venturi and orifice meters, Pitot tubes and weirs. Practically all have pump and water wheel testing equipment. Princeton, Purdue and Rensselaer have towing flumes and carriages.

The detail description of the laboratories visited follows. It is difficult to present an accurate and complete description of any laboratory based upon a single inspection. To guard against serious misstatements, the drafts of these descriptions have been checked by the directors of the laboratories represented. This opportunity is taken to acknowledge the author's indebtedness to all those who helped so materially in the preparation of this paper.

Hydraulic Laboratory of the I. P. Morris Division Baldwin Southwark Corporation

The hydraulic laboratory of the I. P. Morris Division Baldwin Southwark Corporation, located at Philadelphia, Pennsylvania, is designed for the testing of water wheels, pumps and associated apparatus. The laboratory work is under the immediate direction of Mr. K. W. Beattie, and the work is supervised by Mr. R. E. B. Sharp, hydraulic engineer, of the I. P. Morris Division.

There are three flumes in the water wheel testing apparatus. The first is an elevated open flume in which the water wheel and intake are located. The second and third flumes are located on the ground floor and formed by bulkheads in a single tank. This tank is 4½ feet deep, 10 feet to 15 feet wide, and 43 feet long. The part of this tank which forms the weir flume and approaches takes up about 60 per cent of the tank area, and the remainder constitutes the sump for the system.

The supply flume is 19 feet long and 5 feet wide. The height of this flume is 5 feet where the water is introduced and 4½ feet in the section where the model is located. A 16-inch supply pipe from the pumps brings the water into one side of the head tank. Suitable baffles and racks provide quiet flow conditions for the water wheel which is located near the other end of the flume. A spillway having a crest length of about 8 feet and discharging into the sump skims off the surplus water and maintains a constant head for the test.

The draft tube of the model discharges into the weir flume located on the ground floor. The flume at this point is roughly rectangular and about 18 feet by 15 feet in plan. The water flows from this pool around the end of a vertical diaphragm into the weir channel, which is 4½ feet wide and about 25 feet long. At the entrance to the channel is located a shutter type gate for regulation of the water level at the draft tube discharge. The gate is designed to assist in producing smooth flow in the weir approach channel. Racks, constructed of corrugated sheet iron and located downstream from the gate, effectively produce quiet flow conditions for weir measurements. Between the racks and the weir crest the channel is straight and unobstructed for 15 feet. The weir is of the suppressed type, and the crest is 4 feet 5½ inches long and 3 feet above the bottom of the channel. This weir has been calibrated by volumetric measurements. The discharge from the weir falls into the sump tank.

Water for the test is supplied by two motor-driven Moody propeller type pumps which can deliver a total discharge of about 16 c. f. s. under a head of 8 to 10 feet. One of these pumps is of the spiral casing type and is mounted horizontally on the floor. The other is of the

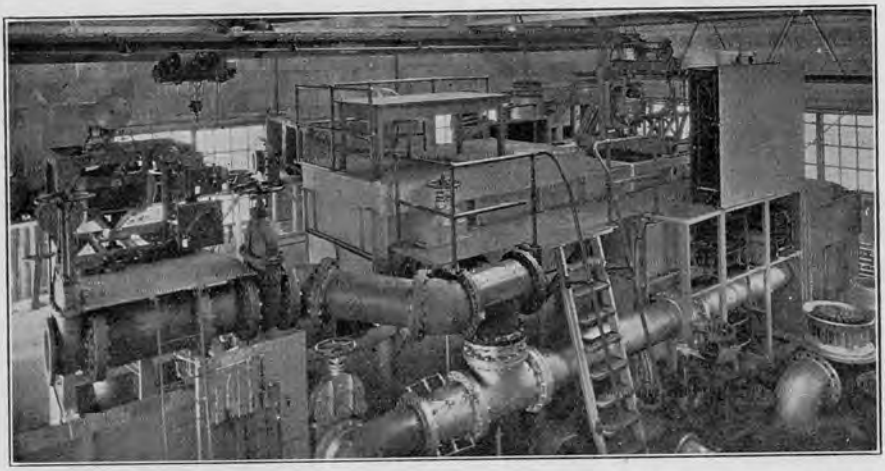

FIG. 1. — WATER WHEEL AND PUMP TESTING LABORATORY OF THE I. P. MORRIS DIVISION OF BALDWIN SOUTHWARK CORPORATION

axial flow type and is mounted vertically over the sump, and driven by a motor arranged to serve as a dynamometer. Both of these pumps have been used for experimental work in pump design.

The water wheel testing flume is designed to test model wheels having a diameter of 16 inches, which has been selected as a standard model size by three leading water wheel manufacturers. The testing apparatus and methods are indicated in the following description. The torque of the water wheel is measured with an electric dynamometer vertically mounted. This piece of apparatus was obtained by altering a standard horizontal dynamometer to make it suitable for a vertical mounting. Since the normal speed rating of the standard machine is considerably higher than the speeds developed by the model turbines, it has been necessary to provide air blast cooling for the absorption of the high torques delivered by the turbines. This equipment is about to be replaced by a new electric dynamometer specifically designed to suit the laboratory requirements.

The test runs are of two minutes' duration. The revolution counter and the signals for the observers are operated through a master clock and relays. The r. p. m. of the wheel are determined by a continuous counter. This counter consists of a large dial, with the circle graduated into 200 divisions, worm-driven from the wheel shaft with a reduction of 200 to 1. The hundreds of revolutions are counted by a Veeder counter which is driven from the same gear train as the disc. An index is mounted on the dial and driven at dial speed through a friction clutch. Ordinarily, this index is held stationary by an electromagnetically operated latch. At the start of a run, the clock, through the latch, releases the index, which then travels with the dial. The observer records this initial reading. The index makes one complete revolution with the dial and is then caught and held by the latch. At the end of the run the procedure is repeated, and the final reading is obtained.

The forebay and tailrace elevations are determined by means of float gages. One of the floats bears a graduated rod and the other a pointer, so that the net pressure head is taken as one reading. The pressure head on the wheel during test varies between 3½ and 4½ feet.

Three men are employed in the test room. One man reads the hook gage on the weir; another operates the dynamometer and takes the readings of the revolutions, weight on the scales and head; the third man takes no readings but computes the results and plots the final results on a curve sheet as the test is in progress.

Governor tests are made in this laboratory in a rather simple but effective fashion. For convenience in testing governors, an oil sump tank, a pressure tank and a pump are permanently installed. When set up for testing, the governor servo-motor operates the shunt field rheostat of a motor-driven generator. The governor head is driven by an electric motor which is connected across the generator loads. Thus, when load changes are caused on the generator, the governor operates to provide steady voltage. The apparatus may be readily modified to simulate various operating conditions, and provides a very simple method of checking governor operation.

Bonneville Hydraulic Laboratory

The hydraulic laboratory of the Corps of Engineers of the Portland district is located at the Government Moorings on the Willamette River near Linnton. It is known as the Bonneville Hydraulic Laboratory, and A. J. Gilardi is resident engineer.

This laboratory covers about two acres, is of temporary construction, and was built especially to study details of the Bonneville project. Its purpose was to verify the hydraulic computations and designs made in the office, and to assist in visualizing the problems involved.

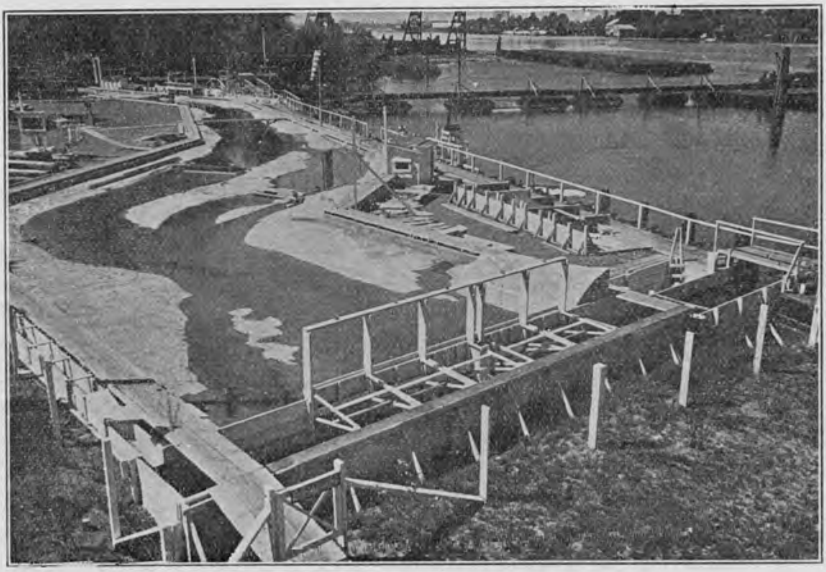

FIG. 2. — BONNEVILLE HYDRAULIC LABORATORY

The water is taken out of the river by means of a large motor-driven propeller pump discharging 18 c. f. s. The water passes through a 24-inch line floating on pontoons into a regulating tank about 30 feet wide and 60 feet long, extending across the end of the river model spillway test flume and other models. From this tank the water can be taken either through the spillway model flume, the river model or other models, and then passed to the recirculating flume and finally to the river. When more water is needed than the river pump can supply, two recirculating pumps can be used so that a maximum discharge of over 50 c. f. s. is available.

The head is maintained at a constant level in the regulating tank by means of a free spillway crest slightly over 200 feet long. When it is desired to vary the head in this tank for spillway tests, there are six Tainter gates about 2 feet wide with variable heights which are remotely controlled by cables. The winches operating these cables are conveniently located beside the spillway flume and in the upper gage house of the river model. A 5-inch gate valve is also provided for fine regulating, and another for filling the flume from below without disturbing the movable bed.

The purpose of the spillway model test is to determine the most desirable shape of the piers, spillway crest, toe and apron of the dam, so as to obtain the highest coefficient of discharge with a minimum scour of the river bed and banks. The spillway model is located in a glass-sided flume 5 feet wide, 5 feet deep, and about 75 feet long. The model consists of three bays of the dam built 1:36 of full size. It was constructed in many separate pieces so that changes can be made readily and the effect of these changes evaluated. At the end of the apron of the model there is a deep layer of gravel which had been screened to a specified grading varying from one eighth inch to three quarters inch in diameter, to represent approximately the upper layer of the bed of the river to a model scale. The discharge from the model is indicated by an uncalibrated suppressed weir at the end of the channel.

The river model was built to determine the details of cofferdam construction, placement of cribs, scour and silting below the dam, backwater studies, handling of the fish and navigation problems.

The river model is nearly 300 feet long and represents about five miles of the Columbia River to a 1:100 scale. Steel templates, representing transverse sections of the river spaced approximately 100 feet in nature, were used to reproduce the river bed from the soundings of a detail survey. The spaces between the templates were filled with sand which was washed and tamped in place. The upper 3 inches of the model surface was made of $1:1\frac{1}{2}$ concrete. The concrete surface was finished smooth, but was later roughened to correct the hydraulic gradient. In some places there were insufficient data to construct accurate templates. As might be expected, these spots gave a little trouble when the hydraulic gradient was being adjusted to coincide with that in the natural river.

About thirty piezometer connections were placed in the model and connected by means of steel pipes to hook gage pots located in two gage houses. The upper gage house contains, in addition, the hook gage measuring the head in the regulating tank and the controls to the inflow weir. The lower gage house contains the hook gage measuring the flow over the d scharge weir and the controls to the five Tainter gates which regulate the water level at the end of the model. The two gage houses are connected by means of a speaking tube and have one interconnection with the model as a check.

Pits were made in the concrete for the placement of the spillway, powerhouse and navigation lock, so that these structures could all be

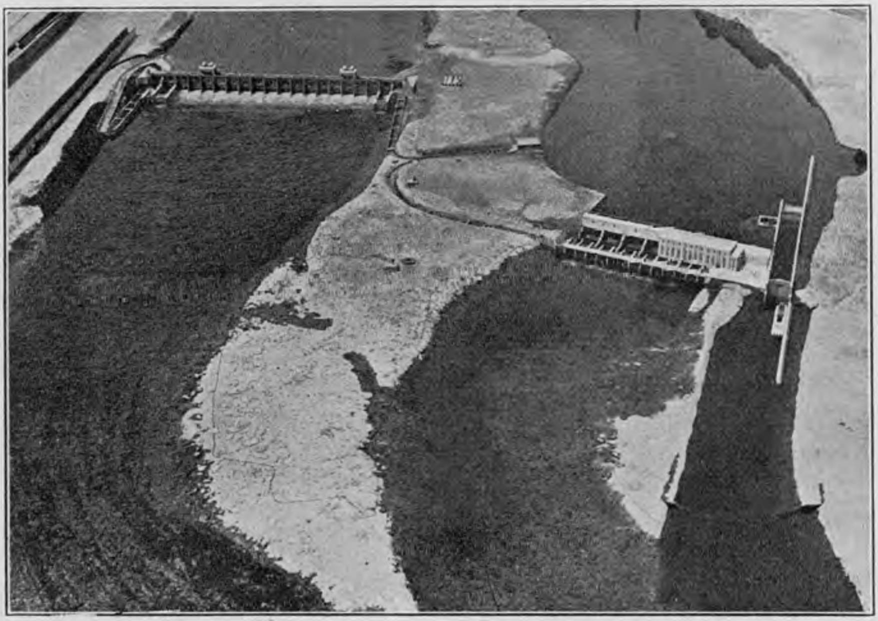

FIG. 3. — BONNEVILLE HYDRAULIC LABORATORY — VIEW OF THE DAM, POWERHOUSE, LOCK AND FISH LADDERS, LOOKING UPSTREAM

placed and taken out as needed. Provision was also made for a movable river bed below the spillway for certain investigations.

At the time of the inspection the river model had been in operation continuously for about eight months. The only work which had been done at that time had been concerned with cofferdam studies and demonstrations. Neither of these details was originally contemplated, and yet it is felt that the whole model investment has been saved several times over in the improvements effected.

There were one or two further details which were worthy of note. In the first place, it was realized that if the water was only measured at the downstream end of the model a great deal of time would be wasted in adjusting flow because of the pondage of the model itself. Therefore a special sliding weir is used at the upstream end so that any desired discharge can be set quite accurately in advance, with a consequent economy of operating time.

Another detail of interest was the construction of a 25-foot portable wooden tower to allow "airplane" photographs to be taken of the model in operation.

The principal source of trouble that has been experienced has been the uneven settlement of the foundation. The land at this point has been raised in part by a hydraulic sand fill dredged from the river. The changes in this fill caused by infiltrations of rain water, river water, leaks, etc., have caused some trouble with the settling of the foundation of the model. Nothing very serious has happened, but it remains a source of worry to those in charge.

Several other models have been built and dismantled as soon as the experimental work connected therewith has been completed; that is, the model of the navigation lock, the model of the diffusion chamber for the fishways in the powerhouse, etc.

Other interesting experiments concerning water wheel and draft tube design were in progress in another department of the Bonneville organization. The purpose of these tests was to determine the best form of draft tube for the Bonneville development.

There are two test flumes set up in a small temporary building. In one of these flumes the draft tube alone is tested, using "spinners" at the entrance of the tube to give various degrees of swirl to the water. The discharge is measured by a "V" notch weir located at the upper end of the flume. The head at the intake, throat and discharge end of the draft tube are measured with open gage glasses. The overall length of this test flume is about 30 feet, the width about 4 feet, and the depth varies from 2 feet to 4 feet. The discharge available is about 1.5 c. f. s.

The other test flume is about 30 feet long overall, 18 inches wide and 2 feet deep. This flume delivers water into a 1:48 model of the Bonneville water wheels. The model wheel is 6 inches in diameter and is constructed of brass and aluminum. The gates, speedring and runner are all reproduced to scale. The intake is made of wood except for the roof which is pyralin. The draft tube is made entirely of pyralin. This model water wheel is actually being tested, using a small Prony brake to measure the torque.

Byron Jackson Company

The Byron Jackson Company, located at Berkeley, California, has devoted one corner of the shops to the testing of their horizontal and vertical centrifugal pumps. Such test work is done in connection with new designs of pumps, with the systematic check of pumps in production, and with all pumps having high efficiency guarantees. During each test the full characteristic curve of the pump is taken and plotted.

The laboratory is located on the ground floor in one corner of the shops. A test bed for the easy erection of centrifugal pumps and electric driving motors is conveniently located beside a concrete sump from which the water for the test is taken. The pumps being tested are usually driven by induction motors which have been calibrated to determine the motor losses. Thus the watt meter input and the motor speed provide the information from which the pump input is computed. The motors are available in all sizes necessary to supply their pump requirements both in horizontal and vertical types up to 1,200 horsepower. A horizontal Amsler torsion dynamometer with four torsion shafts having a maximum capacity of 550 horsepower at 1,800 r. p. m. is used when it is necessary to calibrate a new motor or to check motor characteristics for a more careful test. The speed of the motor and pump is determined with Hasler speed indicators.

The piping system for a test is made as simple as possible. A suction pipe is laid from the pump into the sump. The discharge pipe is installed with a sufficient length of straight pipe so that the discharge pressure piezometers and the Venturi or orifice meter can operate properly.

The discharge pressure is regulated by throttling one or two valves installed in the discharge line. For high pressure pumps one valve is located before the meter with a sufficiently long pipe between the valve and meter to straighten out the flow, and a second valve is used after the meter. For low pressure pumps one valve after the meter is used. After passing through the final throttling valve the water is discharged into the sump.

The suction pressure is measured during a test with a mercury manometer. The same type of mercury gage is used to measure discharge pressures up to about 100 feet of water. From that point to 3,000 pounds per square inch, Bourdon tube gages are used, which are calibrated with Crosby gage testers at regular intervals. For important tests the gages are checked before and after every test.

The discharge of the pump is measured either with a test Venturi meter or an orifice meter. The Venturi meters range in size from 6 inches by 3 inches up to 36 inches by 18 inches. For the smaller sizes of pumps a set of I. S. A. nozzles have been provided ranging in size from ⅜-inch to 2-inch opening.

A dry pit 6 feet by 4 feet is located beside the water sump in order to measure the discharge of low head, totally submerged pumps, such as are used in some reclamation projects in California. In testing such units the Venturi meter and the pump are submerged in the sump and connected through pipes to the gages in the dry pit. This arrangement keeps a positive pressure on all the gage connections and makes the operation of the equipment more reliable.

There is one special piece of equipment in the yard which consists of a 90-foot steel tower erected over a well 54 feet deep. This is used in the testing of deep-well pumps under actual operating conditions; that is, set up in a casing and operated with a very long shaft.

Early this year (1937) the main office and engineering department of this company were moved to Los Angeles, where a factory larger than the Berkeley one was established. The test facilities, with the exception of the deep-well tower, are duplicates of those in Berkeley. Some improvements have been made in the hydraulic equipment, and, in addition, apparatus has been installed for the testing of submersible motors which are manufactured for deep-well turbine drives at that plant.

A total of 9,250 pump tests had been made up to June, 1937, with an average of more than two pump tests per day for the preceding year. It is evident that the equipment of the Byron Jackson Company is adequate for the routine testing of pumps in production as well as for those tests necessary in the development of new designs.

California Institute of Technology

The three laboratories connected with hydraulics are in the mechanical engineering department at California Institute of Technology, Pasadena, and are under the immediate direction of Prof. R. L. Daugherty and Prof. R. T. Knapp. The first is used by the undergraduates, the second is an outdoor laboratory principally for river models, and the third is the pump-testing laboratory.

The floor space given over to the undergraduate laboratory is located in an "L" shaped room, which is 30 feet by 15 feet along one side and 20 feet by 15 feet along the adjoining side. The laboratory for the instruction of students is described in connection with the experiments which the students perform. Water for the experiments is taken from the sump by two motor-driven centrifugal pumps which can furnish 2.2 c. f. s. at a head of 90 feet of water. Both of these pumps can be tested by the students. The suction and pressure heads are measured with mercury manometers. The discharge is determined

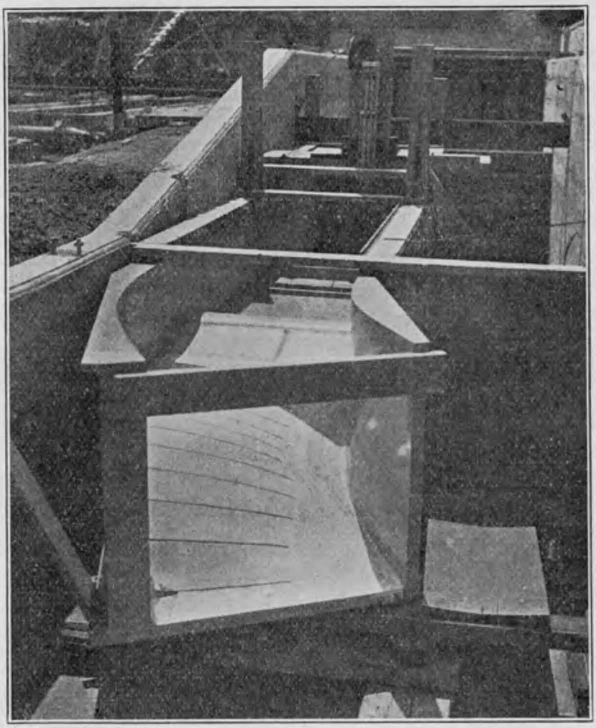

FIG. 4. — CALIFORNIA INSTITUTE OF TECHNOLOGY — MODEL SIDE SPILLWAY INSTALLED IN CONCRETE TEST FLUME

with a calibrated Venturi meter. The input for one is determined with a hand counter and a calibrated torsion dynamometer in the drive shaft between the motor and the pump, while electrical input to the motor is measured for the other, which is a deep-well type. The deflections of the torsion dynamometer are read by means of a synchronized flashing neon light.

A test is performed upon orifices and short tubes. The test plate carrying the orifice or tube to be tested is mounted in the end of a horizontal pressure tank 2 feet in diameter and 5 feet long. The head is measured with a water manometer. The discharge can be caught in a weighing tank. There are a series of orifices of different sizes and tubes of various forms, all of which are interchangeable.

A Pitot tube experiment is performed in a free jet flowing from a 3-inch vertical pipe. The small Pitot tube is mounted on a frame which slides on guides and is driven by a worm. The tube moves at right angles to the motion of the slide, so that all portions of the jet can be explored. The velocity head is measured with a water manometer. The discharge is checked by the calibrated Venturi meter in the supply line.

A 12-inch glass-enclosed Pelton impulse water wheel is tested by the students. The water is supplied by a motor-driven duplex pump which forces the water into an equalizing pressure tank about 2 feet in diameter and 5 feet long. From this tank a 4-inch line supplies the water wheel through a calibrated 4-inch by 2-inch Venturi meter. The deflection caused by the Venturi meter is read with a barometric type of mercury manometer. The head on the wheel is measured by a calibrated Bourdon tube gage. The output of the water wheel is determined with a Prony brake and an electric tachometer.

A contracted weir is located in a channel 30 inches square in section and 30 feet long in the straight section approaching the crest. The contracted weir crest is formed in a brass plate, so that the crest is 15 inches long and 1 foot above the bottom of the channel. The head on the weir is measured with a special point gage which indicates contact with the water surface with a neon light. The discharge over the weir is measured either with the calibrated Venturi meter in the discharge line of the centrifugal pump, or by means of calibrated orifices in the orifice tank equipment.

The outdoor river hydraulics laboratory was built for research work and is not used by the undergraduate students. Models can be mounted upon a reinforced concrete base which is 40 feet square. The water is supplied to a constant level tank by a pump having a capacity of 2.5 c. f. s. At the time of the inspection a tidal model was installed. The scale was distorted, being 1:60 vertical and 1:120 horizontal. Water was brought to the model through three sets of pipes containing calibrated Venturi meters. One set of pipes brought in the water of the main river flowing into a bay. Another set of pipes took care of the water brought into the bay by several small tributaries, and the last set of pipes, together with the discharge pipe, took care of the tides. A plunger type wave-making machine driven by a motor through a variable speed gear box was located at the seaward side of the model.

This model is relatively simple in construction. There are one or two details, however, that are noteworthy. In the first place, the tides are caused by the manipulation of two valves, the inflow manually and the discharge automatically. The inflow is adjusted to give the desired rate of rise of the tide with the discharge valve nearly shut. Then the discharge valve has sufficient capacity to dispose of the inflow and also lower the water level in the model at the desired rate.

The discharge valve opening was calibrated in various positions of opening. It is operated by an electric motor which is started by means of a time clock and stopped by trips mounted on the valve mechanism. The time clock is so designed that a starting impulse can be made on any even minute. The trips on the valve can be placed at any position and there can be any practical number of them. In this way any desired tide cycle can be duplicated as closely as is considered necessary. During this particular test it was only deemed necessary to duplicate the maximum rates of rise and fall during a shortened tide cycle.

In discussing the problem, it was pointed out that the system outlined above was relatively simple. In addition, if it were found that the actual heights were not being attained, the error could be readily reduced by operating the inlet valve. This corrected the tide height without interfering with the operating of the automatic control.

A final feature of interest in the operation of this model is the photographic method of taking contours of the bed after a run. A small observation platform is slung from a swivel derrick so that the whole model can be covered. In taking a set of data, the water level in the basin is first adjusted to the desired elevation and a plan picture taken. This process is repeated at different water elevations until sufficient data has been obtained to correctly represent the bed position.

Near the river and tidal model, and supplied from the same constant level tank, is located a concrete flume 35 feet long, 5 feet wide, and from 3 feet to 4.5 feet deep. This flume is used for spillway tests and similar work. An interesting design, the work of a local consulting engineer, was in place during the inspection. It consisted of a low ogee spillway section located on a side hill. The problem was to deliver the water into the old stream bed with a uniform distribution so that there would be no concentration of stress. Also, it was very desirable to keep the spillway channel as high as possible, to minimize the removal of rock. The channel was laid out on a rather short radius curve, with the bottom, in general, sloping to the inside of the curve. The design worked out very well in the model.

At the time of the inspection, the foundations were being installed for a new flume of variable slope. It was designed for the study of flood flows in channels of steep gradient. The platform was carried on bents 8 feet apart and the bents were adjustable in height. The whole platform was to be about 80 feet long and allowed a maximum slope of 1:8. Since the inspection of the laboratory, this project has been completed.

The pump-testing laboratory at the California Institute of Technology was built with the co-operation of the Metropolitan Water Dis-

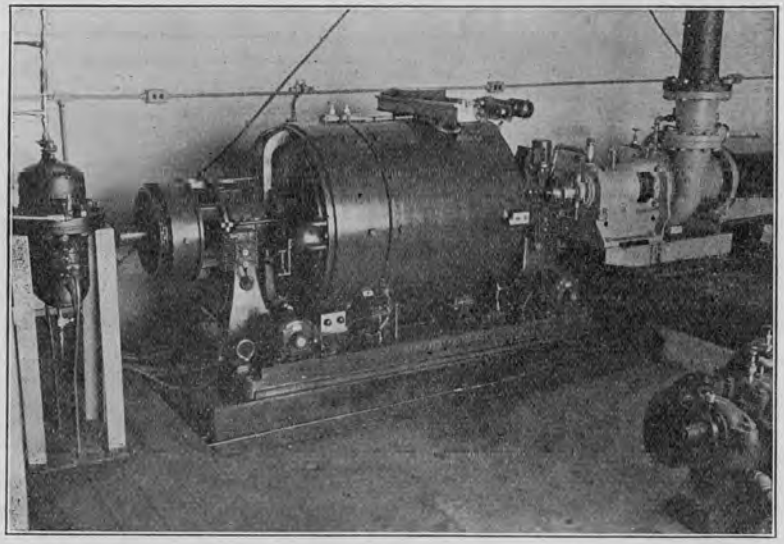

Fig. 5. — California Institute of Technology — Dynamometer and Pump installed for Test

trict of southern California for the purpose of determining the best type characteristics and then the best commercial design of pump to be used in bringing water from the Colorado River to Los Angeles. Th. von Karman, director of the Guggenheim Laboratory of Aeronautics, is associated with Professors Daugherty and Knapp in the direction of this special laboratory.

The equipment is set up in a room about 20 feet wide, 50 feet long and three stories high, with a basement beneath. The suction for the pump is taken from a tank 4 feet in diameter and 25 feet high.

The water is discharged through a bank of four Venturi meters of different sizes and thence, through a throttling valve, back to the suction tank. Inasmuch as this is a closed system, the suction pressure may be adjusted to any desired value by means of auxiliary pumps, allowing cavitation tests to be made very readily. The range in suction pressure is from about − 25 feet of water to a positive pressure of about 125 feet of water. The four Venturi meters are controlled by means of grease-sealed plug valves, so that only one meter is used at any given time, and that within the suitable range of the meter. These Venturi meters have been carefully calibrated in place by calibrated volumetric tanks. The throttling plug valve is motor-operated and serves to regulate the discharge pressure of the pump. This valve is remotely controlled from the operator's desk.

In order to keep tests of different pumps on a truly comparative basis, the pressure piezometers at the inlet and discharge of the pump are located at the same position relative to the pump and tank and in the same pipes for all pumps tested.

The suction and discharge pressures were measured by means of specially designed and constructed gages operating on the principle of the dead-weight gage tester. These gages had a range from a vacuum to 500 pounds per square inch, and were sensitive to 0.01 pound per square inch. Two of these gages were used to measure the suction pressure and the discharge pressure. The same type mechanism was adapted to weigh the mercury differential of the Venturi meters, and is sensitive to 0.0006 inch of mercury.

The input to the pumps was determined by means of a horizontal electric dynamometer which had a capacity of about 400 horsepower at 5,000 r. p. m.

The torque of the dynamometer was measured by a combination of a hydraulically loaded piston and a weight which slides transversely on the dynamometer itself. This apparatus was sensitive to the nearest 0.25 inch-pound of torque.

The speed of the dynamometer was held constant by an automatic speed regulator controlled from a standard time source. A special gear box allowed the speed of the pump to be adjusted in 0.5 r. p. m. steps up to 5,000 r. p. m., and the system was so constructed that the speed is kept at any chosen value to one part in one hundred thousand.

It is thus seen that the speed and pressure conditions for a test were selected, and the dynamometer weight, Venturi deflection, discharge and suction pressures were read from the automatic balancing scales and gages. Since all the gages and apparatus were balanced automatically, there was no personal error introduced into any of the readings. The sensitivity and the accuracy of the apparatus were such that whole series of tests could be made with all test points within 0.1 per cent of the true values.

In addition to the suction pressure tank there were two steel tanks 5 feet in diameter and 40 feet high. These tanks were used to test the pumps under abnormal operating conditions, determining the performance of the unit under conditions of power failure and sudden changes in pressure conditions. A long test program was in progress for the Metropolitan Water District of southern California at the time of the inspection. A detailed description of this laboratory and its work was published in Vol. 59, No. 8, of the November, 1936, "Transactions of the American Society of Mechanical Engineers." The article was entitled "The Hydraulic Machinery Laboratory at California Institute of Technology," by R. T. Knapp.

University of California

There are two hydraulic laboratories at the University of California located at Berkeley, California, both of which are under the direction of Prof. M. P. O'Brien of the mechanical engineering department. Professor O'Brien, who was a Freeman scholar in 1927–28, has been active in hydraulic research work.

Hydraulic Laboratory in the Mechanical Engineering Department

The oldest hydraulic laboratory at the University of California was installed about 1902. It is operated by the department of mechanical engineering and is under the supervision of Prof. M. P. O'Brien. This laboratory is equipped with apparatus to provide for student instruction as well as for hydraulic research. The laboratory is housed in one room 100 feet by 60 feet in plan, with an annex which is 40 feet by 30 feet in plan. The service pumps and sump are located at one end of the main room with a constant head tank and standpipe at the other end. Along one side of the room and at the end, over the pumps, there is a mezzanine floor about 10 feet wide.

There are a number of centrifugal pumps supplying the needs of the laboratory. Specific data on each pump were not recorded, but a maximum discharge of 4.0 c. f. s. is available in the standpipe providing an operating head of about 35 feet on the first floor. This standpipe is 4 feet in diameter and 45 feet high, and overflow pipes are provided at various elevations so that a constant head can be maintained. In addition to the pumps connected to the head tank there are others available which can be used with parts of the distribution system to provide discharges of 2 c. f. s. at 140-foot head, 1 c. f. s. at 270-foot head, and 0.1 c. f. s. at 600-foot head.

The main sump is located directly underneath the service pumps at one end of the laboratory. The water used in various experiments is returned to the sump through channels cast in the concrete floor. There are two square channels running the length of the laboratory near the

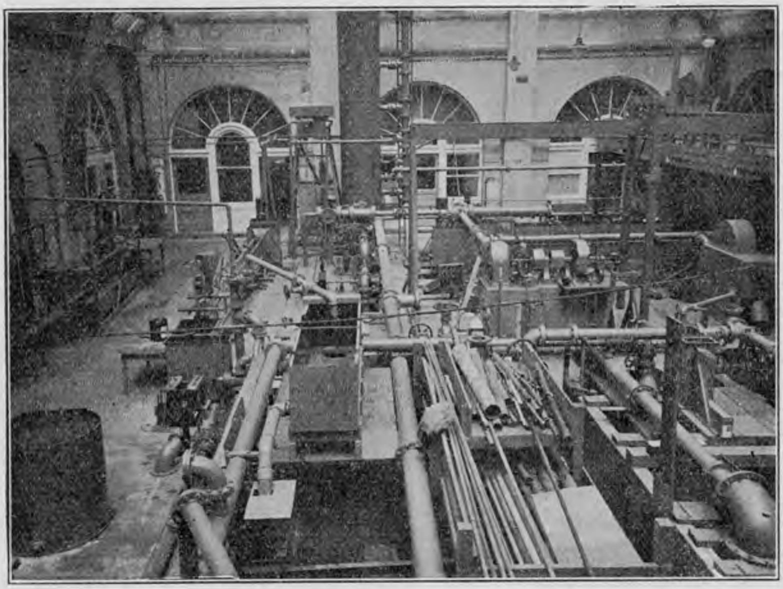

FIG. 6. — UNIVERSITY OF CALIFORNIA — HYDRAULIC LABORATORY LOOKING TOWARD THE HEAD TANK

center of the room. In addition to acting as return channels, they are used as pipe ducts and as auxiliary sumps for pump tests.

The pipe connecting the constant head tank with the pumps is 8 inches in diameter, but the distribution piping through the laboratory varies from 2 inches to 8 inches in diameter according to the needs of the various pieces of equipment. Pressure taps for the introduction of Pitot tubes are provided at suitable locations in the distribution piping.

On the main floor and near the service pumps there are two concrete flumes 15 feet long, 5.6 feet wide, and 3 feet deep, one being equipped with either a rectangular suppressed weir or a semi-circular weir, while the other is equipped with a 90° "V" notch weir. The discharge from the first weir flume falls directly into the sump. The discharge from the "V" notch weir normally falls into the sump, but a deflector is provided by which the water can be diverted into a volumetric tank 7 feet by $7\frac{1}{2}$ feet in plan and 12 feet deep. This tank constitutes the primary discharge measuring standard, and the "V" notch weir, being frequently calibrated, is used as a secondary standard. For smaller discharges there are several portable weighing tanks available having capacities up to 1,500 pounds.

Beyond the "V" notch weir flume, passing from the service pumps toward the constant head tank, there are located two impulse wheels mounted on concrete pedestals. One is used for a student experiment. Water is brought to the impulse wheel through a 6-inch pipe in which is located a 6-inch by 3-inch Venturi meter. The pressure at the nozzle is measured with either a Bourdon tube gage or a dead weight gage tester. The plunger of this latter piece of apparatus is rotated continuously by a small electric motor, and is provided with weights representing pressures of fractional pounds per square inch. The output of the wheel is measured with a calibrated electric generator and volt meter of the "Weston" type. This water wheel is also equipped with a governor which is used for demonstration purposes.

Between the impulse wheels and the head tank end of the room there are located three steel flumes. The first is 24 inches wide, 12 inches deep and 18 feet long. At the end of the flume a chute discharges the water to a return channel in the floor. At the time of the visit there was a semi-circular steel channel set up in the flume with apparatus to determine friction losses or slope. The second flume is 12 inches wide, 18 inches deep and 18 feet long. It was not in use at that time. The last flume is 4 feet wide, 2 feet deep and 7 feet long. At one end there is located a contracted weir 12 inches long and 18 inches above the bottom. This weir measures the discharge from a 4-inch line in which there are located a 4-inch by 2-inch Venturi meter, a sharp-edged orifice, and a nozzle type of metering element.

Beside the main 4-foot concrete return channel, and just in front of the standpipe, there is located an 8-inch water wheel in a special form of cylindrical case. The wheel discharges through a quarter turn draft tube into the concrete channel. The output is measured with a Prony brake and a hand-operated revolution counter.

A centrifugal pump test is set up beside the same channel. Water is taken from the concrete channel and returned to the channel through a short length of discharge pipe and a throttling gate valve. The suction and discharge pressures are measured with mercury manometers. The input is measured with a calibrated electric motor and a hand revolution counter.

On the other side of the room from the impulse wheel there are located a tilting flume and a small rating tank. The tilting flume is 30 feet long, 18 inches deep and 6 inches wide, and is equipped with head and tail boxes in addition to the above length. Both sides of this flume are made of glass. This flume was used in the tests made to determine the effectiveness of a salt water barrier in San Francisco Bay. The flume is also used for bed load tests.

Located on the floor beside the wall there is a steel frame around a flume carrying an overhead pair of steel rails on which moved a small car. This apparatus is used in the rating of miniature current meters.

Between the tilting flume and the pumping section there is set up a horizontal Sprague electric dynamometer, together with a test bed for the ready installation and testing of centrifugal pumps. The capacity of this machine is 160 foot-pounds of torque from 0.0 to 2,000 r. p. m. An Amsler torsion type transmission dynamometer is also available having a maximum capacity of 140 foot-pounds of torque.

The mezzanine floor is occupied with apparatus for student experiments and small steel flumes. There is a small steel flume about 8 inches wide and 12 inches deep running the whole length of that floor, which serves as a return channel to the sump.

On the end balcony there is set up a glass tube 1 inch in diameter and 30 feet long, which is used in the determination of friction losses in a student experiment. There is also a small steel tank about 12 inches square in section and about 3 feet long. It has one glass side and is used for the demonstration of viscous and turbulent flow after the well-known method of Osborne Reynolds.

Along the wall of the side balcony there are a number of small steel flumes adapted for experimental purposes. A 4-inch line serves as a water supply for these flumes. The first of these flumes is 18 inches square in section and 8 feet long; a second, 12 inches deep, 3 feet wide and 6 feet long; a third, 15 inches deep, 18 inches wide and 20 feet long; and the last, 18 inches deep, 6 inches wide and 15 feet long. This last flume is equipped with one glass side through part of its length. It is also provided with manually operated, vertically sliding head and tail gates, so that the phenomena associated with hydraulic jump can be studied readily.

Beside the railing of this section of the balcony there are two pipes used by the students in determining friction losses, using steam and air as fluids. There is also a 2-inch pipe about 70 feet long equipped with a quick-acting valve at the discharge end, which has been used in water hammer studies. Inside the railing there is an experiment upon the flow of air through a Venturi section and a sharp-edged orifice.

The annex to this hydraulic laboratory is located in a room adjoining one side. It is 40 feet by 30 feet in plan and contains three steel and glass flumes which are supplied by a 6-inch line from the standpipe. The first of these flumes is 12 inches wide, 18 inches to 24 inches deep, and 18 feet long overall. The discharge is measured with a weir located between the head box and the flume proper. One wall of the flume is formed of glass and the other painted white to allow ready inspection of the flow phenomena. The tail-water elevation is adjusted with a manually controlled sliding gate operated through a worm gear. The flume is supplied with a 4-inch line and discharges into a steel return channel on the floor. The second flume is very similar to the first except that the dimensions were 24 inches deep, 6 inches wide and 15 feet long. Both of these flumes have been used for the test of small model spillways.

The third flume is 18 feet long, 6 feet wide and 6 inches deep. At the time of the inspection there were three model channels installed consisting of a short tangent section and a 90° long radius bend. These model channels were constructed to different horizontal scales but were made the same depth. The purpose of the test was to determine the effect of distortion.

TIDAL LABORATORY.

The tidal laboratory at the University of California was installed in 1934 by the United States Army Engineers. The sump from which the pumps take the water for test purposes is 75 feet by 40 feet in plan, with a mean depth of 5½ feet. In the past this was the swimming pool of the University, but it had been abandoned for a larger and newer pool. It is proposed to use this sump as a testing basin for ship models. Satisfactory preliminary tests have been made using a gravity type of dynamometer for towing the models, and permanent equipment of the same type is to be installed in the near future.

Water is taken from this sump by three centrifugal pumps capable of delivering 2.5 c. f. s. and 5 c. f. s. at 15-foot head and 1 c. f. s. at 30-foot head, respectively. All of this capacity is used in the test of the Columbia River model.

The tidal model basin is 72 feet by 42 feet in plan and contains two

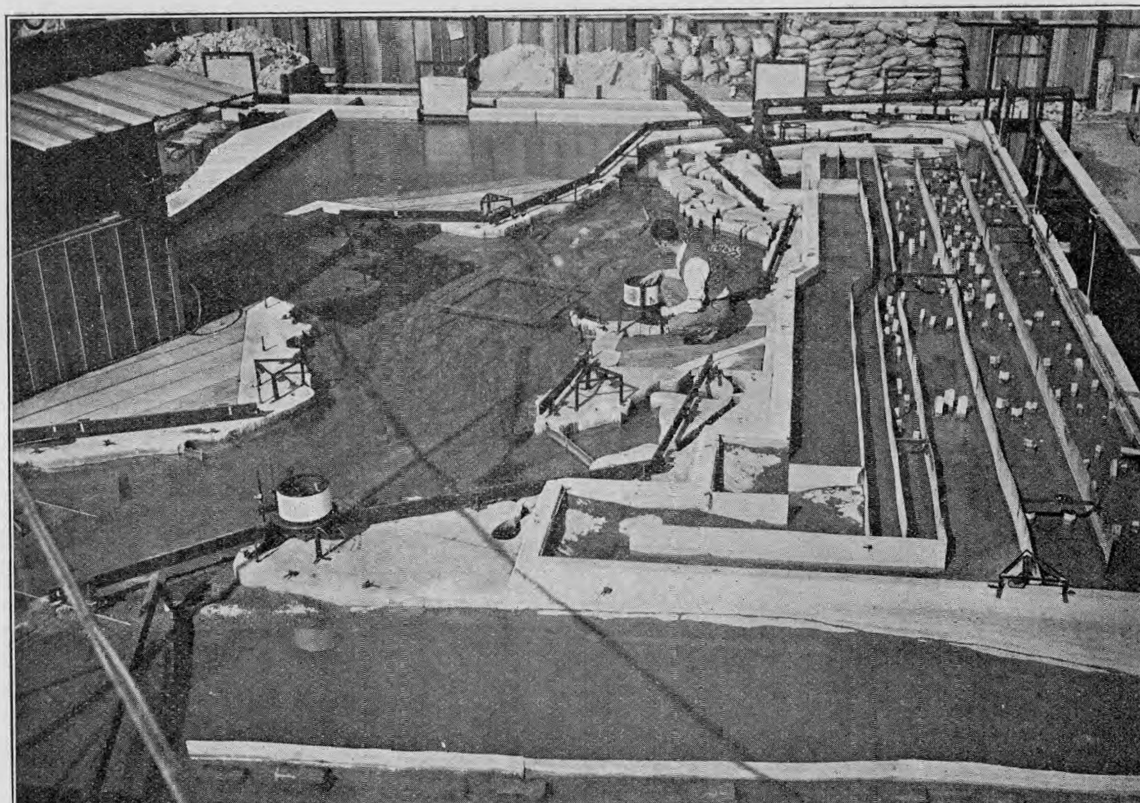

Fig. 7. — University of California — Columbia River Model in Operation

models. The first and most impressive is that of the estuary of the Columbia River. The tests of this model were in progress at the time of the inspection. The object of this model test is to determine in an economical manner a stable, navigable channel for the Columbia River near its mouth. The horizontal scale of the model is 1:3600. During the preliminary tests the vertical scale was 1:64, but for the final measurements a vertical scale of 1:128 was used. A movable bed was used at first, but the bed was fixed in the final test.

The model was constructed with the aid of female transverse sheet iron templates which were backfilled with rock dust tamped in place while damp. The finish coat is made of about 1½ inches of sand concrete.

The model represents in nature a section of the river at its outlet, 9 miles wide and 50 miles long, which does not include the entire tidal prism of the river. This remaining portion, which is duplicated by a labyrinth at the upstream end of the model, represents 140 miles of river and is constructed to provide the proper volume of flow and time characteristics of the tide at the end of the model.

The flow in the model is most complex. The river flow is represented by a discharge of about 0.85 c. f. s., the littoral drift is duplicated with a cross flow of about 2 c. f. s., and discharges up to 10 c. f. s. have to be handled in duplicating the tides. A special cylindrical motor-operated valve duplicates the tidal cycle. The fact that the tides are not of the same height and are not sine waves in form complicates the problem. The cylindrical valve, 12 inches in diameter and 10 feet long, is designed both to rotate and to move endwise in its casing in order to produce all the desired effects.

A movable car or bridge about 10 feet wide was constructed to span the entire model basin. This car houses the principal controls for the operation of the tests, and it facilitates measurements of the bed. Finally, there is a steel mast mounted on the car upon which a camera can be mounted for vertical or airplane views of the model in operation.

In one corner of the tidal basin there had been constructed another model of the Columbia River near Longview. This model is 15 feet wide and 40 feet long. It is purely a river model with no tidal effects. The object of the test is to find a means of preventing silting of the log pond of the Weyerhaeuser Timber Company. The horizontal scale ratio is 1:1240, while the vertical scale ratio is 1:100. The same construction methods were used as in the Columbia River model. A movable bed is used in the central critical portion of the model, but a fixed bed is used throughout the remainder. This model was in the adjustment stage during the inspection so that there were no test results available.

Between the tidal basin and the sump there is located a tilting steel flume which is being fitted for bed load tests. This flume is 3 feet wide, 18 inches deep and 60 feet long.

In addition to the equipment described above, there are shops and offices used by the operating and test personnel, having a combined floor space of about 1,200 square feet. There is also reserved on the other side of the sump a level space of about 10,000 square feet which can be used for other model construction.

A very sensitive liquid level indicator of the null type was observed at this laboratory. A float, carried by the water surface, has a plate glass mirror, which is pivoted at one side, bearing on the center of the float through a jewel bearing. Above the plate glass mirror there is mounted a horizontal piece of plate glass. Monochromatic light is reflected down through the upper glass, and, striking the lower mirror, is reflected back up through the same plate glass. If the mirror and the plate glass are parallel nothing is seen, but if the water level is too high or too low, causing the mirror to be at a slight angle to the plate glass, then interference bands are seen, the number depending upon the angle. As constructed, this indicator allows the water surface to be set to the same elevation with an accuracy of about .00001 inch.

Carnegie Institute of Technology

The hydraulic laboratory of the Carnegie Institute of Technology at Pittsburgh, Pennsylvania, is under the direction of the civil engineering department, with Prof. Harold Thomas directly in charge. There are essentially two distinct hydraulic laboratories at this college, there being the laboratory for student instruction and a research laboratory.

The laboratory for student instruction is approximately 50 feet long and 30 feet wide. Water is taken from a common sump and circulated through the distribution system by any of five centrifugal pumps and one triplex pump. The centrifugal pumps range in size from a 2-inch discharge to an 8-inch discharge. In designing the distribution system every effort was made to keep the operation of the laboratory as flexible as possible. Thus the piping can be, and usually is, sectionalized so that each experiment is being served by a separate pump suited to the needs of that test. When necessary, any pump may supply the whole laboratory with water.

The apparatus in the student laboratory is indicated in the description of the student experiments which follow. A 12-inch glass-enclosed Doble impulse wheel is tested under various conditions of head, load and nozzle opening. Water is supplied under 200-foot head by a 5-inch two-stage centrifugal pump. The pressure at the nozzle is read with a Bourdon tube gage. The discharge is measured by the nozzle opening which has been previously calibrated. The output is determined with a small Prony brake and a portable hand counter.

The performance of a 2-inch Nash centrifugal pump is determined at various speeds, head and discharges. The suction and discharge

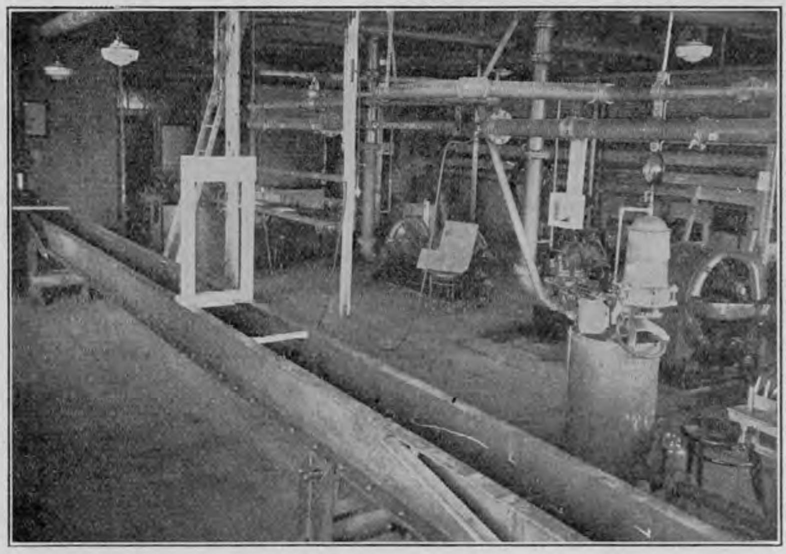

FIG. 8. — CARNEGIE INSTITUTE OF TECHNOLOGY — STUDENT LABORATORY

pressures are read with open and mercury columns. The discharge is determined with a small 90° "V" notch weir set in the end of a steel tank about 36 feet wide, 12 feet deep and 5 feet long, the head on this weir being read from a gage glass set on a 30° slope. The driving motor is cradled so that the input torque is easily measured with scales. A hand counter is used to determine the revolutions of the pump under test.

Orifice and short tube tests are made in a horizontal pressure tank 2 feet in diameter and 6 feet long. The head on the orifice is measured with an open end water column for low values and a mercury gage for high values. The discharge is determined in a volumetric tank. The size of the jet is measured with hand calipers.

The friction losses in 2-inch, 3-inch, 4-inch and 5-inch straight pipes are measured for various discharges. The discharge is determined by a volumetric tank, and the head lost in friction in 32 feet of pipe is measured with a differential water column.

The calibration coefficient and loss of head in a commercial 2-inch by 1-inch Venturi meter is determined. The Venturi deflection is measured with water and mercury differential manometers, and the head loss is determined with a water differential manometer. The discharge is measured with a weighing tank.

The coefficients of loss in sudden contraction and expansion are determined. The test pipe line is initially of 4-inch brass which contracts to 2-inch galvanized iron and finally expands to 4-inch black iron pipe. Sufficient piezometers are installed to determine the hydraulic gradient in each section, the coefficients being computed from the plotted data. The pressure differences are measured in a water differential manometer. The discharge is determined with a 600-pound weighing tank.

Pitot tube traverses of a 3-inch pipe are obtained at three different discharges. A Stevens type of Pitot tube is used with a water differential manometer in measuring the velocities. The discharge is measured with a "V" notch weir equipped with a slope gage to indicate the head. From the data taken, the coefficient of the tube and the pipe factor are determined at the three velocities.

A test of a 2-inch Rife hydraulic ram is made to determine the performance when working against various delivery heads and to determine the effect of changing the cycle frequency upon the operation of the ram while working against constant head. A 2-inch drive pipe about 40 feet long supplies water from a small tank elevated about 10 feet above the floor. The water wasted is caught and measured in a volumetric tank, and the water pumped is caught in a bottle. The input head is measured to the water level in the tank. The discharge head is measured with a Bourdon tube gage. The efficiency is computed both by D'Aubisson's and Rankine's formulas.

The operating characteristics of an 8-inch reaction water wheel are determined at three different gate openings. Water is supplied to the water wheel by an 8-inch Allis-Chalmers centrifugal pump. A Venturi meter is built into the discharge pipe about five or six diameters away from the discharge flange of the pump. This Venturi meter has been rated with a volumetric tank prior to the experiment. The pressure head on the wheel is measured with a mercury cistern type of gage. The output of the wheel is determined with a hand counter and a Prony brake.

A contracted rectangular weir is calibrated under various heads and with two depths of channel upstream from the weir. The weir, which has a crest length of 2 feet, is located in the end of a steel tank 10 feet long, 4 feet wide and 4 feet deep. Water is supplied by the 8-inch centrifugal pump which has a calibrated Venturi in the discharge pipe. The head on the weir is measured with a hook gage and with a gage glass and scale. A false bottom reduces the depth of channel from 2 feet to about 6 inches.

An open channel test is made to determine the relations between depth, slope and discharge for various flow conditions. The channel used in this experiment is made of structural steel and is about 40 feet long and 1 foot square in section. This channel is mounted on two supports, one of which is pivoted and the other adjustable in elevation. Water is supplied at one end from the 8-inch centrifugal pump. Smooth surface conditions are obtained by introducing the water under an adjustable plate which practically fits the flume for about 6 feet. This plate prevents the formation of waves by the incoming water. The water depth is measured at two points 27 feet apart in slope gages attached to piezometers in the bottom of the channel. An adjustable outlet gate acts as a control at the discharge end of the channel.

The hydraulic laboratory is located on a mezzanine floor between the wings of the Engineering Building. The floor space available is an "L" shaped section 21 feet by 88 feet on one side and 30 feet by 73 feet on the other side of the "L". In addition, a one-story building 40 feet by 96 feet has recently been erected to provide floor space for the model testing work of the laboratory. In the original section a 12-inch motor-driven centrifugal pump takes water from a sump below the floor and supplies the various projects with a maximum discharge of 7.8 c. f. s. A calibrated Venturi meter is located in the discharge pipe leading from the pump. In the new section of the laboratory a 4-inch centrifugal pump supplies a constant level tank located just below the ceiling of the laboratory. A 6-inch centrifugal pump is being installed to provide additional supply for the test work now in progress.

The largest test flume is located in the original research laboratory and is a concrete flume 13 feet wide, 72 feet long and 2 feet deep. While the whole flume can be used for a single test if necessary, it is more convenient for most work to form two or three smaller flumes with temporary wooden bulkheads. A model of the spillway, pressure sluices and the stilling pool of Tygart Dam is installed at the upper end of the flume. The scale of this model is 1:80. In the downstream section of the flume a larger 1:24 scale model of three discharge sluices and baffles is installed in a temporary wooden flume to check the details of design of these sluices.

On the concrete floor of the mezzanine a river model of lock No. 9 in the Allegheny River near Brady's Bend is being tested. The scale of the model is 1:180, and the purpose of the test is to change the velocity distribution of the river near the locks so as to improve navigation.

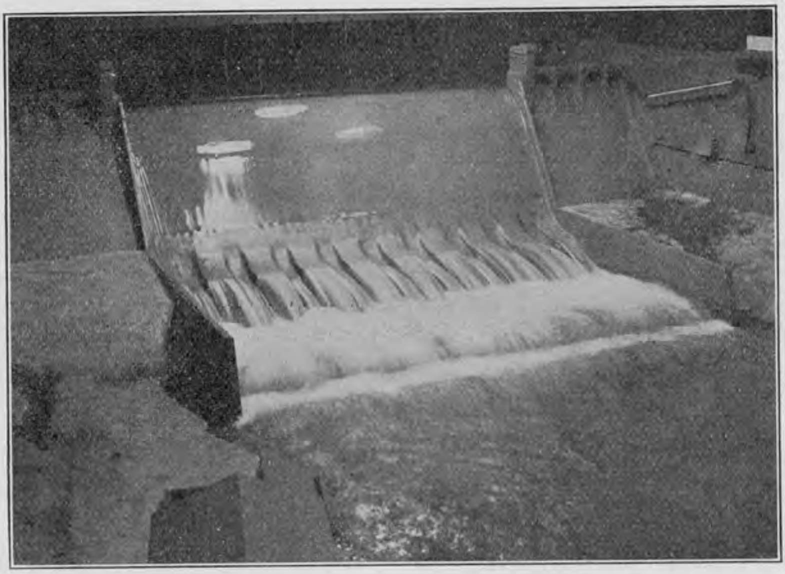

Fig. 9. — Carnegie Institute of Technology — Model of Tygart Spillway in Operation. Model Ratio 1:80

A distorted river model, having a vertical ratio of 1:80, a width ratio of 1:4000, and a length ratio of 1:20000 has been made to study flood waves in rivers. The actual section of the model has the proper areas and volumes for any given section. The hydraulic roughness is adjusted by transverse fins of galvanized iron which project into the channel. These fins are trimmed so as to give the proper hydraulic gradient at various stages with steady flow. It is seen that this adjustment is a cut and try process. Having thus adjusted the model to agree with nature for steady flow, it is planned to analyze the movement of flood waves in the river model. A preliminary test of a relatively short section of river has given very promising results, and more ambitious tests are planned.

A special piece of apparatus has been built to study cavitation in models of outlet conduits of high dams. This consists of a cylindrical steel tank 32 inches by 72 inches connected to a rectangular steel chamber provided with a thick glass window through which the flow in the model conduits may be viewed. Water is circulated through the system by an 8-inch centrifugal pump. A Nash vacuum pump is connected to the system, allowing the absolute pressure of the entire apparatus to be reduced to the proper value corresponding to the model scale.

On June 15, 1937, work was in progress either on the construction or testing of the following models in this laboratory: (1) a general model having a scale of 1:200 of the dam and outlet works of the proposed flood control reservoir on Tionesta Creek, Pennsylvania; (2) a 1:80 model of the saddle spillway of the Tionesta Dam; (3) a 1:36 transparent pyralin model of the outlet tunnel and control tower of the Tionesta Dam; (4) a distorted scale model of the Allegheny-Monongahela River system to study problems of flood crest movements, vertical scale 1:80 and horizontal scale 1:18000; and (5) a 1:16 scale model of the flood gates and pumping station for the proposed Westinghouse flood control project on Turtle Creek, Pennsylvania. A tilting wooden channel 56 feet long and 6 inches by 10 inches in cross section has been installed in the laboratory for use in research on "Travelling Waves in Steep Channels," this being an official research project of the American Society of Civil Engineers.

Case School of Applied Science

The hydraulic laboratory of Case School of Applied Science, located at Cleveland, Ohio, is operated by the civil engineering department under the direction of Prof. George E. Barnes. It is located in one wing of the Worcester Reed Warner Laboratories. The laboratories were built in 1928 and extensively improved in 1934. The wing which is given over to hydraulics consists of two floors 67 feet by 60 feet in plan. The second floor is open for 20 feet along one side of the building, and this open space is served by an overhead crane so that heavy pieces of equipment can be readily handled on either the first or second floor.

The water supply for the laboratory work is kept in a 50,000-gallon sump which is located under the first floor. Three motor-driven centrifugal pumps take the water from this sump and force it either to a constant head tank or to a pressure tank. These pumps can be operated either in series or in parallel, so that a discharge of about 7.0 c. f. s. can be obtained at about 120-foot head or a discharge of 2.2 c. f. s. at about 350-foot head. The constant level tank is located just below the ceiling of the second floor. It is 7 feet long, 5 feet wide and 7 feet deep and is provided with multiple skimming weirs which drain into a 5-inch overflow pipe. There are two outlets from the constant level tank, one 12 inches in diameter and the other 4 inches in diameter. These two pipes supply the distribution system of the laboratory, and each is equipped with Venturi meters complete with registers. The centrifugal pumps are connected by a 6 inch pipe to a vertical pressure tank 5 feet in diameter and 27 feet high, which is located in one corner of the laboratory. This tank is used as an equalizing tank when experiments are made under high pressure.

Discharges are finally checked in this laboratory by six volumetric tanks located on the first floor. Each tank has a capacity of 2,000 gallons, and the tanks are so arranged that they can be used in series, allowing a test run of any desired length to be made and the discharge checked continuously.

On the second floor near the vertical high pressure tank is located another vertical pressure tank 4 feet in diameter and 8 feet high, which is used for the student experiments on orifices and weirs. Water is taken from the large pressure tank and throttled into the student supply tank. Orifices for a test are mounted in the side of the tank, the head on the orifice being measured by an open gage glass manometer. The orifice discharges into an open flume about 2 feet deep, 30 inches wide and about 8 feet long. Suitable baffles in this flume provide quiet flow conditions for a weir which is mounted in the end of the flume. The discharge from the weir can be taken to the volumetric tanks or discharged to the sump, as desired.

On the second floor there is also located a test flume for hydraulic models. It is 3 feet square in section and about 90 feet long, there being one 90° short radius bend in the length of the flume. For small flows, water is taken from the laboratory distribution system into an elevated head box which is about 3 feet wide, 10 feet deep and about 12 feet long. At the end of this head box is located a "V" notch weir which provides a check on the flow to this test flume. For larger flows, water reaches the flume through the 12-inch Venturi meter and 10-inch supply line. The test flume is made of steel throughout except for one section 9.0 feet long in which the two sides are made of glass.

On the first floor is located a river flume which is 44 feet long, 12 feet wide and 7.5 feet deep. Water is supplied to this flume from the constant level tank, and is measured by the calibrated Venturi meters.

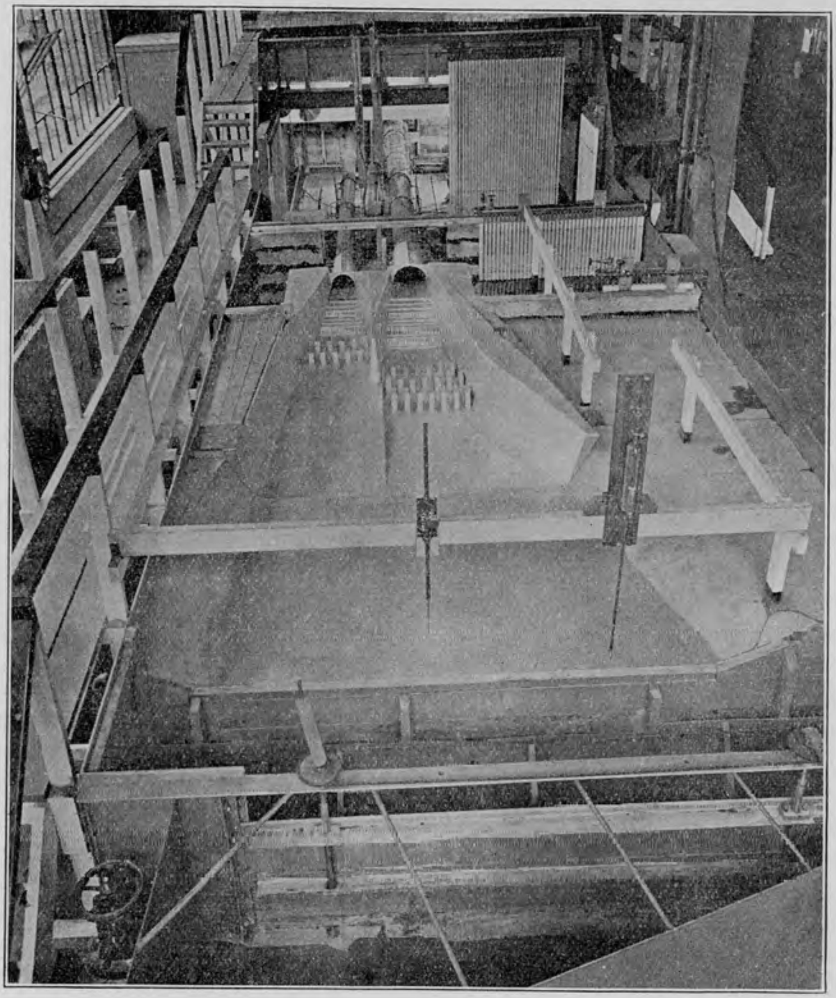

FIG. 10. — MODEL TESTING FLUME AT CASE SCHOOL OF APPLIED SCIENCE

An adjustable weir is located at the downstream end of the flume for tail-water regulation. At the time of the inspection a model of the Pleasant Hill Dam was being tested in the river flume. The model included all of the hydraulic structures about the dam, such as the Morning Glory spillway and outlet tower, the tunnels through the dam, stilling basin, and the discharge channel below the dam.

At the time of the inspection of this hydraulic laboratory, considerable work was in progress for the United States Army Engineers of the Zanesville office in connection with the Muskingum flood control work in Ohio. In all there were eleven different model tests of the hydraulic structures of as many flood control projects, the tests of which have been completed in about eleven months. In this work Professor Barnes was being assisted by Mr. J. G. Jobes and Mr. W. A. Snyder of the Army Engineers.

Columbia University

The hydraulic laboratory of the civil engineering department of Columbia University in New York City is operated under the direction of Prof. B. A. Bakhmeteff. It is designed for fundamental research by members of the staff and for a limited amount of graduate thesis work.

This hydraulic research laboratory is located in a room about 20 feet by 40 feet in plan, in the basement of the building. Water is stored in a sump of 750 cubic feet capacity below the floor level. A single-stage 8-inch motor-driven centrifugal pump, capable of supplying 4.6 c. f. s. at the existing head of about 25 feet, takes water from the sump and discharges into a constant head tank located on the floor above. This rectangular steel head tank is equipped with 60 feet of skimming weir crest so as to maintain a constant head of about 20 feet above the laboratory floor.

Volumetric tanks are used for calibration of discharge meters. Two tanks have been constructed of concrete below the floor level. The largest has a capacity of about 350 cubic feet and the smaller of 70 cubic feet. Both tanks have been calibrated by weighing tank measurements. Water levels are determined approximately with gage glasses and accurately with a point gage.

There are two concrete return channels 15 inches square in section traversing the floor of the laboratory. One of these channels leads directly to the sump. The other discharges into a basin which, in turn, discharges into either volumetric tank through 14-inch quick-acting valves.

At one side of the room there is situated a tilting flume with glass sides, which is 20 feet long, 6 inches wide and 22 inches deep. Water is brought to the flume through a head box provided with suitable baffles and convergent intake for the flume section. A graduated straight edge is mounted horizontally over the axis of the flume. Hook or point gages may be mounted on this straight edge for the measurement of the water elevation.

A steel sluice gate installed in vertical guides is located at the upstream end of the tilting flume. The gate is operated through a rack and pinion which, in turn, is driven through a worm, allowing fine adjustment of the gate position.

An adjustable weir, driven by a similar gear train, is mounted at the downstream end of the flume and is used for controlling the elevation of the tail-water. Brass piezometer plates are inserted in the bottom of the flume, and an open-end manometer panel holding 40 glass tubes is provided for convenience in determining the hydraulic gradient. The discharge of the flume is measured with a 4-inch rounded orifice installed in the 8-inch supply pipe of the flume. The differential pressure across the orifice is measured with either water or mercury differential manometers. This flume has been used in the study of flow in open channels.

Work on flow through granular materials is being done on another piece of apparatus which consists of a smaller, independent circulating system. The water for this system is stored in a steel tank 4 feet by 4 feet by 4 feet, located under the floor of the laboratory. A 2-inch Ingersoll Rand motor pump delivers the water to a cylindrical tank 2½ feet in diameter, 4 feet high, which is suspended from the floor beams of the second floor above the laboratory. Constant head is maintained by means of a 10-inch funnel. The water passes through a gravel filter in this tank and then flows by gravity through a 3-inch line to the test section. The test section consists of either a 2-foot or a 5-foot brass pipe 3 inches in diameter. Extra heavy brass flanges at the extremities of the test section are fitted with dowels to insure centering on reassembly and piezometer rings. The piezometer rings are connected to four 6-foot lifts of open-end water manometers. City pressure connections to the piezometer rings permit forcing air out through the manometer tubes. Discharge measurement is made by means of a tipping bucket, tank and scales. This piece of apparatus was designed to be of use for other studies when the present work has been completed. One of its features is the use of brass and galvanized iron pipe exclusively to minimize introduction of impurities due to corrosion.

A Reynolds apparatus has been built for the demonstration of laminar and turbulent flow. It consists of a head tank 3 feet 6 inches long, 2 feet 3 inches wide and 3 feet deep, and a 5-foot glass tube 1 inch in diameter, which protrudes 1 foot into the head tank. A carefully rounded approach section has been blown on to the upstream end of the tube. A valve at the discharge end controls the quantity of flow. Dye is injected at the approach to show the characteristics of laminar and turbulent flow.

A flume 15 feet long, 14 inches wide and 10 inches deep is used to demonstrate and photograph the nature of flow around various objects. A carriage is mounted on the sides of the flume. The object is attached to the carriage which is fitted with a camera rack and lighting facilities. Water in the flume is permitted to come to rest and then aluminum powder is sprinkled on the surface.

A cylindrical tank equipped with glass observation panels has been installed for the demonstration of vortex flow. The tank is about 2 feet in diameter and 8 inches high. Water is admitted tangentially at the rim and discharged through a ¾-inch pipe and throttling valve connected at the center of the bottom of the tank. Dye may be injected to show the flow characteristics of the vortex.

The photographic darkroom of the department is located in the basement and adjoining this laboratory. This is a matter of great convenience when photographic studies of flow phenomena are being investigated.

Cornell University

There are essentially two hydraulic laboratories at Cornell University, Ithaca, New York. The first, located in the mechanical engineering department, is devoted to hydraulic machinery and operated under the direction of Prof. A. C. Davis. The second is operated by the civil engineering department under the direction of Prof. Ernest Schoder.

Mechanical Engineering Department

The hydraulic laboratory in the mechanical engineering department comprises one section of the mechanical engineering laboratories, and is designed primarily for student instruction, a floor space of about 40 feet by 70 feet being used for this purpose. The water used for the experiments is stored in three sumps located below the first floor. Each sump supplies a separate system, assuring complete freedom from interference between various parts of the test equipment.

A 15-inch S. Morgan Smith reaction water wheel is located near one wall of the room. Water is supplied for this test by a 16-inch motor-driven Gould centrifugal pump designed to deliver 11.1 c. f. s. at 20-foot head. Between the pump and the water wheel there is installed a 14-inch by 8-inch Venturi meter which is used to measure the discharge. The S. Morgan Smith vertical water wheel discharges directly into the sump through a conical diverging draft tube.

All the pressure measurements are made at a central gage point. The Venturi differential is read from either a water air or mercury water

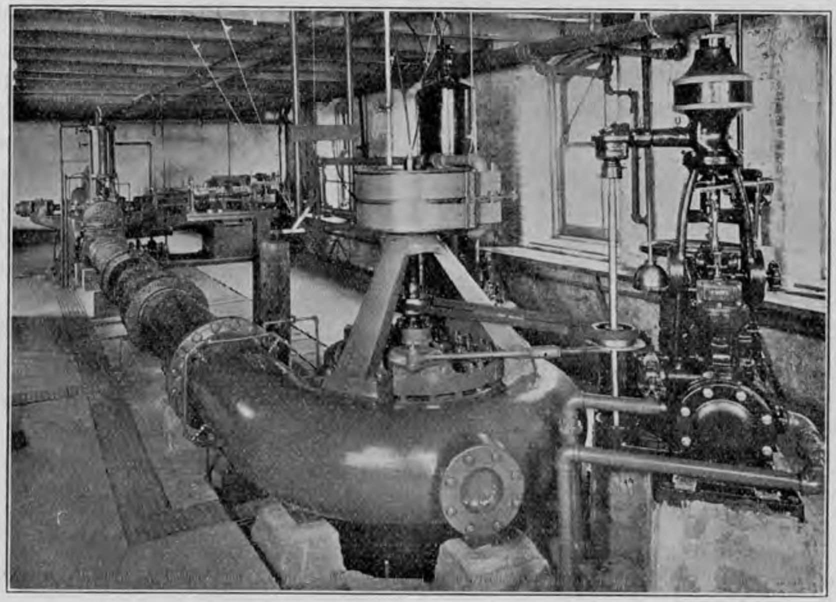

FIG. 11. — WATER WHEEL TESTING EQUIPMENT IN MECHANICAL ENGINEERING DEPARTMENT, CORNELL UNIVERSITY

manometer. A Bourdon tube gage in parallel with a mercury-water manometer is used to measure the pressure head, and a float gage indicates the tail-water elevation.

The torque of the wheel is measured with a Prony brake and platform scales. The wheel speed is determined with a chronometric tachometer driven by a flexible shaft.

The centrifugal pump test is located at the end of the room. This installation has been the subject of research investigation as well as student test. Centrifugal pumps delivering up to 2.2 c. f. s. at 230-foot head may be driven by a 15-horsepower electric dynamometer. There are two Venturi meters connected in parallel in the discharge line from the pump, one being 3 inches by 1½ inches, and the other 2 inches by 1 inch. These meters are used either singly or together to provide an accurate measure of discharge over a wide range. The Venturi differentials are read with mercury manometers located at a central gage board. The discharge and suction pressures are measured either with Bourdon tube gages or mercury U-tube gages mounted on the same board.

An auxiliary motor-driven centrifugal pump is connected into the suction line of the main pump. This arrangement is used to facilitate the performance of cavitation tests. By using the auxiliary pump or by throttling a gate valve in the suction line in the main pump, the pressure at this point can be varied readily from −25 feet to +25 feet of water.

A glass-enclosed 12-inch impulse wheel is the subject of a student test. Water is supplied to the wheel by a motor-driven pump designed to deliver 0.5 c. f. s. at 300-foot head. The discharge is measured by triangular weir. A hook gage indicates the head on the weir. The output is determined with a Prony brake and scales together with a hand counter. A neon tube stroboscope is arranged for visual demonstration.

A number of discharge measuring devices are connected in series for calibration and use. Water for this experiment is supplied by a motor-driven pump which can deliver a maximum discharge of about 0.5 c. f. s. First, the water passes through a 3-inch by 1½-inch Venturi meter, and then, in succession, a sharp-edged orifice mounted between flanges, and a house type water meter. Finally, at the end of a pipe there are mounted four different types of nozzles, any one of which may be used and calibrated. The discharge from the nozzles is caught in a rectangular flume. At the downstream end of this flume is mounted a "V" notch weir (several angles are available) which discharges into a second flume. At the end of this second flume is installed a rectangular contracted weir. A third flume has a rectangular suppressed weir. The discharge of this weir may be caught in a weighing tank of 6,500 pounds' capacity, mounted on Toledo scales, or else diverted directly to the sump.

A demonstration apparatus for viscous and turbulent flow consists of a tank in which constant head may be maintained, discharging through any one of three different-sized glass tubes. One of these tubes continues as a brass tube with connections for measuring the head loss by means of a very sensitive differential hook gage. A capillary discharging a colored fluid into the entrances of the glass tubes furnishes a visual means of studying the character of flow.

There are two tests involving fluid flow which use air instead of water as a fluid. In the first a Buffalo forge blower, which is driven by a cradled motor, discharges into a straight section of brass pipe 15 feet long. A Pitot tube is installed and a pipe traverse is made about 5 feet from the downstream end. A series of well-rounded discharge orifices are available for mounting on the end of the pipe, providing a check on the discharge.

In the second test a motor-driven steel plate fan with a 12-inch discharge pipe supplies air to a duct where a number of methods of air measurement are applied. About 10 feet downstream from the fan there is installed a thin plate orifice together with a large number of piezometers, so that the hydraulic gradient may be portrayed in the region of the orifice. Downstream from this orifice there is located a Venturi meter. Several locations are provided for Pitot tube traverses, near the blower, before and after straightening varies. Below the Venturi meter a Thomas electrical gas meter with heating coils has been mounted in the pipe which is used to measure the discharge by the cooling effect of the air upon the coils. Finally, the end of the pipe enlarges into a square cross section, and a traverse is made at this point with an anemometer.

A small wind tunnel is used for instruction concerning Reynolds' number, as well as for an introduction to the behavior of a plane in flight.

Civil Engineering Department

The hydraulic laboratory of the civil engineering department at Cornell University is located on a natural water privilege adjacent to the campus. The facilities of the laboratory are adapted for a wide range of investigational work as well as student instruction.

The principal water supply is obtained from Beebe Lake which has an area of about 20 acres. This reservoir was formed by the construction of a concrete dam at the head of the gorge of Fall Creek just upstream from Triphammer Falls. This stream is supplied by a watershed having an area of 126 square miles, so that a very considerable discharge is available during most of the year. The maximum discharge that may be handled in the outdoor flumes is 400 c. f. s., while discharges as large as 60 c. f. s. may be handled inside the laboratory.

The largest piece of outdoor equipment is a rectangular concrete-lined canal 16 feet wide and 420 feet long. The upper portion of this canal is 18 feet deep, and the lower portion is 10 feet deep. It is supplied with water from Beebe Lake through six head gates. About 50 feet below the gates there may be located experimental weirs and dams, leaving a clear run of 350 feet to a downstream weir which is used to measure the discharge. This clear section of the canal may be used for water measurements with floats and current meters. Just at present the downstream half of the lower canal is enclosed and houses a river model 150 feet long. The upstream part is occupied by an overflow dam model 12 feet wide and 50 feet long.

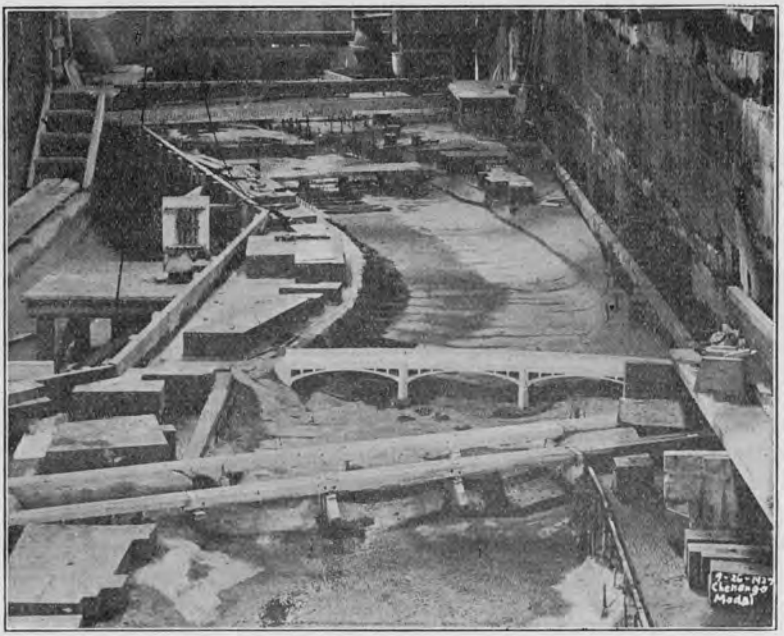

FIG. 12. — CIVIL ENGINEERING DEPARTMENT, CORNELL UNIVERSITY — VIEW LOOKING DOWNSTREAM OF MODEL OF CHENANGO RIVER, HAVING MODEL RATIO 1:75

There are also two parallel concrete flumes which are supplied from Beebe Lake independently of the large canal. These flumes are 2 feet wide, 2½ feet deep and 90 feet long. At the upper end they connect into a short canal 7 feet wide, 3 feet deep and 40 feet long, and at the downstream end discharge into a concrete volumetric tank of 2,000 cubic feet capacity. Recently these flumes have been enclosed by a shed roof. The shed also houses a 15-inch by 15-inch wooden flume 120 feet long, hung from steel bents so the slope may be varied.

The laboratory is built against the south cliff of Fall Creek Gorge and extends vertically about 70 feet from the pool below Triphammer Falls to the top of the Gorge. There are four floors, viz., the basement, the "Junior lab. floor" 30 feet above, the lecture room, and the top or entrance floor stepped into several levels. Water is brought to the laboratory from the lake through a 48-inch steel pipe line which runs parallel to the main canal. A short 30-inch penstock brings the water into the top floor of the building, where it discharges directly into a 6-foot wide, 12-foot deep, 35-foot long flume, the discharge being regulated by a valve. Just upstream from this valve a 10-inch pipe is connected, which supplies other experimental apparatus and flumes lower down in the building.

The 6-foot concrete flume is used for weir and model tests. The discharge from the flume may flow into a 6-foot steel standpipe or else be diverted directly to waste.

The standpipe is 60 feet high and is equipped with a float gage which provides an accurate indication of the elevation of the water surface when the standpipe is used as a measuring tank. A 36-inch hydraulically operated discharge valve is connected at the bottom of the tank, allowing easy and rapid operation of the tank as a volumetric check of discharge. The time of a volumetric run is measured with a chronograph. The standpipe is used also as the pressure reservoir to which large Venturi meters, flow nozzles, etc., may be attached. A 24-inch and smaller saddle nozzles are available. In connection with the upper weir and diverter the standpipe may be used alternately as a pressure tank transmitting a steady flow coming over the weir, and as a measuring tank to measure this flow.

There is a second concrete flume in the building 2 feet wide, 4 feet deep and 25 feet long, which is used for smaller scale weir and model tests. A maximum discharge of about 11 c. f. s. may be used in this flume and measured in tanks at the bottom of the building.

The 10-inch pipe which is connected to the 30-inch pipe at the wall of the building supplies the small concrete flume mentioned above, and, in addition, provides the water supply for the apparatus installed in the lower floors of the building. A 12-inch by 9-inch calibrated Venturi meter is installed in the upper portion of the pipe, allowing the discharge to be checked conveniently. This line supplies the needs of a lecture room which is located on the second floor down and some experimental apparatus which is set up in the third floor down and in the basement. In addition, it is used as a supply when small commercial Venturi meters are calibrated.

In the basement a 5-inch reaction water wheel is mounted over a concrete channel. The channel is equipped with baffles to provide quiet flow conditions to an 18-inch suppressed weir at the downstream end which measures the discharge. The head on the wheel is measured with a U-tube gage. The output of the wheel is determined with a small Prony brake and a hand counter.

Beside the reaction water wheel a 24-inch Doble impulse wheel is mounted on a concrete pedestal. The discharge in this case is determined with a volumetric tank, the pressure with a U-tube gage, and the output with a Prony brake. Finally, there are tests of a nozzle on an 8-inch pipe and a 6-inch water meter which use the same volumetric tank.

The lecture room is located on the second floor down. At one end of the lecture table there is installed a steel tank 2 feet in diameter and about 5 feet high. A gage glass is connected into the side of the tank, indicating the water level. Auxiliary equipment is provided to illustrate the phenomena of hydrostatics, the performance of orifices, short tubes, Venturi meters, weirs, friction of flow in pipes, a small Pelton wheel, and the trajectory of jets during the course of student lectures which are closely co-ordinated with the recitations.

The Holyoke Water Wheel Testing Flume

The Holyoke water wheel testing flume at Holyoke, Massachusetts, is of historial interest because, so far as is known to the writer, it was the first laboratory designed for the commercial testing of water wheels. It was in operation until March, 1937, but its use has now been discontinued.

A testing flume was first put into operation in 1874 by James Emerson, who had received his engineering training at Lowell. In 1881 and 1882 the business was purchased by the Holyoke Water Power Company, who built a new testing flume at another location, with Clemens Hershel in charge of the work.

Water is brought to the flume through a 9-foot circular penstock which discharges through racks into a rectangular opening about 11 feet by 13 feet in section, which leads at right angles into the testing flume. This flume is 20 feet square in section and about 22 feet high. The water wheel draft tubes are mounted on a cast iron plate at the center of the bottom of the flume. The water discharges from the water wheel into the weir flume which is 20 feet wide and 35 feet long. There are two sets of racks in this flume to provide quiet flow conditions, located 13 feet and 24 feet upstream from the weir. The weir crest is 6 feet above the bottom of the flume. The whole length of 20 feet can be used for measuring water, or detachable end contractions can be used to reduce the effective length where small discharges are to be measured accurately.

The power output of the water wheel is measured by means of hand-operated Prony brakes, there being a range of sizes available. The revolutions of the water wheel are indicated by a worm-driven pointer which is continuously connected so that readings are taken "on-the fly."

Tests are made in this flume under heads varying from 14 to 18 feet. It is possible to test wheels delivering up to 400 horsepower or discharging up to 250 c. f. s. The largest water wheel which has been tested at this flume was 52 inches in diameter, but wheels over 35 inches in diameter are penalized somewhat by the cramped setting and disturbed flow conditions. As stated at the beginning, this flume was formally closed March 1, 1937.

University of Illinois

The hydraulic laboratory at the University of Illinois, at Urbana, is designed primarily for student instruction, although space is available and equipment is being developed for various types of research investigations. The laboratory is operated in the department of theoretical and applied mechanics, under the direction of Prof. F. B. Seely. It is located in the basement and first floor of the west wing of the materials testing laboratory, each floor being 187 feet by 50 feet in plan.

The water supply is taken from the sump and return channel by five centrifugal pumps which are connected to a constant level tank or standpipe. One of these pumps has a capacity of 1.1 c. f. s. at 80-foot head, two others have a capacity of 2.2 c. f. s. each at 80-foot head, and the last two have a capacity of 4.4 c. f. s. each at 80-foot head. In addition there is a motor-driven centrifugal pump which is capable of supplying 30 c. f. s. at 35-foot head. It delivers water through 200 feet of spiral riveted pipe 24 inches in diameter to a large concrete flume on the first floor. There is also a three-stage motor-driven centrifugal pump that can deliver 0.60 c. f. s. against a head of 400 feet. This pump is used in experiments requiring higher heads than can be obtained from the constant level standpipe.

The vertical constant level tank is 6 feet in diameter and 65 feet high, with four skimmer weirs having crest lengths of 16 feet each installed at different elevations, so that the equipment can be operated at four different heads. As a convenience in operating the apparatus, there is an automatically controlled red electric light bulb that lights when there is water flowing in the overflow pipe, which indicates that the pumps are supplying the needs of the experiment and that the head is remaining constant. There are several outlets from this constant level tank supplying the laboratory. The main 12-inch distribution piping connects all parts of the laboratory, while branches of 8-inch, 6-inch and 4-inch pipe supply various experiments.

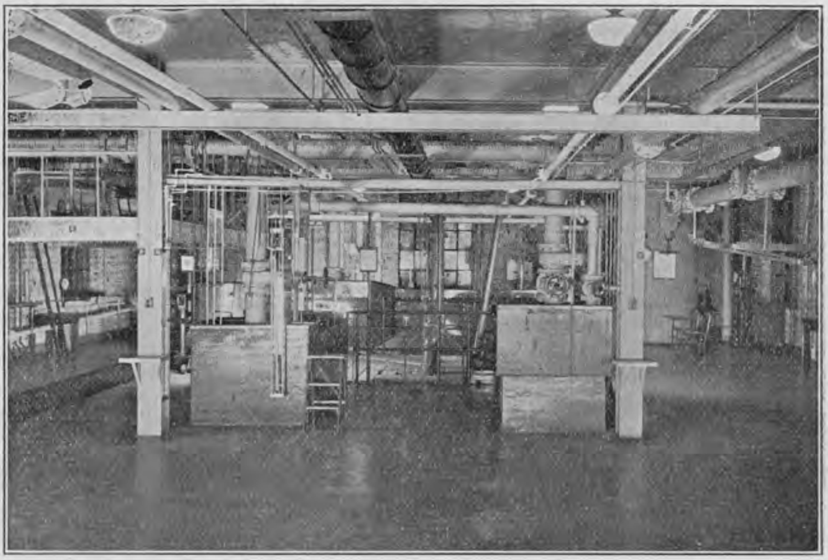

FIG. 13. — UNIVERSITY OF ILLINOIS — NORTH END OF THE HYDRAULIC LABORATORY

In general, the student experiments are set up on the first floor, discharging the water into volumetric or weighing tanks located in the basement beneath. The scales indicating weights and volumes can be read and the discharge valves of all tanks are operated from the first floor. The waste water and the drains from the measuring tanks discharge into a return flume which is 5 feet square in section, 175 feet long and located below the basement floor level.

The apparatus in the laboratory is described in connection with the experiments performed by the students, since this comprises most of the equipment. There are three sets of equipment for all of the student experiments. With this arrangement only three students work together during the performance of a test.

The use of simple "U" tubes and differential gages is given to the students in a test comprising (*a*) simple U-tube mercury gage; (*b*) differential gage with a fluid heavier than water, such as carbon tetrachloride; and (*c*) a differential gage with a fluid lighter than water. These gages are calibrated against water columns.

A Bourdon tube pressure gage is calibrated by means of a Crosby dead weight gage tester and by comparison with a mercury manometer.

The calibration of square-edged orifices and standard short tubes is the subject of three experiments, only one of which is performed by any one group of students. In the first case the orifices are mounted in the side of a rectangular steel vertical tank about 3 feet by 5 feet in section and 8 feet high. The head on the orifice is measured with a gage glass, and the discharge is caught in a volumetric tank, the elevation in the volumetric tank being determined by means of a float gage. In the second case a standard circular orifice is mounted on the end of a 4-inch pipe. The head on the orifice is measured with a gage glass for low heads, and a mercury manometer is used to measure the higher heads. The discharge is determined by a weighing tank and a stop watch. The diameters of the orifices and jets are measured with hand calipers.

A commercial type of test stand is used to determine the accuracy of a house type water meter and the loss in head at different rates of flow. In addition, a mercury differential gage is connected across the meter in order to measure the head loss. The discharge is measured by a small weighing tank and an Eastman timer. A quick acting valve in the inlet pipe is used to start and stop the flow through the meter to the weighing tank.

The calibration of a Venturi meter is combined with the friction loss determination in a 4-inch pipe. The Venturi meter used in this experiment is 4 inches by 1¼ inches, and it discharges into a line of 4-inch steel pipe. This pipe has a straight section 133½ feet long in which the friction factor is determined, and another section 271 feet long containing two elbows which provides an indication of bend loss. The 4-inch pipe finally discharges into a calibrated volumetric tank. The Venturi differential and the head loss through the Venturi are measured in a three-column mercury manometer. A similar manometer is used to measure the pressure differences in the pipe loss tests.

There are three experiments on weirs, one with a 12-inch rectangular contracted weir, one with a 12 inch suppressed weir, and one with a

90° "V" notch weir. The equipment is similar in all three experiments, so that only one is described. The weir is mounted in a steel bulkhead in a steel tank which is about 4 feet square in section and about 20 feet long. The head on the weir is measured by a hook gage and the discharge by a calibrated volumetric tank.

Pipe friction loss is also determined in a straight length of 2-inch pipe 120½ feet between piezometers. Another test section having a length between piezometers of 260 feet contains two elbows. A three-legged mercury manometer is used to determine the difference in pressure, and the discharge is determined by a weighing tank.

The friction loss in fire hose is found in conjunction with the calibration of a fire nozzle. The head loss is measured in 100 feet of 2½-inch rubber-lined fire hose operating with a ⅞-inch nozzle at the end. Two calibrated Bourdon tube gages are used to measure the pressures at the inlet to the hose and the entrance to the nozzle. The discharge is measured in a calibrated volumetric tank, using an Eastman timer to time the test.

The friction loss at low Reynolds numbers is measured in 36 feet of ¼-inch standard steel pipe, using a water differential manometer. Three sets of the apparatus are available. The discharge is measured in a small weighing tank, using an Eastman timer. The flow in the pipe in this experiment is well within the viscous range for the low velocity and extends into the turbulent range for maximum discharge.

Efficiency tests are made on a 1-inch Chicago ejector pump. The pressure in the supply pipe is measured by a Bourdon tube gage, in the discharge line by an open manometer, and in the suction line by a mercury manometer. The water pumped is measured in one weighing tank and the total discharge in another, Eastman timers being used to time the test.

There are two impulse water wheels available for test, one being a 12-inch Doble wheel set in a glass case, the other a 16-inch Pelton water wheel in a cast iron case. The pressure at the nozzle is measured by a Bourdon tube gage and the discharge by weighing tanks. The pressure is maintained by the three-stage centrifugal pumps previously described. The output of the wheel is measured by a Prony brake, Hasler tachometer, Eastman timer, and small scales.

There are two centrifugal pump tests in which the efficiency and operating characteristics of the pumps are determined. In the first experiment the test is conducted on a two-stage centrifugal pump driven by a calibrated direct current motor, the efficiency of which has been determined in the electrical laboratory. The input to the motor is measured with an ammeter and a voltmeter. The suction and discharge pressures are measured by calibrated Bourdon tube gages. The discharge is determined by a weighing tank, and the speed is indicated by a direct-driven tachometer. In the second test the same information is obtained in connection with an Allis-Chalmers single-stage 4-inch centrifugal pump driven by a calibrated three-phase induction motor. The power input to the motor is measured by a polyphase wattmeter. The pressures in the suction and discharge pipes are measured by calibrated Bourdon tube gages. The speed of the pump is determined by a tachometer or a hand revolution counter. The discharge is measured by a calibrated volumetric tank. In connection with this test an elbow

FIG. 14. — UNIVERSITY OF ILLINOIS — SOUTH END OF THE HYDRAULIC LABORATORY

in the discharge line above the pump is calibrated as a flow meter. Two piezometers are drilled into the elbow on the 45° line, one being on the outside of the elbow and the other on the inside. A differential gage attached to these piezometers provides a deflection which is proportional to the square of the discharge in the pipe.

The distribution of velocity in an 8-inch pipe is determined by means of a Pitot tube. The traverses are made in an 8-inch pipe 9 feet below a conical reduction which connects the 8-inch pipe with a 12-inch pipe. This provides more smooth flow conditions than customarily found in pipe traverse work. The discharge from the 8-inch pipe passes over a 12-inch rectangular contracted weir and then falls into a calibrated volumetric tank. The Pitot tube used in this experiment is home-made, consisting of a piece of bent 3/16-inch brass tubing, the end of which is in the plane of the supporting rod. The Pitot tube is inserted into the 8-inch pipe through a 1-inch pipe equipped with a stuffing box. The Pitot tube is mounted off center in the 1-inch pipe so that the whole rod can be withdrawn into the 1-inch pipe when desired, allowing velocity determinations to be made in the plane of the 8-inch pipe wall. The pressure is measured in a differential gage, using a mixture of carbon tetrachloride and gasoline having a specific gravity of about 1.25. Two differential manometers are used in this test, being filled with gage fluid from the same mixture. One of these gages is connected to the Pitot tube, and the other is used to determine the specific gravity of the gage liquid. Velocity distribution is also studied in the 24-inch spiral riveted steel pipe by Pitot traverses in both horizontal and vertical planes at various stations along the pipe.

In addition to the equipment used by the undergraduate students in their laboratory work there are a number of other pieces of apparatus which are used either in advanced hydraulics laboratory work or in graduate research work. There is a concrete flume on the first floor in which is located a Leffel water wheel. The flume is 6 feet wide and 18 feet deep for a distance of 24 feet. At this point is located a 6-foot suppressed weir with a depth of 13½ feet below the crest. Then the water discharges into a lower continuation of the flume which is 13½ feet deep for a distance of 59 feet. Finally, the flume is 10 feet deep for a distance of 37 feet, and then it discharges into the return flume below the basement floor. At the time of the inspection the reaction water wheel was supplied by the 12-inch distribution system of the laboratory, so that only a small water wheel (11.5-inch diameter) was being used. However, the 24-inch piping is now installed connecting the 24-inch centrifugal pump with this concrete flume, and it is hoped to install a more modern water wheel in the near future.

A 3-inch Rodney Hunt water wheel is installed in a cylindrical glass case for a demonstration test. The speed of the wheel is controlled by a small Prony brake at the top of the case. The discharge passes through a concentric conical glass tube into a steel flume about 18 inches by 36 inches in section and about 8 feet long, containing a 90° "V" notch weir at the downstream end. A check on the discharge is obtained with a calibrated elbow meter, the differential pressure being read in a mercury manometer.

For hydraulic model studies a steel tank 9 feet by 18 feet in plan is used. At the present time a model of the spillway and approach channel of one of the water supply reservoirs of the State is being tested. The scale of the model is 1:20, the width of the model spillway being 5 feet. The water delivered to the model is measured by calibrated orifices on the end of an 8-inch pipe.

A hydraulic ram which is supplied with water from a tank through a 4-inch drive pipe 55 feet long is equipped with a Maihak engine indicator for obtaining pressure time diagrams in the study of the characteristics of the ram.

Equipment for the study of water-hammer phenomena consists of about 600 feet of 2-inch pipe with apparatus for determining pressure time diagrams under various conditions of flow.

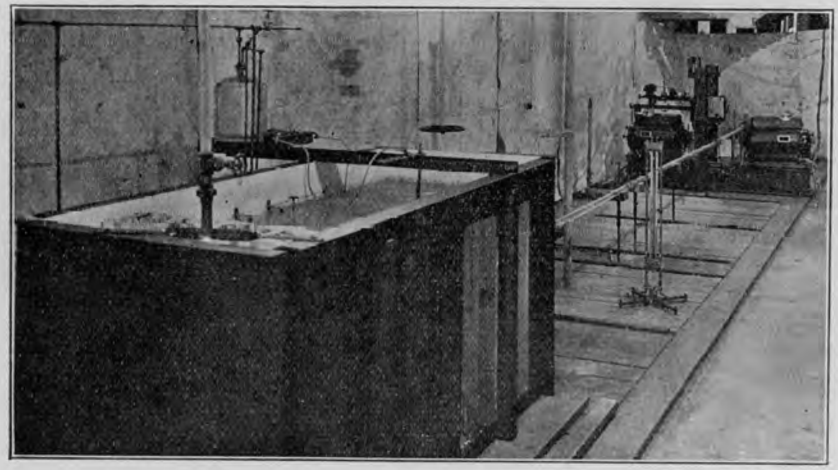

FIG. 15. — UNIVERSITY OF ILLINOIS — EQUIPMENT FOR MAKING PHOTOGRAPHIC DETERMINATIONS OF VELOCITY IN GLASS PIPE

Equipment for the photographic study of the characteristics of the flow of water in a pipe consists of a glass pipe 1¾ inches in diameter and 30 feet long, a portion of which is intensely illuminated by two powerful projection lanterns. Fine drops of an insoluble liquid of the same density as that of water, in suspension in the water, are photographed at various velocities of flow by a movie camera mounted directly above the illuminated portion.

In studying the dynamic action of jets, there is an apparatus for measuring the force exerted on stationary vanes or blades of various shapes or contours by high velocity jets of water up to 1½ inches in diameter. The laboratory equipment also includes two types of viscosimeters, a glass apparatus for performing Reynolds' classical experiment, and a small metal flume for demonstrating hydraulic jump and other open channel flow phenomena.

A motor generator set of 50 kilowatt capacity provides direct current for experimental purposes.

University of Iowa

The Iowa Institute of Hydraulic Research at Iowa City was organized to encourage co-operation in hydraulic research between the University and Federal or other agencies which might wish to make use of the facilities of the hydraulics laboratory. F. M. Dawson is dean of the college of engineering and director of the institute. The laboratory operates under the direct supervision of Prof. E. W. Lane, associate director.

The principal co-operating agencies are the Bureau of Agricultural Engineering, United States Department of Agriculture, represented by Mr. D. L. Yarnell,* the United States Engineer Department, represented by Mr. M. E. Nelson, and the Water Resources Branch of the United States Geological Survey, represented by Mr. R. G. Kasel. Each of these departments maintains a staff at the institute for the investigation of their respective projects. Since the summer of 1936 the National Association of Master Plumbers has co-operated with the institute in an investigation of the occurrence and prevention of pollution of water supplies by cross-connections and back siphonage.

The institute also has its own research program. In addition to this, classes in hydraulics laboratory technique and graduate research projects are conducted in the laboratory by the department of mechanics and hydraulics of the university of which Prof. F. T. Mavis is head.

The building devoted to laboratory work is 164 feet by 44 feet in plan. There are three full stories and a basement of this size. Then there is a central tower 45 feet by 44 feet in plan, which continues upwards for two stories. The basement and first two floors are devoted to active laboratory work, the third floor contains the constant head tank, offices and shops of the Army Engineers, a student classroom and a silt testing laboratory. The tower contains drafting rooms, offices and a library.

* The death of Mr. Yarnell on March 9, 1937, has temporarily interrupted the program of the Department of Agriculture.

The water used in the experimental work inside the laboratory building is recirculated by pumps. Two reservoirs located on the basement floor are used as sumps for the supply pumps. At the time of the inspection there were two centrifugal pumps in the pump room, which is located in the basement at the upstream end of the reservoirs. Both of these pumps are electric motor-driven, and are connected to the constant head tank on the third floor. One of the pumps has a 6-inch discharge pipe and delivers 2.7 c. f. s. under a head of 50 feet. The other is a 10-inch pump and delivers 6.7 c. f. s. under a head of 50 feet. The constant head tank has an area of approximately 350 square feet and is equipped with 700 feet of skimming weir crest. Several pipe connections ranging from 3 inches to 10 inches in diameter are made separately to this tank.

The principal laboratory equipment is located on the first and second floors of the building. The most important piece of apparatus on the first floor is the pair of 18,000-pound weighing tanks located near the center of the building. A switchway is set up over both of the tanks, allowing the water to be measured in either tank or else diverted back to the sump. The switchway and the emptying valves of the tank are remotely operated by hydraulic servo-motors. In this way continuous measurements of discharges as large as 5 c. f. s. can be made. The entrance of the switchway is located at the level of the second floor.

Between the weighing tanks and the upstream end of the building there are three flumes. The largest of these is 30 inches wide, 39 feet long and of varying depth. Both sides of the flume are made of glass for a length of about 20 feet, which is used normally as a testing section. Upstream from this section the flume is fitted with racks to quiet the flow of water approaching the model. The discharge of the model test is measured before entrance to the model flume with a "V" notch weir. This weir is installed in a flume 30 inches wide, 36 inches deep and about 12 feet long. This whole flume is mounted above the testing flume so that the weir discharge falls into the upper end of the model flume.

A test of a Tainter gate is in progress in this flume. The purpose of this test is to determine the pressure distribution on and near the gate, and also to determine the erosion of the river bed below the gate with various methods of gate operation. The model represents one bay of Mississippi River Dam No. 4 to an undistorted scale of 1:15. All of the piezometers are connected to a battery of water manometers. This group of manometers, which contains about forty tubes, is located

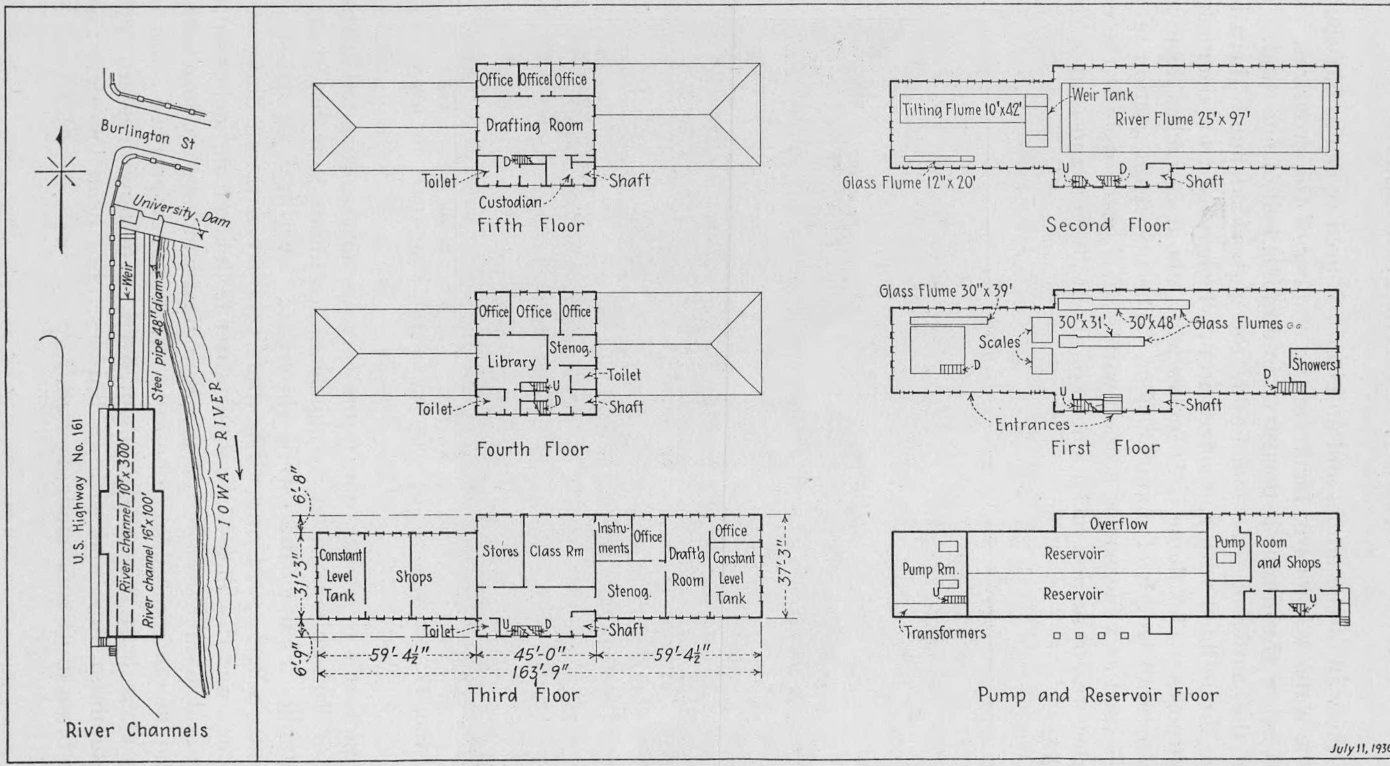

FIG. 16. — FLOOR PLANS OF LABORATORY AT IOWA INSTITUTE OF HYDRAULIC RESEARCH, UNIVERSITY OF IOWA, IOWA CITY

above the wall of the flume, and an ejector is used to pump out the air over the water columns to facilitate the reading of the pressures. The erosion below the aprons is portrayed in a model bed of fine sand.

In the center of the room beside the glass-sided flume there is a wooden flume lined with galvanized iron, which is used for demonstration purposes. This flume is 27 inches wide, about 24 inches deep, and has an overall length of about 30 feet. The upstream portion of the flume is used as a measuring section with a "V" notch weir at the end. The downstream section has a length of about 20 feet, and is at a lower elevation.

FIG. 17. — HYDRAULIC LABORATORY OF THE UNIVERSITY OF IOWA

Beside this demonstration flume there is an experimental investigation of draft tube flow. A circular head box about 30 inches in diameter supplies a model draft tube through a "swirling" device similar to a water wheel speed ring. The draft tube has a throat diameter of $1\frac{1}{2}$ inches, and discharges into a tail-water tank about 30 inches square in plan and about 20 inches deep. Two glass windows are provided so that the flow in the tubes can be inspected and photographed. For this work a glass draft tube model is employed. The flow lines are traced with aluminum dust and with air bubbles. For head loss determinations a brass draft tube model is used.

The space on the first floor at the downstream end of the building is being left for development. Several small tests are in progress, but the apparatus can be moved readily in case room is needed.

In the center of the room to the rear of the weighing tanks there is installed about 25 feet of 6-inch square pipe with an elbow at the end. Much of this pipe is made of galvanized iron, but there is about 6 feet of it which is made of pyralin so that the flow can be studied. Water is supplied to this experiment from a standpipe about 2 feet in diameter and 8 feet high. The discharge falls into a "V" notch weir flume and then into a return channel to the sump beneath the floor. A large number of piezometers are installed in the pipe and are connected to a differential manometer board for the measurement of the hydraulic gradient.

This square pipe is a part of a model for the study of characteristics of ports and side tunnels for locks. A galvanized iron tank 30 inches square in plan and about 3 feet high serves as a head tank and simulates the chamber of the lock. The square pipe simulates the culvert used for filling and emptying the lock. The port being tested connects the tank to the square pipe. With this apparatus it is possible to measure the discharge through the port under different heads and for different velocities past its face in the culvert.

Beyond this model a percolation test is in operation. A wooden tank 4 feet deep, 2 feet wide and 20 feet long is used for the test. The head at each end of the flume is kept at the desired elevation by means of adjustable overflows. About fifteen piezometers connected into the sand bed are brought out to a gage board indicating water levels directly. The discharge is measured in a small tank on portable scales.

Since the time of the inspection, two large glass-sided steel flumes have been installed on the first floor. One of these is 26 feet long, 2 feet 6 inches wide and 3 feet deep. The walls are of heavy plate glass for 20 feet of the length. This flume has been used in investigations of the hydraulic jump on a sloping apron. The other flume is of the same size in its length. It has been used for calibrating Tainter gates and roller gates with various settings under different degrees of submergence.

Near by a battery of experimental filters is set up for student use. Each filter unit is constructed of a 6-inch diameter glass tube about 3 feet long with pressure connections at each end. This equipment is used in the courses on sanitation and water supply.

The principal piece of equipment on the second floor of the building is the river flume, which is located at the downstream end of the building. It is constructed of steel and is 2 feet deep, 25 feet wide and 97 feet long. At the time of the inspection a distorted scale river model was being tested. This model represents a seven-mile reach of the Mississippi River near Alton, Illinois, to a horizontal scale of 1:400 and a vertical scale of 1:50. The bed of the model river is made of sand so as to show the erosion caused by the dam located in the middle of the reach. The hydraulic gradient and the river currents in the vicinity of the lock are being investigated.

The discharge of the flume is measured in a "V" notch weir flume before entering the model flume. This weir flume is about 3½ feet square

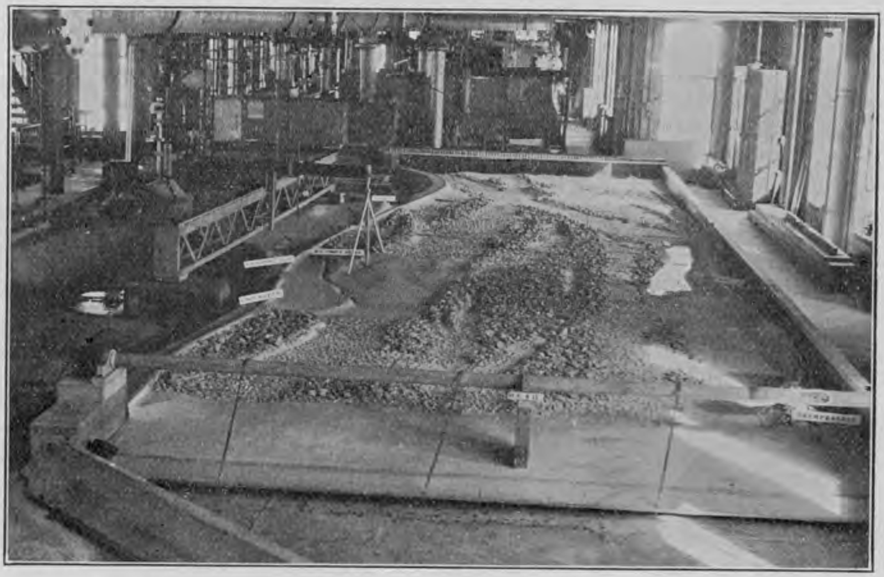

FIG. 18. — UNIVERSITY OF IOWA — RIVER MODEL IN TESTING FLUME ON THE SECOND FLOOR

in section and 7 feet long. A labyrinth, racks and a raft are used to obtain quiet flow conditions at the entrance of the model.

The tail-water elevation is adjusted to the proper level with a pivoted tail gate at the end of the model.

A unique feature in this test is the use of a special Gurley hook gage which can be read directly to .0001 foot and allows the fifth place after the decimal point to be estimated.

Near the center of the building, and just over the weighing tank, is located the collecting basin for the switchway. At one side of this collecting basin there is erected the orifice and weir tank which is used by the students. This flume, built of steel, is about 12 feet long, 5 feet high and 3 feet wide. Water is supplied to the flume through a 10-inch pipe. A weir can be mounted in the end plate of the flume near the top, and four connections for mounting orifices are located in the same end plate at different elevations. An assortment of sharp-edged orifices and short tubes is provided. The discharge is caught by a collecting tank 20 inches high and 4 feet long, which connects with the collecting basin of the switchway.

On the upstream side of this tank the largest piece of equipment is a steel flume 10 feet wide, 2 feet deep and 42 feet long. This flume is carried on jacks so that it can be tilted over the range of slopes encountered in river model testing. At the time of the inspection this flume was occupied by a complete model of the Pickwick Landing Lock built to a model ratio of 1:30. The purpose of the test was to determine the hydraulic characteristics of the side tunnel and multiple port system. The model was designed to study the pressures and velocities in the distribution system and the filling time of the lock.

In connection with the velocity distribution in the tunnel and side ports a small flow model has been built of the Hele-Shaw type. The head box and tail boxes are built of sheet pyralin one quarter inch thick. The water passages represent a horizontal section of the model lock tunnel and port passages, but the depth is made one sixteenth inch. This small separation of the walls assures viscous flow. Fluorescein is injected at various points at the entrance to the model and shows the division of flow. It should be borne in mind that this type of model shows the flow following theoretical laws without any effects of turbulence. However, with this limitation in mind, it offers an excellent method of visualizing the fundamental flow and pressure conditions in a system.

Beside the tilting flume there is installed a small steel flume for student use. It is 15 feet long, 2 feet deep and 12 inches wide. Water is supplied by a 6-inch pipe from the constant head tank. A 6-inch by 3-inch Venturi meter is installed in this pipe and allows the discharge to be measured. In the central portion there are two glass channels 2 feet square on each side of the flume, allowing the flow over a model to be studied. At the time of the inspection graduate students were determining the pressure distribution and discharge coefficients of a 1:10 model of the university dam on the Iowa River.

On this same floor was seen a hand-operated rotating tank for the calibration of miniature current meters. The tank is about 4 feet in diameter and 12 inches deep. It is mounted on a vertical axis which coincides with the axis of the tank. Vanes are attached to the sides and the bottom of the tank to keep the water and the side walls moving with the same speed.

The laboratory building at this university is carried on an elevated concrete foundation. Beneath the concrete sump and pump rooms there are located two concrete flumes which can be used for large scale tests. One of these flumes is 10 feet square in section and about 300 feet long. It connects with the university dam and extends to the downstream end of the laboratory. A flow of 900 c. f. s. under 10-foot head is available at the dam 50 per cent of the year. The other channel is 16 feet wide and 100 feet long and is located entirely beneath the building. Water from the 10-foot channel can be diverted into the 16-foot channel, or the latter can be supplied directly from the dam with a 4-foot diameter steel penstock. The discharge in the 10-foot channel is measured with a 10-foot suppressed weir, while in the 4-foot pipe a side contraction Venturi meter is used.

At the time of the inspection a three-bay model of a dam with roller gates was being tested. The model ratio was 1:18. The purpose of the test was to check the stilling pool characteristics of this type of dam. A smaller model had already been checked in the 30-inch flume, and this test constituted a careful check of that model work.

Langley Field

The towing tank at Langley Field, Hampton, Virginia, is operated by the National Advisory Committee for Aeronautics. The tank is 24 feet wide, 12 feet deep and 2,000 feet long. The maximum speed of towing which has been attained to the present is 60 miles per hour. This equipment was designed and installed primarily for the testing of large-sized model pontoons for aircraft use.

The towing carriage is made of 2-inch steel tubing heavily cross-braced and the whole structure welded together. The resulting structure is relatively light and very rigid. The carriage runs on four pneumatic tires about 40 inches by 8 inches cross section carrying a pressure of 120 pounds per square inch. To insure vibrationless operation these tires have the treads ground to a true concentric surface in place. This grinding process is repeated at intervals to maintain perfect operation. The track consists of 10-inch I beams which are accurately aligned, in both the vertical and sidewise directions. The carriage is kept in place on the rails by rubber guide wheels mounted at the front and rear of the carriage on one side only. These guides bear against both sides of the web of the rail. Due to the exceptional care which has been used in constructing the rails and wheels, there is no perceptible vibration at any speed.

Each wheel of the carriage is gear-driven by an individual electric motor of 75 horsepower, continuous rating. These motors are compound wound with heavy series fields so as to allow rapid acceleration. During the starting period, each motor delivers 200 horsepower so that the carriage is brought up to speed smoothly and quickly. The series fields of the front and rear motors on each side of the carriage are interconnected so that the torque is thus automatically equalized. All of the electric controls for the carriages are located in an operating house, at the starting end of the track. Economy rather than convenience dictated the location of the control compartment.

There are three independent methods of braking the carriage at the end of a run. Normally the carriage is stopped by the control operator, who changes the motors into generators by manipulation of switches. This regenerative braking provides a deceleration just as rapid as the acceleration. As a further safety device, each wheel is equipped with hydraulic brakes which can be operated from the carriage. As a reserve set of brakes, along the last 100 feet of the track T beams are mounted on either side of the track with the cross bar of the T down and the web vertical. The web of the T beam engages several pairs of plates mounted on the carriage, the web wedging these plates apart. These pairs of plates are about 18 inches long and of ½-inch material. It is calculated that this emergency system of braking will stop the car with full power on in case the other controls fail.

The drag of the model and the speed of towing are recorded on a photographic balance. The towing force is resisted by a very stiff cantilever spring, the small deflections being measured by a mirror and a beam of light. The advantage of this design is that the natural speed of vibration of the system is very high.

In order to obtain a record of speed there is a steel tape stretched from one end of the flume to the other, with holes drilled in the tape at uniform intervals. An electro-magnet on the car is mounted so that this steel tape completes its magnetic circuit. When a hole passes by the magnet there is a change in the magnetic flux, with a consequent voltage change induced in a coil. This voltage change is amplified in vacuum tubes and results in a deflection of a beam of light on the recording apparatus.

In addition to the drag which is recorded, observations are taken of the fore and aft trim, the settlement and the list of the model. The record of a test run is completed by the taking of two pictures of the model in operation during the run. For this purpose the model is illuminated by banks of electric lights. Two Leica cameras are permanently set up, one taking pictures of the model from a point about 30 degrees off the bow, and the other a rear view of the model taken from a similar point off the stern. These cameras are admirably suited for the purpose because a pull on one string by the observer takes both pictures and resets the cameras automatically for the next set of pictures.

The waves caused by the passage of the model are damped out by wave suppressors mounted on one side of the flume. The suppressors consist of window screening mounted on frames about 12 inches wide and 20 feet long. These frames are mounted horizontally at the normal quiet water surface elevation and line the side of the flume almost continuously. Simple as the device may seem, it is remarkably efficient in action, resulting in no loss of time between runs waiting for quiet conditions.

Leffel Hydraulic Testing Flume

The present hydraulic testing flume of James Leffel & Co. at Springfield, Ohio, was installed in 1929. The flume is of welded plate steel construction and is of the recirculating type. Considerable thought has been given to the design, so that the equipment is, to a large extent, automatic in its operation.

The dimensions of the weir flume and also the weir itself, as well as the width of the pressure flume, are homologous to the Holyoke testing flume at Holyoke, Massachusetts, where numerous tests of commercial sizes of Leffel turbines and draft tubes have been made during the past forty years. Exact homologous models of many of these Holyoke test wheels and draft tubes have been constructed and tested in the new Leffel flume in order to accurately determine the relative differences in results between commercial and model sizes tested under homologous conditions. Since the Leffel flume has been put into operation, hundreds of tests of turbines and draft tubes have been made covering open flume and closed and spiral flume settings, together with many duplications in model sizes of special field settings.

The testing flume of this company is a self-contained unit, the pressure tank and weir flume being mounted above the sump tank which serves as a base. This latter tank is 7 feet wide, 4½ feet high and 19 feet long. Above this the tailrace or weir flume tank is mounted, being 4 feet wide by 2 feet 6 inches deep and 19 feet long. Over one end of the 4-foot flume is set the pressure tank, which is 4 feet wide, 6½ feet high and 7 feet long. Glass windows are set into the flumes to allow the inspection of the water wheel, draft tubes and weir under operating conditions.

Water is taken from the sump and forced into the pressure tank by a special design of propeller type pump which is driven by a variable speed motor. This tank has baffles to provide quiet flow conditions approaching the water wheel. An adjustable overflow is used to

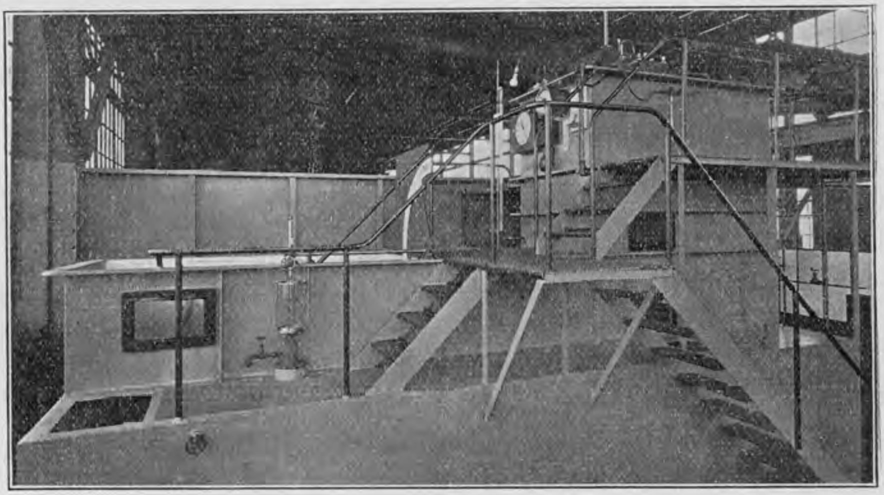

FIG. 19. — WATER WHEEL TESTING FLUME OF THE JAMES LEFFEL COMPANY

keep the headwater at constant elevation and to eliminate ripples and waves on the headwater surface. The floor of the pressure tank is equipped with rings of various sizes accommodating all standard model runner sizes up to 16 inches in diameter. The water discharged from the unit flows through baffles and racks to the 4-foot brass-edged suppressed weir located near the end of the weir flume. From the weir the water returns to the sump.

The head on the water wheel is regulated by adjusting the variable speed motor driving the pump and adjusting the elevation of the overflow. The total head on the wheel is measured by means of a piezometer connected to the pressure tank and to a water column which is located beside a scale mounted on a float gage in the tailrace flume, which permits reading the head directly.

The head on the weir is measured with a manually operated hook gage of special construction with a large vernier and scale. The reason for this special scale is to allow the test readings to be recorded photographically.

The torque of the wheel is measured with a special Prony brake in which dead weights, placed upon the scale beam, are balanced by means of a special pilot valve regulating the pressure in a small servo-motor acting on the brake. A separate needle valve is also provided for manually regulating the servo-motor pressure, if desired. A brake beam level indicator is provided in which the motion of the beam is multiplied on a separate pointer operating in mercury so that 0.016-inch movement of the beam on either side of the neutral position gives a corresponding pointer movement of 0.3 inch. By this device the operator can easily and accurately keep the beam in the neutral position, resulting in uniform water wheel speed during a three-minute test.

The ratio of the leverages of the brake beam is so proportioned that the horsepower output is computed by simply multiplying the weight on the beam by the r. p. m. and pointing off the proper number of decimal places. Permanent gage and scratch marks accurately indicate the brake beam link radius which can thus be checked at any time.

The revolutions of the wheel are determined with a special counter having a double pointer system. One of the pointers is mechanically connected through gears to the water wheel shaft, while the second is carried around by the first until released by an electro-magnet. When thus released and held stationary by means of the brake, the second pointer can be read. When the magnet is de-energized, this pointer is picked up by the mechanically operated pointer on its next passage. This system allows one-minute readings of the revolutions to be taken during a three-minute run, thus checking the whole and its parts simultaneously. An indicating tachometer is also provided which enables the operator to set any predetermined speed instead of waiting to get a reading of the revolution counter at the end of a minute.

The signals for the taking of readings and the impulses for the operation of the revolution counter are provided by a program clock.

All of the instruments are closely grouped so that they can be readily photographed when desired. This has been done, using a Leica type camera which uses 35-millimeter moving picture film. In this case the camera is itself operated by the time clock so that a picture is automatically taken every minute. The camera is so operated that the film is transported and the shutter set for the next picture automatically. The readings thus recorded are time of day, head on water wheel, revolutions of past minute, head on weir, weight on scale beam, temperature of the water, test and run number, and the date. In this way a permanent record of a test is obtained. When the negative is developed it can be projected upon a screen for study. At the present time (1937) the manually controlled overflow which maintains constant head in the pressure flume is being replaced with an automatic device for keeping the head constant. A device is also being installed to weigh the hydraulic thrust of water wheel runners at all speeds and heads.

The test department is equipped with all the machine tools necessary for their ordinary work in the fitting and adjustment of model water wheel runners. Where special work is required, the facilities of the plant are always available.

Louisiana State University

The hydraulic laboratory of Louisiana State University at Baton Rouge is operated under the direction of Prof. Glen Cox, a member of the engineering mechanics department. The laboratory equipment is designed particularly for student instruction and is installed in the engineering laboratory building.

The water supply for the experiments is taken from the sump in the basement of the building by two 4-inch motor-driven centrifugal pumps which can supply 2.2 c. f. s. under a head of 65 feet, or half that amount under a head of 125 feet, by using pumps in series. On the roof of the engineering building there is located a 20,000-gallon tank which is used as a reservoir to provide more steady head conditions for some of the experiments. The head to the ground floor of the laboratory is about 50 feet. The distribution piping in the laboratory is 6 inches for the main supply pipe and becomes smaller as branches are taken off for the various experiments.

The laboratory equipment is described in connection with the student experiments. An experiment is performed with differential gages, using fluids heavier and lighter than water. The differential gages, in the one case containing carbon tetrachloride or mercury, and in the other kerosene, are checked against deflections of water.

There are three weir tests available, using rectangular contracted, Cipolletti and suppressed weirs. The installations are similar so that only the first is described in detail. The rectangular contracted weir, which is 6 inches long and 6 inches deep, is mounted in the end of a steel tank 3 feet 6 inches by 3 feet in section and 6 feet long. A rock screen at the upstream end of the tank provides quiet flow conditions. The discharge is checked by a weighing tank having a capacity of about 1,200 pounds. The head on the weir is measured by means of a hook gage.

A 3-inch by 1¼-inch Venturi meter is calibrated by the students. The deflection of the meter is read at the high discharges by a mercury manometer and at the low discharges by a three-legged water and air manometer which is connected so as to indicate the loss of head in addition to the normal deflection. The discharge is weighed in a tank of about 1,200 pounds' capacity.

A Pitot tube test is made determining the distribution of flow of water in a 3-inch pipe and calibrating the instrument. The water first flows into a 12-inch pipe about 6 feet long, the purpose of which is to prevent any abnormal flow conditions which might exist in the upstream piping from being communicated to the test section of the pipe. The traverse is made in a length of 3-inch pipe which is connected to the downstream end of the 12-inch pipe, the distance to the gaging station being approximately 14 feet. A Collins or Stevens type of Pitot tube is used. The deflection caused by the Pitot tube is read in either a water or mercury manometer. The discharge is measured in a weighing tank.

A small impulse wheel is tested to determine the best speed or maximum efficiency at one nozzle opening. This test is performed on a 12-inch Doble wheel mounted in a glass case. The wheel is operated with full nozzle opening. The pressure at the nozzle is measured with a Bourdon tube gage and the discharge with a small weighing tank of about 1,200 pounds' capacity. A Prony brake is used to determine the torque and a hand tachometer to measure the speed.

Pipe friction tests are made on 1-inch and 2-inch galvanized pipe. The total test section is about 90 feet long, and in this length four sets of piezometers are installed to determine the hydraulic gradient. The water entering passes through about 15 feet of straight pipe before reaching the first piezometer connection. The water from either test is weighed.

An efficiency test is conducted upon a Deming No. 5 hydraulic ram. The supply head is measured by means of a staff gage and the discharge head by means of a Bourdon tube gage. Both the water pumped and the water wasted are weighed.

A current meter test is made in which the discharge of a river is measured. The standard Price meter is used, and the readings are taken from a bridge.

In addition to the above equipment there is also a weir box equipped with a 12-inch contracted weir which has been calibrated and which is chiefly used in testing the different pumps. A 6-inch Trump water wheel is also available, and is to be connected for student use as soon as possible.

Proprietors of the Locks and Canals on Merrimack River

The Locks and Canals on the Merrimack River at Lowell, Massachusetts, were visited primarily for historical reasons. It was found that there was no apparatus permanently installed for check measurements of water, but all water wheels in place serve as meters, having previously been rated either at the Holyoke testing flume or in place. At the time of the inspection it was found most convenient to measure the discharge by rod or current meter measurements of velocity in straight reaches of lined canals.

So far as is known, American hydraulic laboratory work started here with the investigations of Francis upon the flow of water over weirs, through gates and expanding tubes, and the design of water wheels.

Naturally, the greatest interest lay in the work which Francis himself had done. For his weir tests (1851) water was taken from one of the power canals and diverted through a channel in which the weir was located, either to waste or to a volumetric tank which was constructed of wood in one of the abandoned locks. In a similar fashion his work with expanding tubes (1854) was done at one of the regulating dams in the lock system, utilizing an old lock for volumetric measurements. These experiments have been ably reported in the "Lowell Hydraulic Experiments," by James Bicheno Francis, to which reference may be made.

The same power canals have been used from time to time in recent years for slope and friction loss measurements, and the locks for bulk measurements to rate pitometers, Venturi meters, meter nozzles and small water wheels. These outdoor facilities are extended each year to the members of the class in water power engineering of the graduate school of engineering of Harvard University, under the direction of Mr. Howard M. Turner.

American water wheel design was started on its modern trend by the work of such pioneers at Lowell as Swain, Boyden and Francis.

This probably occurred because the Proprietors of the Locks and Canals owned all the water rights of the Merrimack River at the Pawtucket Falls, and they sold water privileges and surplus water to manufacturing plants on an input basis; that is, the manufacturer purchased the right to use a certain quantity of water under an existing head. For that reason it was to the interest of the manufacturer to use the most efficient water wheel obtainable. Previous to this time reaction wheels were well known and widely used because they were simple to construct, but their efficiency was very low. The most efficient of the early wheels were the breast and overshot wheels, but, of course, for a given power output, the installation was very large and costly. Boyden first succeeded in making a reaction wheel which attained an efficiency greater than 80 per cent, but his outflow wheel was quite bulky. His designs were purchased by the Proprietors of the Locks and Canals and used by Francis, who, with Swain, produced the mixed flow turbine which is so well known at the present time. According to the tests of Francis, there were several water wheels at that time which attained an efficiency of 80 per cent. Some of the original Boyden and Swain water wheels are still kept as models at Lowell, and several Swain wheels are operating at relatively high efficiencies.

An interesting sidelight on the character of James Francis was afforded in his design of the flood gate at the entrance to one of the power canals which led through the center of the city of Lowell. From his study of the river, Francis was convinced that higher flood stages would be encountered than those for which the canal intake structures were originally designed. For that reason he had the so-called "Francis Gate" installed at the gate house near the entrance of the Pawtucket Canal, which could be dropped across the lock section and cut off the water at a point about 5 feet higher than any previous flood. This gate was suspended from a double "A" frame by means of a heavy clevis. Since the easiest way to drop the gate was to break the clevis, there was left on a shelf beside the gate two sledges, two cold chisels and a bottle of oil. The Francis Gate was used for the first time in 1852, two years after it was placed in position, and not again until the Great Flood of March, 1936. Had this gate not been dropped on March 19, 1936, the amount of water discharged over and around the other structures would have produced conditions which would have wrecked a portion of the business section of the city below, instead of simply ponding the water quietly above this gate. With the additional structures built to aid this gate, the city of Lowell survived this flood without serious damage and practically no loss of human life.

After the flood of 1927 the engineer was convinced that floods that were to come might even top the Francis Gate. For that reason concrete cut-off walls were run from the gate house out into the bankings on either side and equipped with flashpin holes. During the 1936 flood, flashboards were set up on these cut-off walls 3 feet high and the water rose 18 inches on these boards.

University of Maine

The hydraulic laboratory of the University of Maine at Orono is operated by the department of mechanical engineering under the direction of Prof. W. J. Sweetser. The laboratory occupies a space of 70 feet by 90 feet on two floors of the laboratory building. This laboratory is designed primarily for student instruction.

Water for laboratory use is stored in a sump having a capacity of 5,850 cubic feet and located below the level of the first floor. All the water used in the experiments is pumped, there being several sizes and types of pumps for this purpose. The largest pump is a 24-inch centrifugal pump capable of supplying 33.5 c. f. s. against a total head of 35 feet. It is driven by a 190-horsepower triple expansion steam engine. Then there is a 6-inch induction motor-driven centrifugal pump capable of supplying 2.2 c. f. s. against a head of 150 feet. These two pumps are normally used for laboratory purposes. In addition, there is a duplex steam pump which can supply 1.1 c. f. s., and a motor-driven triplex pump which can supply .28 c. f. s. These two pumps are normally used as the subject of student tests.

The distribution system of the laboratory is so designed that all these pumps can discharge directly into the volumetric tanks which are used as a final check of discharge in this laboratory. Cross-connections are also provided so that any piece of apparatus may be operated from almost any one of the pumps.

There are ten steel rectangular volumetric tanks available in this laboratory having a total capacity of 9,000 cubic feet. They are 14 feet high and the tops are built level with the second floor. The four largest tanks have capacities of 1,365 cubic feet each, the two smallest, 375 cubic feet each, and the other tanks have intermediate values of capacity. The water levels in the tanks are read on a central gage board. The tanks have been calibrated with known weights of water.

The discharge from the 24-inch centrifugal pump passes through a 24-inch by 16-inch Venturi meter, and thence by a riser to a steel head tank on the second floor. This tank is 16½ feet by 11½ feet in plan and 8 feet deep. The discharge pipe is baffled at the exit to secure as quiet flow conditions as possible in the head tank. In one side wall of this tank is mounted a 6-foot, 90° "V" notch weir which discharges through a switchway to either one of a pair of the large volumetric tanks. The entrance to a rectangular steel flume is located at the opposite side of the head tank. This flume, which is 4 feet by 3 feet in section, makes a 180° bend and then has a straight run of 57 feet before discharging into the water wheel test pit.

The water wheel flume is a plate steel circular tank 10 feet in diameter and 22 feet deep. A 17-inch vertical Samson water wheel, designed

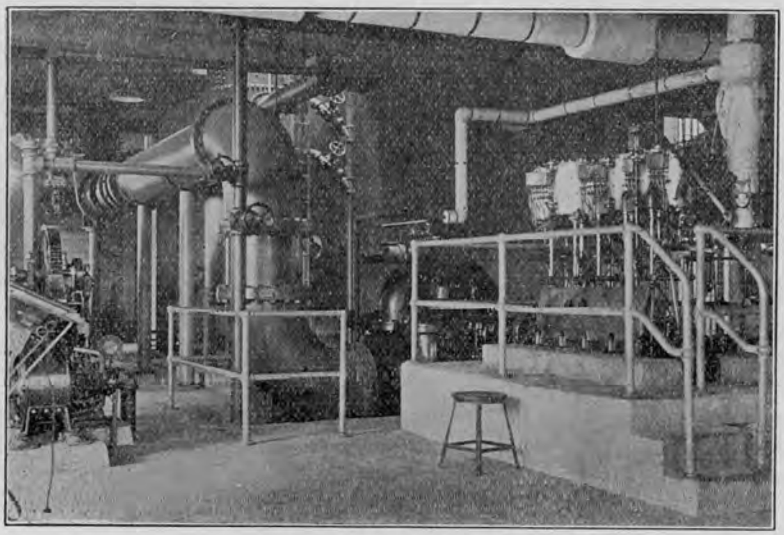

FIG. 20. — UNIVERSITY OF MAINE — VIEW ON FIRST FLOOR SHOWING 24-INCH CENTRIFUGAL PUMP AND VOLUMETRIC TANKS

to deliver 40 horsepower under the available head of 20 feet, is mounted in the center of the bottom of the tank and discharges through a conical draft tube into the tailrace flume. This flume is 5 feet square in cross section, 30 feet long, and is constructed in the concrete floor. A contracted weir is located at the end of the flume and discharges into the sump. Racks are provided downstream from the draft tube to provide quiet approach conditions to the weir.

The head on the wheel is measured with a water column, the tailwater elevation with a float gage, and the head on the weir with a hook gage. The output of the wheel is measured with an Alden dynamometer and the wheel speed with a hand-operated counter.

In one of the discharge lines between the pumps and the volumetric tanks is located a 5-inch by $2\frac{1}{2}$-inch Venturi meter. The deflections are measured with mercury and water manometers.

Below the first floor level and beside the volumetric tanks there is located a concrete channel 4 feet by 3 feet in cross section and 41 feet long. At the downstream end is located a bulkhead in which rectangular contracted "V" notch or suppressed weirs may be installed.

Near this flume is located a 12-inch glass-enclosed Pelton water wheel. The output is determined with a Prony brake and a hand

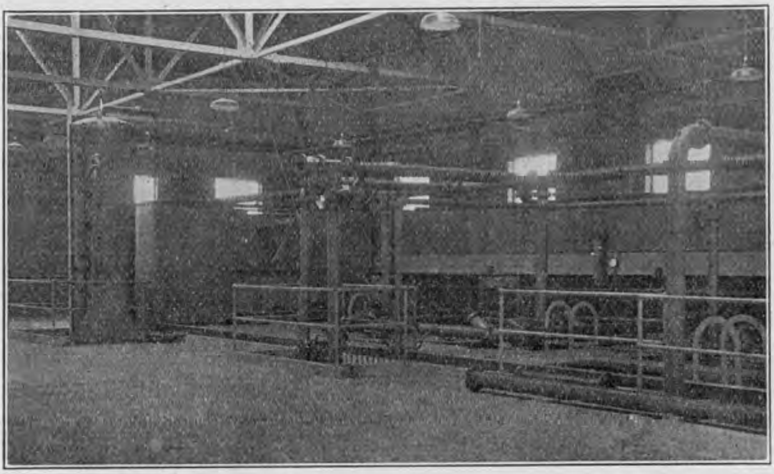

FIG. 21. — UNIVERSITY OF MAINE — VIEW ON THE SECOND FLOOR OF THE HYDRAULIC LABORATORY

counter. The head at the nozzle is measured with a calibrated Bourdon tube gage.

At the upstream end of the weir flume there is installed a vertical, cylindrical steel pressure tank, 4 feet in diameter and 20 feet high. An 8 inch connection is provided in the side of the tank about 2 feet above the bottom for the installation of sharp edged orifices and nozzles. The head on the orifice is measured with a gage glass for low pressures and with a Bourdon tube gage for higher pressures ranging up to 150 feet. The discharge is deflected either into the weir flume or directly into the sump.

The second floor of the building has been left free of apparatus as far as possible. As noted above, the head box for the large pump is located in one corner, with a steel flume located along the wall of the building. The volumetric tanks come flush with the floor and are located just in front of the steel flume. The remainder of the floor space, about 30 feet by 90 feet, is available for river model tests and similar work.

Massachusetts Institute of Technology

There are several laboratories at the Massachusetts Institute of Technology, Cambridge, Massachusetts, operated by both the mechanical engineering and the civil engineering departments. The laboratories concerned with student instruction in elementary hydraulics, hydraulic machinery and for research in cavitation work are located in the mechanical engineering department. The river hydraulic laboratories are operated under the direction of the civil engineering department.

The student experiments in hydraulics are conducted in the steam and hydraulic laboratory of the mechanical engineering department. The water needed for experimental work is taken from a sump in the basement, which is connected to the Charles River Basin. There are a number of pumps available for testing purposes. A steam-driven Warren pot valve pump, having a capacity of 3.3 c. f. s., is used for general student laboratory requirements, supplying water up to 250 pounds per square inch pressure. A pressure tank 5 feet in diameter and 35 feet high is connected into the discharge line of this pump. The distribution piping throughout the student laboratory section is 6 inches in diameter. Some of the other pumps which are available are of the triplex, centrifugal, steam duplex and air lift types, but these are more often used as the subject of a test.

Most of the experiments are located on the first floor of the laboratory. The weir and orifice experiments are set up in small steel flumes about 3 feet wide, 3 feet to 6 feet high, and about 12 feet long. These flumes discharge into another steel flume 3 feet square in section and about 90 feet long, extending along the edge of the mezzanine. This connecting flume can be subdivided, and it allows the water to be carried to either of two sets of volumetric tanks in the basement or directly to the sump. At one end of the flume there is a pair of calibrated volumetric tanks 6 feet in diameter and 10 feet high. At the other end of the flume there is a pair of calibrated volumetric tanks 10 feet in diameter and 10 feet high. The fire nozzle which is calibrated by the students is supplied with a 2-inch line and mounted near the ceiling of the first floor over the weir tanks. The discharge in this experiment passes into one set of volumetric tanks in the basement. Over the 3-foot square steel return channel is set up a 3-inch line with a Pitot tube permanently installed. Near by there is a 4-inch line equipped with a small Venturi meter and a square-edged orifice. On the floor of this section of the laboratory there are located two 30-inch impulse water wheels. Both of these wheels have glass windows in the sides so that the jet can be seen striking the buckets. These wheels are supplied from the high pressure tank, and the output is determined with Prony brakes.

The water wheel test flume is practically an independent unit. Water is supplied to the flume by a Ball angle compound 350-horsepower steam engine, direct connected to a 30-inch Worthington centrifugal pump which is capable of supplying a discharge of 50 c. f. s. against a head of 38 feet. A 30-inch by 15-inch Venturi meter is located in the discharge line about 12 feet from the flange of the pump. At the end of the Venturi meter diffusor there is located an elbow from which the water is carried by a 30-inch diameter riser into a steel flume located on the second floor of the building. This flume is 5 feet square in cross section and 130 feet long, and serves as the head race to the water wheel testing tank. The testing flume is a vertical steel cylindrical tank 12 feet in diameter and about 38 feet high. An 18-inch S. Morgan Smith water wheel is located on the bottom of the tank discharging through a draft tube to the pit beneath. The water level of the pit is controlled by a grid type of gate 10 feet square. Downstream from this gate is located the weir flume which is 10 feet wide and about 50 feet long, with a depth of water below the crest of approximately 3 feet. The water flows from the weir back to the sump.

The output of the water wheel is determined by means of an Alden absorption dynamometer. The revolutions of the wheel are counted by permanently installed revolution counters with hand-operated clutches.

In the hydraulic machinery laboratory there is installed a cavitation unit. It consists essentially of a closed recirculating system with a small Venturi throat at one point where very high velocities are developed resulting in very low absolute pressures and cavitation. The water is circulated by two 60-horsepower centrifugal pumps which can discharge 13.3 c. f. s. at 60-foot head when operated in parallel, and 6.7 c. f. s. at 120-foot head when operated in series. The water is discharged from these pumps into the end of a vertical steel head tank

$4\frac{1}{2}$ feet in diameter and 10 feet high, which is equipped with baffles to insure quiet flow conditions and with openings for pressure gages and means of sampling the water. From this head tank the water flows through a converging entrance into the Venturi test section which is approximately 4 inches square in cross section. Two parallel sides of this Venturi section can be replaced by plate glass, allowing the cavitation phenomena to be observed and photographed. The discharge from the Venturi section connects with the suction side of the pumps.

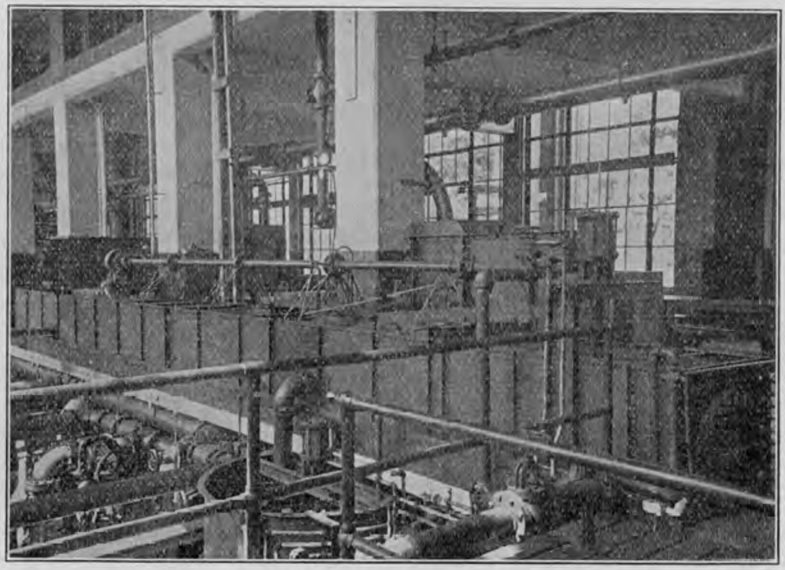

FIG. 22. — MASSACHUSETTS INSTITUTE OF TECHNOLOGY — VIEW OF THE STUDENT HYDRAULIC LABORATORY IN THE MECHANICAL ENGINEERING DEPARTMENT

This apparatus was installed under the direction of Dr. Wilhelm Spannhake, who conducted a series of tests for the Safe Harbor Water Power Company, the results of which have been published in the "Transactions of the American Society of Mechanical Engineers." Active research was then in progress for the Passamaquoddy tidal power project, determining the resistance of various materials to the effect of cavitation. The test specimens were introduced through valves to a location in the Venturi section where the effect of cavitation was the most severe, and left there for a test run under arbitrary standard conditions of pressure and discharge. The test results were plotted as curves, with the loss in weight of a standard specimen plotted against time. At the time of the inspection it was felt by the staff that while cavitation was principally a mechanical phenomenon, the chemical effects, on occasion, might be very important.

Another form of apparatus to study the cavitation phenomena and its effect on materials has been recently installed. In operation, longitudinal vibrations are set up in a metal tube, the end of which is immersed in fluid. The cavitation effects are manifested on the end of a rod. As designed, an electrical oscillator and amplifier circuit maintains longitudinal vibrations of the natural frequency of the nickel tube about three quarters inch in diameter. The test specimens are mounted on the lower end of this vertical rod and immersed in the bath of the liquid which is being tested with the sample. The temperature of the bath and of the vibrating rod are kept constant with cooling coils. The nature of the pitting found on the test specimen under these test conditions has the same appearance as specimens tested in the cavitation stand described above. At the time of the visit, tests were being run with this experimental set-up in an effort to correlate the two types of cavitation testing.

In this same department there is installed an experimental centrifugal pump. One side of the casing is made of plate glass, and the vanes of the impeller are finished so as to operate next to the glass with a small clearance. The impeller is drilled out so that dye can be injected into the water at various strategic points during the operation of the pump, thus allowing the flow conditions to be studied.

To facilitate the study of flow conditions a "rotoscope" has been installed. This device was developed by Professor Thoma of Munich, Germany. It consists of a horizontally mounted telescope having an objective prism which rotates on the same axis as the pump rotor but at only half the rotor speed. When the pump is observed through this telescope the rotor always appears to be standing still, so that the flow relative to the vane can be studied easily.

River Hydraulic Laboratory

The river hydraulic laboratory of Massachusetts Institute of Technology is operated under the supervision of Prof. Kenneth C. Reynolds in the department of civil and sanitary engineering.

This laboratory is housed in a separate building of single story construction, 90 feet by 45 feet in plan. All of the water used is pumped from a sump having a capacity of 5,200 gallons and located just below the floor level. The pump, which has a capacity of 3 c. f. s. under the existing head of about 12 feet, delivers the water into a constant head tank located in the center of the room and very close to the roof. Skimming weirs having a total length of 45 feet are used to maintain constant head conditions for test purposes. Several pipes ranging from 6 inches to 10 inches in diameter are connected separately to the head tank, so that one test can only affect another by the amount that the head is changed in this head tank.

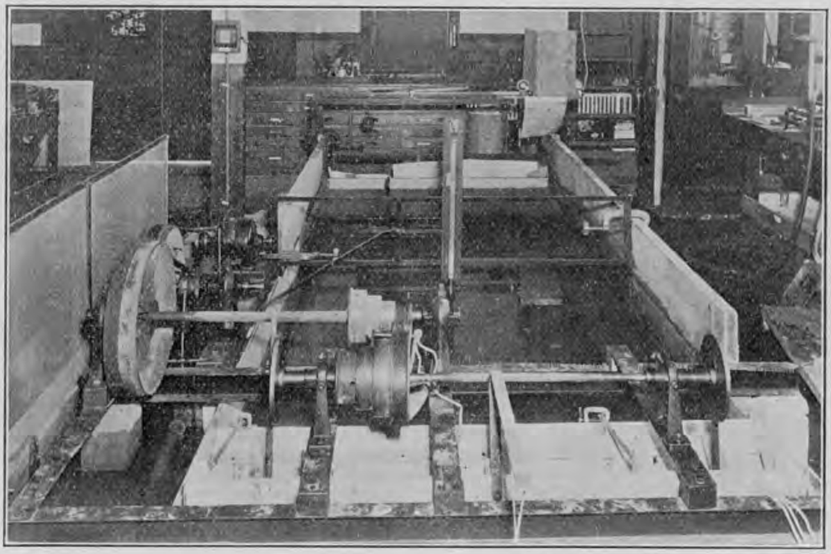

FIG. 23. — MASSACHUSETTS INSTITUTE OF TECHNOLOGY — EQUIPMENT FOR STUDYING WAVE ACTION ON SEA WALLS IN THE RIVER HYDRAULIC LABORATORY

Several flumes are available for test purposes. The longest is located near the center of the floor. This flume, of steel and glass construction, has an overall length of 51 feet, a depth of 27 inches and a width of 20 inches. Water is brought to the steel head box through an 8-inch pipe. After being quieted by screens, the water flows over a standard rectangular suppressed weir set between glass walls. Below the weir the floor of the flume drops about 10 inches so that any backwater effect in the lower flume will not interfere with the proper operation of the weir. This lower section of the flume has a length of about

35 feet, and both walls are made of glass for the last 20 feet. A set of racks with Venturi-shaped openings is installed in the steel section below the weir to restore quiet flow conditions.

The heads on the weir and on any model dam or weir that may be installed in the flume are measured with hook gages of German construction which are graduated in millimeters. Level rails, mounted on the top of the flume, carry a frame on which, in turn, is mounted a point gage. This arrangement is used for determining the water surface elevation in the flume and in the nappe of a weir.

This flume has been used for a number of investigations, among them the study of velocity and pressure conditions in the nappe of a weir by Hunter Rouse. The results of this work were published in the January, 1935, issue of "Civil Engineering."

Beside the glass-sided flume there is installed a flume which has been used in the study of the movement of bed materials of streams. Water is taken from the constant head tank through an 8-inch valve into a small steel head box about 48 inches by 30 inches in plan and 24 inches deep. From this head box, which is equipped with baffles and racks, the water passes into the wooden flume which is 32 feet long, 2 feet wide and 15 inches deep. Longitudinal rails mounted above each side of the flume are adjusted for any desired slope. At the end of this flume there is located a sand trap and regulating tail gate. Also at this point the channel is divided into three parts, — the central portion, consisting of 67 per cent of the flume width, and the two side portions, being 16½ per cent of the flume width each. The water and material in the two side strips are diverted to the sump without measurement. The sand from the central portion is caught in the sand trap and weighed, while the water flowing in this section drops into a tail box which contains racks and a small weir so that this discharge can be measured.

Sand may be added at a uniform rate during the test by means of a hopper, a rotating drum and a slice bar. The sand that is caught in the sand trap is weighed and the weight recorded continuously on a chronographic chart. The results of some tests in this channel were presented in the 1933 issue of the "Transactions of the American Geophysical Union," by C. H. MacDougall. The title of the article was "Bed Sediment Transportation in Open Channels."

Beyond the transportation flume there is installed a concrete flume for the testing of spillway models. Water is taken from the head tank through a 6-inch pipe into a steel flume about 2 feet square in section and 6 feet long. A rectangular suppressed weir at the end of this flume measures the water discharged into the concrete head box, about 10 feet square in plan and about 30 inches deep, which acts as a forebay for the spillway test. The model spillway is installed in the end wall of this flume and discharges directly into the sump.

Between the glass-sided flume and the entrance to the building there is located a shallow concrete flume in which a test of sea walls is in progress. The flume is effectively 6 feet wide, 20 feet long and about 15 inches deep. At one end there has been installed a plunger type of wave machine. At the other end the sloping beach and model sea wall are duplicated. The sand carried over the sea wall is caught and its weight determined under water. The mean water level in the flume is kept constant during tests by means of a 6-foot weir and a small constant inflow of water. The results of this investigation are contained in a doctor's thesis by K. C. Reynolds, entitled "An Experimental Investigation of the Reliability of Models for Determining Wave Action on Sea Walls."

Located near the side wall, and to the rear of the sea wall test, there is a small test flume for spillway models. Water is supplied from an 8-inch line to a steel weir tank about 4 feet square in plan and about 5 feet high. Baffles and racks provide smooth approach conditions to a "V" notch weir which measures the water discharged into the test flume. The upstream end of the test flume, which is about 12 feet long and 2 feet square in section, has concrete side walls and bottom, and in this portion straightening racks are installed. The downstream end of the flume is fitted with glass side walls, and the model spillway is installed in this part. The discharge from the flume is deflected into a return channel to the sump.

Along the side and end of the building there is a space devoted to river models. Water is supplied from an 8-inch pipe and measured in a small steel weir flume at the entrance to the model. The discharge from the model falls into a concrete box from which it returns to the sump through a 10-inch pipe. At the time of the inspection a fixed bed preliminary model of the Cape Cod Canal had been made and tested. The horizontal scale ratio was 1:1000 and the vertical scale ratio, 1:49. This model had been used to check the hydraulic gradient of the canal under various conditions of tide heights at the two ends.

In the far corner of the river laboratory there is located a single glass-walled steel tank built especially for dike studies. This flume is used co-operatively with the soils mechanics division of the civil engineering department. The testing tank is 20 feet long, 24 inches wide and 30 inches deep. The steel side of the tank is fitted with 40 piezometers for pressure determinations within the dike. In operation flow lines are traced by dye moving with the water which seeps through the model dike. A study of this nature was in progress at the time of the inspection.

River Hydraulic Laboratory Annex

This annex to the river hydraulic laboratory became necessary when the final models of the Cape Cod Canal were studied for the Corps of Engineers, United States Army, Boston. A room 150 feet by 35 feet is available, and of this space an area of 115 feet by 35 feet is used by the models. Water is pumped from a small rectangular sump into an elevated constant head tank, the maximum discharge being 2.4 c. f. s. with an effective head on the model floor of about 10 feet. The skimming weir has a total length of about 30 feet, and a 6-inch pipe returns the excess water to the sump.

The larger of the two models is a fixed bed distorted model of the entire Cape Cod Canal, the horizontal scale being 1:600 and the vertical scale, 1:60. Water is fed to both ends of the model with 6-inch pipes. In order to secure economy in the use of water and better regulation of water levels, a motor-driven double-valve operating mechanism regulates the flow into each end of the model, so that only a slight flow in excess of model requirements is fed to each end at any given instant. The water level is maintained at the proper elevation at each end of the model by motor-driven regulating weirs controlled by a tidal cam operating with a very sensitive water level gage. This gage uses the condenser effect upon a vacuum tube circuit of a horizontal metal plate fixed over the water surface but not touching it. The design details of this gage have been published in the February, 1937, issue of "Electrical Engineering." The article was entitled "Electrical Water-Level Control and Recording Equipment for Model of Cape Cod Canal," by H. L. Hazen. This tidal mechanism maintains water elevations at their proper values within .001 inch of water. The same form of gage is used to check the hydraulic gradient at nine places in the model.

This model was first constructed to duplicate the original canal, and the hydraulic gradients for various flow conditions were checked for a model verification. Then the model canal width was increased to duplicate the final design and the final hydraulic gradient determined. The model has also proved useful in locating the mooring basin and in the solution of various problems concerning navigation. The results of these tests are contained in "Report on Model Study of Cape Cod Canal and Approaches" made to the Corps of Engineers, Boston.

The mooring basin was made the subject of a separate study. The model was of the fixed bed type and was constructed to analyze the velocities that might exist in the mooring basin. The model scale was undistorted with a value of 1 : 150. Water is introduced at one end

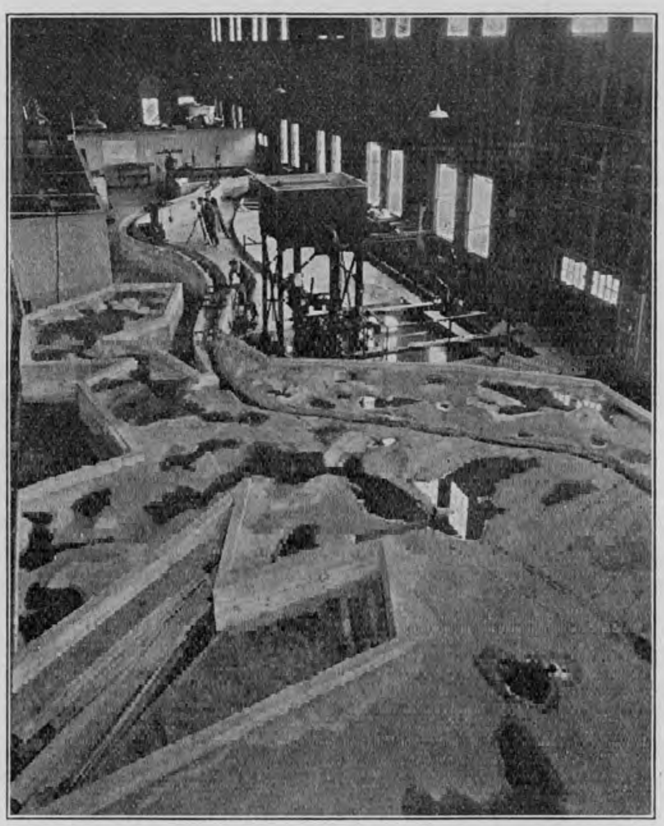

FIG. 24. — MASSACHUSETTS INSTITUTE OF TECHNOLOGY — GENERAL VIEW OF THE CAPE COD MODEL FROM THE BUZZARDS BAY END. MODEL RATIOS 1:60 AND 1:600. FIXED BED MODEL. MOORING BASIN MODEL LOCATED BEHIND THE CONSTANT HEAD TANK

from a 6-inch pipe which discharges into a rectangular suppressed weir flume and thence into the forebay of the model. A rock screen is used to obtain smooth flow conditions. The water discharges over a tail gate and directly into a sump at the other end of the model. Velocities in the canal and the mooring basin are measured with a Bentzel tube and indicated with confetti. At the time of the inspection this model test had been completed. A number of modifications of the mooring basin design had been tried and a satisfactory solution obtained. "Report on Model Study of West Mooring Basin, Cape Cod Canal," made to the Corps of Engineers, Boston, contains the results of these investigations.

McGill University

The hydraulic courses at McGill University, Montreal, Canada, are given by the department of civil engineering under the direction of Dean Ernest Brown. The laboratory is installed in the basement of the civil engineering building and has a floor space of about 40 feet by 100 feet. In addition, there is a mezzanine about 60 feet long and 15 feet wide which provides space for several of the smaller experiments. The laboratory equipment is designed primarily for student instruction, but tests of water turbines, pumps and small models of hydraulic structures have been made from time to time for power companies and industrial firms.

The water supply for general tests is taken from the city mains, and a 50-horsepower propeller type pump provides the larger volume required in turbine testing and for other tests, and some forms of commercial testing. The 18-inch discharge pipe from the pump feeds into a "Y," one side of which goes to the surge tank and overflow in one corner of the laboratory. The other side of the "Y" enlarges to 24 inches and has a run of about 15 feet before entering the 24-inch by 9-inch Venturi meter. The concrete pressure box for the water wheel test is connected to the end of the Venturi meter. A 24-inch gate valve at the pressure box prevents leakage through the wheel when this test is not being operated. Just upstream from the 24-inch valve there is a 10-inch tap which can be used for special purposes, such as those named above. In the basement below the main floor is located a sump which can be subdivided into a number of volumetric tanks, as desired.

The water wheel is set up in the concrete pressure chamber which is about an 8-foot cube. The water is supplied through a 24-inch by 9-inch Venturi meter which has not been calibrated by any primary method. A surge tank in the line provides a steady head of about 14 feet for tests. The head is measured by a float in the tailrace carrying a gage board and a piezometer column from the pressure box. The discharge is checked by a 5-foot suppressed weir in the tailrace channel. It is equipped with precise hook gages mounted on a heavy cast iron beam. The brake horsepower is measured by an Alden absorption dynamometer which is permanently mounted in place on the vertical shaft. The r. p. m. is determined by a large type Veeder counter which is hand-operated. A Francis runner and a propeller type runner are available for test in the same setting.

A small centrifugal pump with about a 2-inch discharge is driven by a cradled electric motor. The discharge is measured by means of calibrated volumetric tanks, and the pressures by means of calibrated Bourdon tube gages. The r. p. m. is determined with a portable Veeder counter.

Friction loss in a pipe is determined in a loop of pipe having an overall length of about 120 feet and located in the mezzanine. The pipe size is varied throughout the length to illustrate contraction and expansion losses. All manner of fittings and several types of orifices are included. Losses are measured with differential mercury or water manometers, as the case requires. The discharge is measured by means of volumetric tanks located on the main floor. The pipe is so arranged that the discharge may be sent through the pipe under test in either direction merely by manipulating valves.

The Venturi meter test is located on the balcony. A 1-inch by ¼-inch Venturi meter is tested, the discharge being measured by a small calibrated volumetric tank. The upstream and throat pressures are measured by means of Bourdon tube gages which are calibrated as part of the experiment.

An efficiency test is made on a glass-enclosed impulse wheel made by the Pelton Water Wheel Company. The water supply is taken from the city mains and is under a head of about 280 feet. The discharge is measured by a small volumetric tank. The pressure at the nozzle is determined with Bourdon tube gages. The torque is measured with a rope brake and the r. p. m. by a portable Veeder meter counter.

An orifice tube is mounted for test in the center of the bottom of a small vertical tank which is suspended from the ceiling. The head on the orifice is maintained constant by means of a suitable overflow pipe, and is measured by means of a float gage. The discharge is measured by a small volumetric tank.

A vertical tank 5 feet in diameter and 14 feet high is supplied with water for a second orifice experiment. The orifices to be tested are mounted on a plate in the side of the tank. The head on the orifice is measured by means of a gage glass or a float gage. Mounted in line with the discharge from the orifice is a swinging beam of cast iron which carries a weighing apparatus, and a cast iron arm upon which may be mounted various types of plates or reversing buckets. The angle of the plate is adjustable, and counterweights allow the sensitivity of the scales to be adjusted, so that the pressures on the vanes or buckets can be measured with great accuracy. Additional equipment provides for measuring directly the contraction of jets for orifices of various shapes.

In addition to the above equipment which is used for instruction purposes there is installed a small cavitation test stand. A bronze casting containing the Venturi-shaped passage in which cavitation occurs is connected to the city water supply. A heavy plate g ass window allows the flow phenomena to be observed. This apparatus was installed and the early tests made in 1934.

Michigan State College

The laboratory connected with the civil engineering department of Michigan State College at East Lansing, Michigan, is laid out to perform tests on orifices, small weirs and pipe fittings. It is located in a room in the basement of the engineering building and has a floor space about 30 feet by 50 feet. The water supply is taken directly from the city mains. After the water has been used it flows to waste into a sump which is connected with the sewer.

The orifices or short tubes to be tested are mounted in a drilled blank flange on the end of a 14-inch pipe. This piece of 14-inch pipe, which contains a gate valve, is connected to a vertical pressure tank about 30 inches in diameter and 8 feet high. The discharge from the orifice under test falls into a sump or else is deflected into a portable weighing tank of about 1,000 pounds' capacity. Pressures are read with Bourdon tube gages.

The pipe loss tests are made in a rack of 2-inch and 3-inch pipes. Each fitting to be tested is arranged in the piping in a group of four; that is, there are four 2-inch gate valves set on 12-inch centers. A short distance away are located four 2-inch globe valves on 12-inch centers, and so forth. Piezometers are formed by tapping a ¼-inch nipple into the side of the 2-inch or 3-inch pipe, as required. The losses are measured with differential mercury manometers conveniently located on the wall of the building. A Venturi meter, a Pitot tube and a pipe orifice are included in this pipe rack. The discharge is measured with the weighing tank mentioned above.

The weir and submerged orifice tests are performed in a tank 2.5 feet square in section and 20 feet long. Each weir is mounted in a removable diaphragm, which in turn is mounted near the center of the flume. A check 6-inch contracted weir is located at the end of the flume. The heads on the weirs are measured with Gurley hook gages. The discharge is measured with the 1,000-pound weighing tank. Suppressed, contracted trapezoidal, parabolic and proportional weirs are tested, together with rectangular submerged orifices.

The laboratory in the mechanical engineering department is relatively simple. There are two centrifugal pumps which take water from the common sump under the floor and supply a 16-inch Doble wheel through a 4-inch line. Either pump is driven by a portable 50-horsepower cradled electric motor which allows the characteristics of the pumps to be determined. The Doble impulse wheel discharges into a steel weir flume 2 feet square in section by 16 feet long. A 6-inch contracted weir is used to measure the discharge. Bourdon tube gages are used to measure the pressure in the system. The output of the impulse wheel is determined with a Prony brake and hand counter.

University of Michigan

The hydraulic laboratories of the University of Michigan at Ann Arbor are located in the west engineering building. The equipment used by Prof. H. W. King of the civil engineering department is as follows. The water used in the laboratory work is stored in a sump located below the first floor. A 100-horsepower 16-inch motor-driven centrifugal pump takes water from the sump and supplies a wooden test flume on the third floor with a maximum discharge of about 12 c. f. s. The wooden flume is 2 feet wide, 4 feet deep and approximately 50 feet long. The discharge from the wooden flume drops into a steel flume 6 feet deep, 8 feet wide and about 25 feet long, which is suspended near the ceiling of the second floor. This steel flume can be independently supplied from the 16-inch discharge pipe of the pump. A 90° "V" notch weir 4 feet wide across the top is located in the steel flume, together with suitable baffles to provide proper velocity distribution. The discharge from this steel flume passes through a switchway either to one of two 25-ton weighing tanks on the first floor or else directly to the sump.

Of the equipment described above, the pump, steel flume and weighing tanks are used in conjunction with Professor Sherzer of the mechanical engineering department. In addition, this latter department has other apparatus which is used for student experiments and research work. A 4-inch pipe with a Venturi meter installed connects with a steel tank 3 feet square in section and about 9 feet long, in which is located a "V" notch weir. A 12-inch Pelton wheel is mounted over this weir so that the wheel discharges into the weir flume. The 4-inch pipe mentioned above has piezometers installed for the determination of pipe losses.

In connection with pipe loss experiments there are two 2-inch motor-driven centrifugal pumps which supply a network of 2-inch pipe. In this case the students measure the pipe, estimate the losses and the division of flow. Finally, the pump is started up and the calculations are checked with experimental values.

A centrifugal pump test for the students is set up with an electric dynamometer for a driving unit. The pump can be changed as conditions demand, but at the time of the inspection a 2½-inch discharge pump of medium head was on the test stand. In the case of small pumps the discharge is measured with a portable weighing tank, and larger pumps have the discharge checked by the Venturi meter in the 4-inch line which is used by the students. Low pressures are read with mercury columns and higher pressures with Bourdon tube gages.

Professor Sherzer is very much interested in pump design, and several experimental pumps were seen in the course of construction and test. One of these pumps was designed to handle corrosive liquids, while another was a special design adapted to very low lifts.

Many of the lectures given to the students of elementary hydraulics are accompanied by demonstrations of hydraulic phenomena which are performed in the lecture room. To this end there is located at one end of the lecture table a pressure tank 2½ feet in diameter and 8 feet high equipped with various connections for pipes and orifices. This tank can also supply a glass-sided flume 12 inches by 18 inches in section and 12 feet long, which is mounted on the lecture table. At the other end of the lecture table is located a measuring tank so that the discharge can be conveniently determined. Various experiments in connection with the flow through orifices and short tubes are performed with the pressure tank. In the glass-sided flume the flow of water over contracted, suppressed, "V" notch, broad crest and ogee weirs can be shown, as well as the flow in the hydraulic jump and through submerged orifices. The experiments illustrating the hydraulic gradient and the losses in sudden expansion and contraction are performed in a glass pipe which is attached to the pressure tank. Finally, there is a glass cylinder 18 inches in diameter and 2 feet high in which orifices and short tubes can be mounted for some experiments.

The naval towing tank at the University of Michigan is one of the outstanding pieces of apparatus. It is operated under the direction of the department of naval architecture and marine engineering. This tank was installed in 1906 and is, so far as is known, the only large tank in the country which was not built by the government.

This towing tank is 10 feet deep, 22 feet wide and 300 feet long, and is adapted for the testing of models of a length of 10 feet.

The car which tows the models is about 25 feet long and of very heavy construction, since the motor generator set which supplies the

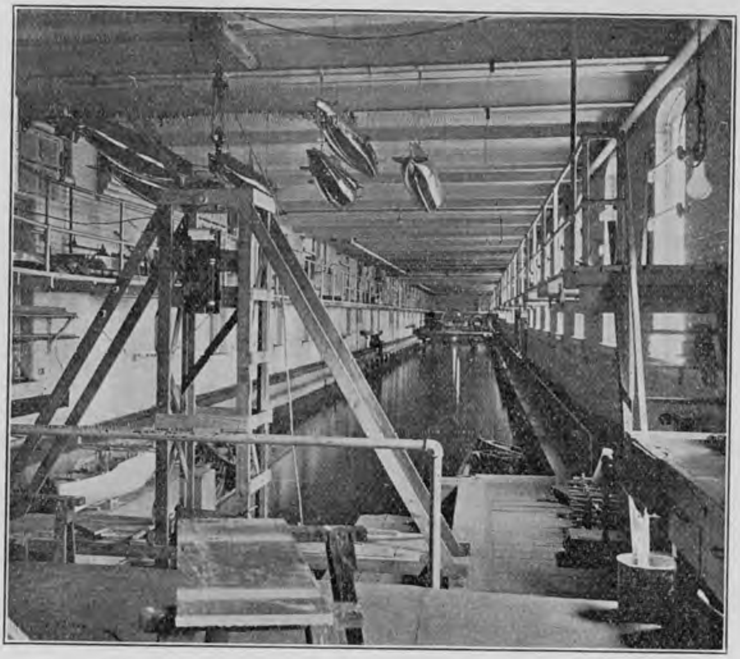

FIG. 25. — TOWING TANK AT THE UNIVERSITY OF MICHIGAN

power to the direct current driving motor is mounted directly on the car. The recording apparatus is also mounted on the car. This apparatus records the drag of the model hull, time of day, and the distance the car has traveled on a drum type of chronograph. The car can attain speeds of about 12 feet per second.

In connection with the towing tank there is a small machine shop in which the models are constructed. Most of the models at this laboratory are made of a hard wax, and the method of construction is rather interesting. A blank is first poured into a mold with a core which provides the hollowed-out portion of the hull. This wax blank is then mounted on a planer bed which carries an auxiliary table. On the auxiliary table is mounted a drawing of the longitudinal sections of the hull at various elevations, these sections being made one half size. Above the planer table and drafting table is mounted a vertical pantograph. A tracing point is mounted at one end of the linkage and two motor-driven cutters are carried at suitable points in the pantograph. The linkage is so arranged that when the pointer is located on the longitudinal center line of the drawing the two cutters should just touch each other theoretically, and if the pointer is moved along the section and out from the center line, the two cutter heads move away from the center line of the model hull by equal amounts and in opposite directions. In this way both sides of the hull are carved out at once. The cutters are used to remove the stock to the finished dimension of the hull at ½-inch intervals of elevation. The excess material between the cuts is removed and the final finish is put on by hand scraping.

The determination of the model friction and the ship friction is always a very difficult problem. At the time of the inspection it was found that a series of tests had just been completed on the subject of model friction by a visiting student from the towing tank at Teddington, England.

University of Minnesota

The hydraulic laboratories of the University of Minnesota at Minneapolis are operated in the department of mathematics and mechanics and the engineering experiment station under the direction of Lorenz G. Straub. One laboratory is located in a part of the experimental engineering laboratories building, the hydraulic section having a floor space approximately 30 feet wide by 100 feet long on three floors of the building. The other laboratory or hydraulic laboratory group is located in the Mississippi River on Hennepin Island at St. Anthony Falls, about a mile upstream of the main campus of the university. Construction of the latter is not yet completed.

Main Campus Hydraulic Laboratory

The laboratory located in the experimental engineering building is fitted for a variety of experiments requiring a moderate supply of water. There is a low pressure and a high pressure water circulating system. The two systems can be thrown together in case a fairly high rate of flow is required, or they may be operated in series in case especially high heads are needed. The general needs of the laboratory are supplied by four motor-driven centrifugal pumps. Two of these pumps each have a capacity of 1.75 c. f. s. at a head of about 150 feet, and they can be connected either in series or parallel — in series smaller quantities of water can be delivered at heads up to about 600 feet. The discharge of these pumps normally passes through a steel pressure tank 5 feet in diameter and 20 feet high. This tank supplies a reaction water wheel, two Pelton wheels, and other regularly used high pressure equipment.

The second pair of motor-driven centrifugal pumps has a capacity of 2.6 c. f. s. each at a head of 60 feet. Normally, these pumps deliver water to a constant level tank which is 5 feet square in section and 15 feet long, and which is located at the second floor of the building. The low pressure pumps can also be operated in series, thus making it possible to obtain a fairly wide range of heads and discharges.

Where small quantities of water are required, the city water is frequently used. This source of supply is used to make tests on an impulse water wheel, hydraulic ram, water meter, flow through pipes, and orifices.

Much of the equipment in this laboratory is used for student experiments in connection with the individual tests below. There are usually eight experiments given to the students in the elementary hydraulic laboratory class. A brief description of each of a typical series follows:

In a differential manometer experiment the effective specific gravity of mercury, carbon tetrachloride and kerosene is determined for "U" tubes connected so as to measure the difference between two water pressures.

The maximum capacity and calibration of a standard house type water meter is obtained, using a calibrated pressure gage and a small calibrated volumetric tank. The discharge is started and stopped for a test with a quick-acting valve.

A 1½-inch diameter square-edged orifice is mounted in the side of a wooden tank which is 5 feet long by 4.5 feet deep by 4 feet wide. The head on the orifice is measured in a gage glass. The discharge is measured with a small weighing tank. The diameter of the jet at the vena contracta is calipered so that the coefficients of discharge, contraction and velocity may be determined.

A 2-inch by 1-inch Venturi meter is calibrated in a line from the constant level tank. The discharge is determined with a 600-pound weighing tank. The deflections are read in a differential mercury manometer.

A 12-inch rectangular contracted weir is mounted at the end of one of the 4-foot square by 30-foot long concrete channels. The water supply is pumped directly into the channel, and the discharge is measured with the large twin weighing tanks.

There are two impulse wheels which may be tested by the students. One is a 12-inch Doble wheel in a glass case, while the second is a 24-inch Doble wheel in a cast iron case containing a glass section. In the

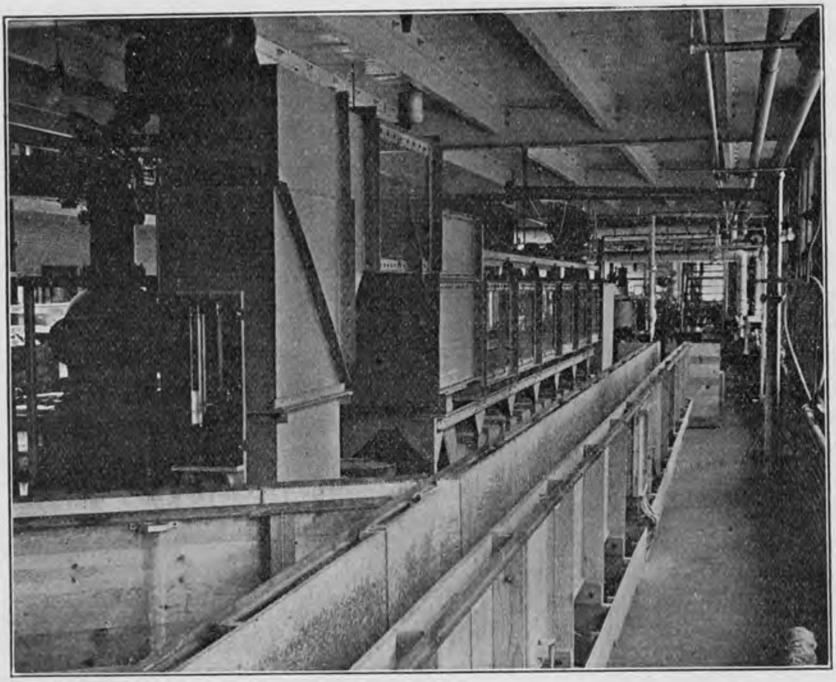

FIG. 26. — UNIVERSITY OF MINNESOTA — GLASS-SIDED TESTING FLUME AND SPECIAL FLUME FOR THE STUDY OF BED LOAD MOVEMENT AT RIVER CONFLUENCES

first case the discharge is measured with a calibrated Venturi meter, and in the second, with a calibrated orifice in the side of the tailrace tank. The output of the wheel is measured with a rope brake and a hand counter. The pressure on the nozzle is determined with a calibrated Bourdon tube gage. The efficiency and output of the wheel is determined at one nozzle opening for the complete range in speed of the wheel.

A pipe loss experiment is performed in a 20-foot section of a 1-inch pipe line which is connected to the constant level tank. The discharge is determined with a 600-pound weighing tank. The losses are measured with kerosene and mercury differential manometers.

An efficiency test is performed on a 2½-inch centrifugal pump driven by a cradled electric motor. The discharge is measured in a calibrated volumetric tank. The suction pressure is measured with a mercury manometer and the discharge pressure with a calibrated Bourdon tube gage. The performance curves of head and input horsepower plotted against discharge are determined.

There are a number of experimental flumes in use in this laboratory. Probably the most impressive is a glass-sided flume which is 27 inches deep, 20 inches wide and 60 feet long overall. The flume proper is about 35 feet long. Both sides of this section are of glass throughout the length, and about one half of the bottom is of the same material. The discharge is measured in a raised portion of the flume at the inlet, using a calibrated rectangular suppressed weir. At the entrance and the discharge end of the glass flume are located both slow-acting and quick-closing gates, so that steady flow and unstable flow conditions can be studied. The tailwater elevation is regulated by a steel hinged adjustable lattice work, both the opening and inclination of which can be varied. Below this fence the water passes over a sand trap and then flows either to the sump or to the weighing tanks. Water is supplied to this flume from the constant level tank through an 8-inch pipe.

There are two concrete flumes on the first floor which are used for model testing and weir work, as required. They are 4 feet square in section and 30 feet long. Over one of these flumes is mounted a small reaction water wheel which is tested by the students. The discharge from this wheel falls into a stilling pool and flows through rock-filled racks to a rectangular contracted weir. Below this weir models can be installed for study. The discharge from this flume passes either to the sump or to the large weighing tanks. The second flume is a duplicate of that just described, except that a "V" notch weir is located near the upper end instead of a rectangular contracted weir.

On the first floor there is also installed a small steel flume with one glass side. It is 24 inches square in section and 15 feet long. The apparatus is arranged so that the water supply can be taken from the constant level tank or operated entirely by means of an independent recirculating unit. The flow is metered with a calibrated square-edged orifice which is mounted between flanges in the pipe. A cofferdam test was in progress in this flume during the inspection (1935). This piece of apparatus has also been used for experiments on the stability of sand dams and the investigation of sedimentation basins.

Still another flume on the first floor is designed for special studies of river confluences. The main channel is about 80 feet long, 12 inches wide and 20 inches deep. The tributary channel has the same cross section but is only one third as long. Both are constructed of wood with

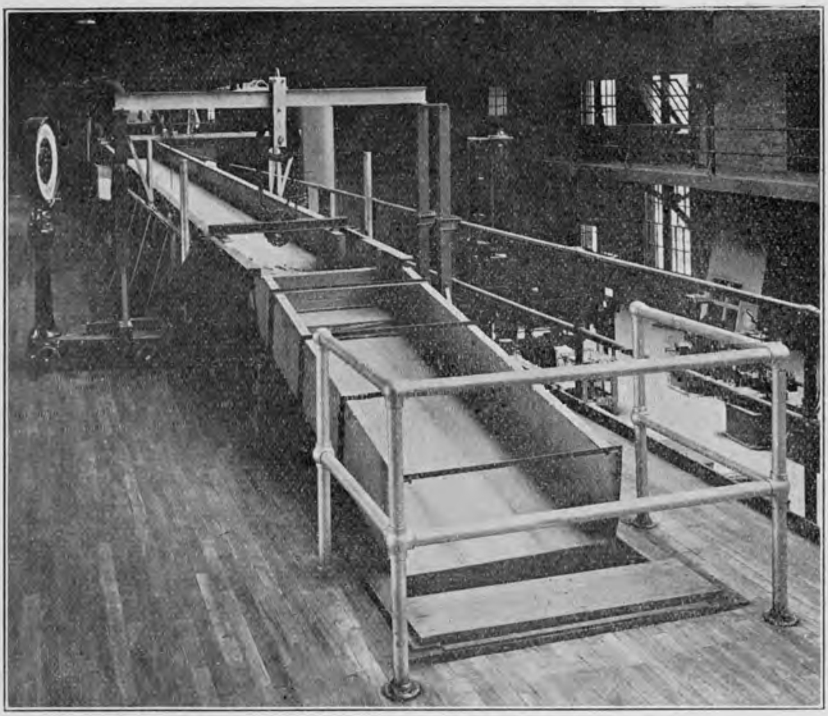

FIG. 27. — UNIVERSITY OF MINNESOTA — TILTING FLUME FOR THE STUDY OF BED LOAD MOVEMENT

sheet metal lining, have rails on both sides to provide a datum plane for elevation measurements, and are provided with piezometric connections at 5-foot intervals. Sand for sediment transportation studies and sedimentation at the confluence is added at the inlet ends of the channels and collected at the discharge end. The water supply comes from the constant level tank and is measured by means of Venturi meters in the two 4-inch inlet pipe lines.

In the basement is located a wooden flume 12 inches wide, 18 inches deep and 30 feet long. A 4-inch line from the constant level tank supplies water to the test. The discharge is measured with a "V" notch weir mounted in the head box. Rails are mounted on either side of this flume and carry a traversing point gage by means of which the water surface and the bed surface are determined. This flume has been used in a number of tests on the transportation of bed load in flowing water.

The large weighing tanks mentioned above are located in the basement so as to take the discharge from the concrete flumes, the large glass-sided flume and the tilting flume. The two tanks have a capacity of 14,000 pounds each, and they are installed so that they can be used in series so as to measure the discharge over any desired length of time.

On the gallery or second floor of the laboratory there is a large steel tilting flume. It is 15 inches deep, 3 feet wide and about 60 feet long. The head tank and discharge tank structures are attached to the flume and swing with it, so that flow conditions at the ends of the flume are not changed when the slope of the flume is changed. A 12-inch line from the constant level tank supplies water to this flume. The discharge passes over two sand traps, a rectangular suppressed weir, and then either falls into the sump or into the weighing tanks. The sand for the tests, which is used to maintain a constant thickness of bed, is fed in by means of an electrically operated elevator at the head end of the channel. The sand caught in the traps is weighed continuously during the course of the tests. A set of fixed horizontal rails is installed to carry a car which, in turn, carries a point gage used in traversing the bed of the flume and the water surface. The flume is center pivoted at the balcony floor level, and is also supported by four large screw jacks, two at each end. There is thus provided a three-point support on each side of the flume. The flume is tilted to various angles by a central electrical control which operates all screws simultaneously. Piezometer connections are spaced at 5-foot intervals along the flume with 2-inch glass stilling wells immediately adjoining the piezometers. There is also a central system of piezometric tubes where all water surface readings can be taken at the same time.

Near the tilting flume the apparatus for testing flush valves for toilet seats is installed. A large pressure tank supplies water for the flush. Then a vacuum system is connected behind the flush valve, and the back leakage from the bowl is accurately measured. These tests were being made for the Department of Public Health in Minnesota, and the interest was aroused by the trouble that was experienced in Chicago with dysentery which, in turn, was caused in some cases by faulty plumbing fixtures. Apparatus has also been set up for the study of grease traps and for the investigation of head losses in various types of plumbing pipe lines.

A small experimental flume is set up on the first floor, being designed to study fundamental laws of fluid flow. It is provided with a small sump, motor-driven gear pump, and weighing tank, so that any fluid, such as kerosene, oils and other special fluids, can be used. The channel itself is 15 feet long, 2 inches wide and 3 inches deep. The slope can be varied easily. The elevations of the fluid surface are measured with a pair of point gages mounted on a small car which travels on an independent horizontal track.

The laboratory contains various other smaller pieces of equipment which are used variously in connection with research projects. Thus there are two portable centrifugal trash pumping units, each having a capacity of 1 c. f. s. at 30-foot head, which are used for independent recirculating systems; also a triplex displacement pump and some smaller gear displacement pumps. A number of types of permeameters have been developed for studying the permeability of sands. One is arranged to measure permeability for pressure drops varying from less than one tenth of an inch to more than 500 feet in 3-foot length specimens approximately 1 square foot in cross-sectional area.

St. Anthony Falls Hydraulic Laboratories

The newly constructed laboratory at St. Anthony Falls is designed for flows up to 300 c. f. s., the water being diverted through the laboratory from the Mississippi River at the head of the falls. Close regulation of both the headwater and tailwater levels of the Mississippi River at this location provides a head of 48 to 50 feet at the laboratory at all times. Water rights of very early priority were acquired from the city of Minneapolis, permitting a flow of about 40 c. f. s. through the laboratory at all times, and larger quantities with higher discharges of the river. (The water rights attached to the site were utilized in early times for a sawmill. They were later acquired by the city for the operation of water turbines directly connected to a pump delivering a municipal water supply.)

The laboratories may be grouped into essentially five units, — the main experimental laboratory, the hydraulic machinery laboratory, the turbine testing laboratory, the large-scale volumetric measuring tanks, and the administration and lecture rooms.

The main experimental laboratory is approximately 300 feet long and 45 feet wide. It is two stories high and contains three large channels extending the entire length of the structure. One is an overhead flume 8 feet wide and 9 feet deep, connected directly to the headwater above the falls, and is provided with numerous offtakes to supply water for the various experimental projects. The others are low-level channels below the level of the main floor. Of these, one is a wasteway and the other an experimental flume arranged for a wide variety of experiments. The latter is 9 feet wide and 6 feet deep, and is supplied directly from the upper pool of the river through a pressure tunnel.

FIG. 28. — UNIVERSITY OF MINNESOTA — PERSPECTIVE RENDERING OF ST. ANTHONY FALLS HYDRAULIC LABORATORY DEVELOPMENT

(1) Headwater pool; (2) Intake to laboratory and gate control house; (3) Main experimental laboratory for open channel flow and river hydraulics, extending over roadway; (4) Hydraulic machinery laboratory, offices, demonstrational lecture room, etc.; (5) Turbine-testing laboratory below roadway and parking area; (6) Discharge measuring basins; (7) River high-water wasteway; (8) Mississippi River tailwater pool

Enough head is available to put water through the flume at the rate of about 35 feet per second for shallow depths. A towing car will make it possible to pull current meters, model ships, and the like, through the flume with the water either at rest or in motion.

The hydraulic machinery laboratory also has a clear height of two stories and is 34 feet wide and 25 feet long. It will be provided with an overhead crane. At one end of this laboratory there is a penstock shaft about 20 feet square and 30 feet deep below the machinery testing floor. The shaft provides a means of bringing the water from the overhead channel to the turbine testing laboratory, the floor of which is about 46 feet below the headwater pool.

The turbine testing laboratory adjoins the hydraulic machinery laboratory, but at a lower level. It is of irregular shape in plan, two sides being formed by the limestone ledge of St. Anthony Falls. The turbine laboratory is approximately 60 feet long and 75 feet wide. A tailrace channel traverses the length of the laboratory beginning in the penstock shaft and extending to the tail-water pool below St. Anthony Falls.

The volumetric measuring basins are constructed with their bottom just above the tail-water pool. They are so located that the flow from all laboratories except the turbine testing laboratory can be measured. A central control house is arranged to operate large cylindrical valves in a diverter system for the tanks, and in the tanks themselves. Recording and indicating gages will be located in the control house. The valves are laid out to operate pneumatically. The measuring system is designed to handle a continuous flow up to 300 c. f. s. It is intended to use this discharge measuring arrangement for check measurements on large-scale experiments and for calibrating water measuring devices to be used in connection with the turbine testing laboratory.

Administration and lecture rooms are provided in a superstructure above the hydraulic machinery laboratory. A unique feature here is a demonstrational lecture room so arranged that large quantities of water can be readily handled in various types of demonstrational experiments. Below the lecture platform is the main overhead supply flume for the laboratories, while above the lecture platform is a head control room containing a constant level reservoir. At one side of the lecture platform is a stair well and pipe shaft providing access to the laboratory below and the control room above. At the other side an apparatus room is arranged for housing the various pieces of demonstrational equipment.

A service tunnel used for bringing in a fresh-water line from the city main and for disposing of sewage extends from a shaft within the laboratory to the adjoining mainland. The entire structure is built primarily of reinforced concrete and stone masonry, the latter being quarried from the construction site. It rests on a horizontal limestone ledge at the extreme edge of the former falls. Access to the laboratory is by means of a roadway which bridges over the headrace to an adjoining power plant, and also over the roof of the main experimental laboratory down a ramp to the main level about 20 feet below the headwater pool.

National Hydraulic Laboratory, National Bureau of Standards

The National Hydraulic Laboratory at Washington, D. C., was founded for the purpose of determining fundamental data useful in hydraulic research and engineering, including laboratory research relating to the behavior and control of river and harbor waters, the study of hydraulic structures and water flow, and the development and test of hydraulic instruments and accessories. The laboratory is located at the National Bureau of Standards in Washington, D. C., and is operated under the direction of Mr. Herbert N. Eaton.

The building which houses the hydraulic laboratory was erected in 1932. That portion of the building which contains the offices is 82 feet by 92 feet in plan and four stories high. From one side of the administration section a three-story wing 60 feet wide extends for 203 feet, so that the total free length of the building at present is 285 feet. The floor space which is available for experimental work is 34,000 square feet. A detailed description of the National Hydraulic Laboratory was given in the May, 1932, issue of "Mechanical Engineering." A brief description of the building and apparatus follows.

The water supply of the laboratory is stored in two sumps which are called the high level and low level sumps. The high level sump, which has a surface area of 4,760 square feet and a normal capacity of 66,000 cubic feet, will have its water level 9 feet higher than the low level supply basin which has a surface area of 7,880 square feet and a capacity of 45,000 cubic feet. In order to carry the maximum anticipated flow of 300 c. f. s. away from the weir of the 12-foot channel, using the available return channels, the present water level in the low level basin could not be exceeded. However, as this large flow would only be used a small portion of the time, a great saving in pumping costs could be effected by having the sump at as high an elevation as possible. To realize both of these advantages the two sumps were installed. Other advantages in the use of the divided sump are that one may be used as a stilling basin to remove suspended silt from the water, and that one basin may be drained for repair work while the other maintains the laboratory in operating condition.

The outstanding piece of equipment at this laboratory is the main flume and its head tank. The head tank has a cross section 26 feet by 27 feet in plan. The floor elevation is 2 feet below the normal water surface of the low level sump, and the walls of this tank are 40 feet high. The tank is supplied with water at the present time by a centrifugal pump which delivers 85 c. f. s. under a head of 27 feet, and which discharges only into the head tank and by three other pumps having capacities of 20, 10 and 5 c. f. s., respectively. Thus the maximum flow available at the present time in the flume is 120 c. f. s. This arrangement of pumps is economical in power requirements. The head tank is connected through two 6-foot sluice gates to a 12-foot by 12-foot flume which is 217 feet long. At the end of the flume is a weir over which the water flows into a short cross channel fitted with baffles. From this channel the water can flow into a volumetric measuring basin or through return channels to either sump. The volumetric

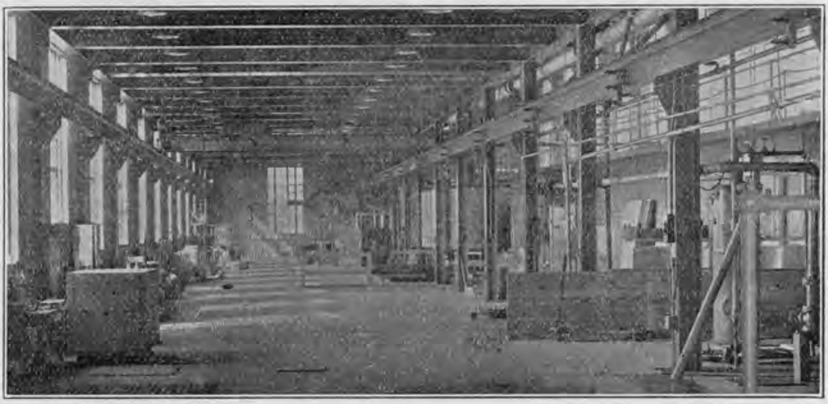

FIG. 29. — GENERAL VIEW OF EQUIPMENT ON THE MAIN FLOOR — NATIONAL HYDRAULIC LABORATORY OF THE BUREAU OF STANDARDS

basin is 60 feet long, 42 feet wide and 14 feet deep, having a capacity of little more than 35,000 cubic feet. The low level return channel is 6 feet wide and 13 feet deep, and it is equipped with slots to facilitate the installation of bulkheads. The high level return channel has the same width and depth as the low level channel, and also acts as a discharge channel for any experiments which are set up on the main floor of the laboratory, returning the water to the high level basin.

Provision has been made for the installation of two Venturi meter lines to measure flows in the main flume. One of these lines, 8 feet in diameter, will connect the cross channel from the weir to the low level sump; and the other, 3 feet in diameter, will connect the cross channel with both the low and high level sumps. The meter to be installed in this latter line will be capable of measuring flows up to 50 c. f. s. The 3-foot line and meter are now on contract.

The three smaller pumps, having a combined discharge of 35 c. f. s. which supply the large head tank, are also connected through piping and valves to a constant level tank on the third floor. This constant

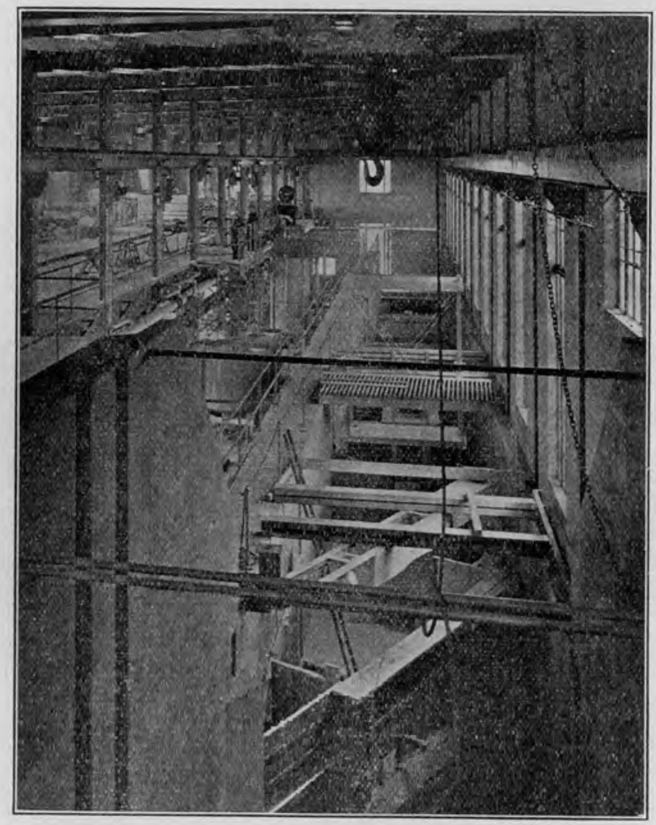

FIG. 30. — VIEW, LOOKING DOWNSTREAM, OF THE 12-FOOT TEST FLUME IN THE NATIONAL HYDRAULIC LABORATORY OF THE BUREAU OF STANDARDS

level tank is 30 feet long, 15 feet wide and about 5 feet deep. It is divided into three compartments, each connected to one of the above-mentioned pumps, with outlets from each compartment so that three separate investigations may be supplied from this single tank. On the fourth floor there is a smaller four-compartment constant level tank

14 feet long, 10 feet wide and 6.5 feet deep. It is supplied at present by a centrifugal pump having a discharge of 2.5 c. f. s.

There is a tilting glass-sided flume which is used for investigations of channel flow. Exclusive of approaches, the flume is 45 feet long, 20 inches wide and 17 inches deep. It is supplied by a pump delivering 3 c. f. s. under a 20-foot head. The grade of the flume is adjusted by means of screw jacks. The discharge from the flume passes a sand trap and a back water control and then falls into the weir flume which is 36 inches wide, 28 inches deep and 45 feet long. The weir flume has at its downstream end a contracted sharp-crested weir made of stainless steel. The weir crest is 32 inches long and the depth of the channel below the crest is about 22 inches. A second glass-walled flume 18 inches wide is under construction.

Weighing tanks are used for a primary standard in determining discharges. Two weighing tanks mounted on scales have a capacity of 18,000 pounds each. For experiments requiring the measurement of relatively small discharges, cylindrical steel volumetric tanks are used. These are calibrated by the weighing tank method. For this purpose a carefully calibrated weighing scale having a capacity of about 40,000 pounds is used. The volumetric tank to be calibrated is placed on the scale by means of a crane.

This laboratory is provided with two 5-ton cranes, one supplying the main (second) floor under the gallery and the other running over the 12-foot flume and a portion of the main floor. This second crane serves the main flume and a portion of the first floor, and can also be used to lift heavy objects to the third floor or to lower them to the first floor. In addition, a 5-ton hoist traveling on a rail can be used to service the head tank. These cranes constitute a most essential part of the equipment at this laboratory.

One room of the laboratory has been fitted for soil analysis. The customary mechanical analysis equipment has been installed, together with evaporating equipment used to determine clay content. Facilities are also available for measuring the density and kinematic viscosity of water.

Meter Rating Station, National Bureau of Standards

The meter rating station at the Bureau of Standards is operated by Mr. W. F. Stutz. The station is of the tangent type and is in continuous operation calibrating current meters.

The reinforced concrete tank, of approximately rectangular cross section, is 400 feet long, 6 feet wide, and has a water depth of about 6½ feet. The meters are towed through still water. The towing car spans the flume, traveling on steel rails mounted on the walls of the flume. It is driven by a 7½ horsepower motor through a Waterbury hydraulic speed gear, which affords a continuous range of constant speeds in either direction, from about one half foot to about 12 feet per second. An additional gear reduction is employed for velocities below one half foot per second. A controller handle operating over a graduated scale permits setting for any desired speed.

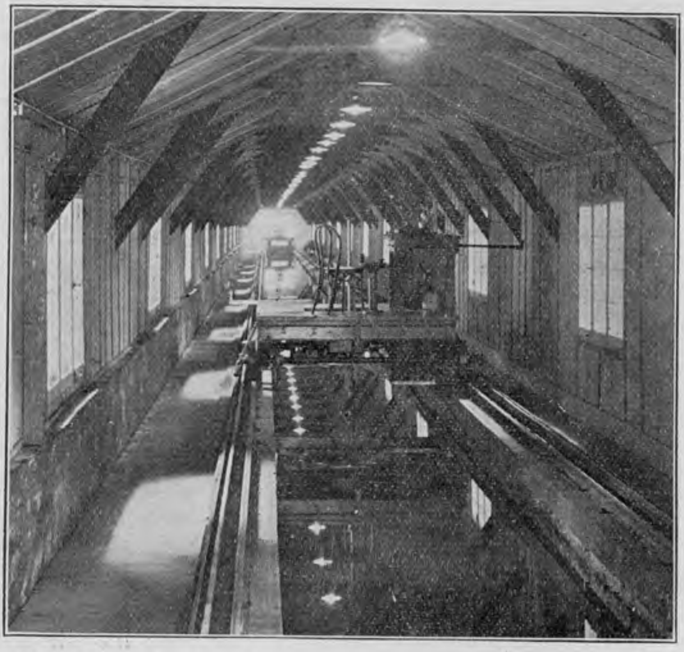

Fig. 31. — Current Meter Rating Flume at the Bureau of Standards

The observations of the total number of revolutions made by the meter rotor, of the time and distance traveled in a trial run, are measured, respectively, by a revolution counter magnetically actuated by electrical signals from the meter, by darts shot from the car into a graduated scale along one side of the flume, and by a synchronous timer operated from an accurate frequency source. The apparatus is so arranged that the revolution counter can be set for a run of a definite number of revolutions of the meter rotor. Contacts on revolution counter then automatically discharge the darts and start and stop the timer at the beginning and end of a trial run.

Newport News Shipbuilding and Dry Dock Company

The hydraulic laboratory of the Newport News Shipbuilding and Dry Dock Company at Newport News, Virginia, is equipped for the performance of operating and cavitation tests of water wheels, comparative tests of model draft tubes and of ship models. Mr. John R. Reilly directly supervises the test work.

The laboratory building is 36½ feet by 60 feet inside in plan and three stories in height, including the basement. Water is taken from a 5,200-cubic foot sump through a 36-inch suction header by two 115 horsepower electric motor-driven centrifugal pumps. One of these pumps delivers 22 c. f. s. against a dynamic head of 25 feet for the water wheel testing flume. The other supplies the cavitation unit with a flow of 16.7 c. f. s. under a dynamic head of 52 feet. Both units may be used together to supply 40 c. f. s. to the water wheel flume.

In the basement there is also located a test bed for the ready installation and test of centrifugal pumps having discharge pipes as large as 24 inches in diameter. The power to drive these pumps is taken from a 65 horsepower horizontal electric dynamometer which, at the time of the inspection, was being used on the cavitation stand.

The water wheel testing flume is an open circular steel tank 12 feet in diameter. An opening in the bottom is provided with various rings so that any size model may be readily fitted in place, the standard size being about 16 inches in diameter. For open flume settings, the water is pumped into the headrace tank 6 feet wide, 7 feet deep and 20 feet long, connecting with the top of the circular tank. The discharge from the wheel passes from the 12-foot circular pit, under the tank, into a flume 6 feet wide, 8 feet deep and 22 feet long. Crushed rock racks are installed and 6-foot suppressed weirs are located at the end of each of these flumes, so that either pumps or water wheels may be readily tested without any appreciable change in the apparatus. To facilitate the testing of model water wheels in closed settings, a 24-inch pipe is installed between the discharge line of the pump and the side of the circular steel flume. The scroll case of the model is bolted to this pipe connection.

The total head on the water wheel is measured in one reading by means of two float gages, one connected to the tailrace flume bearing

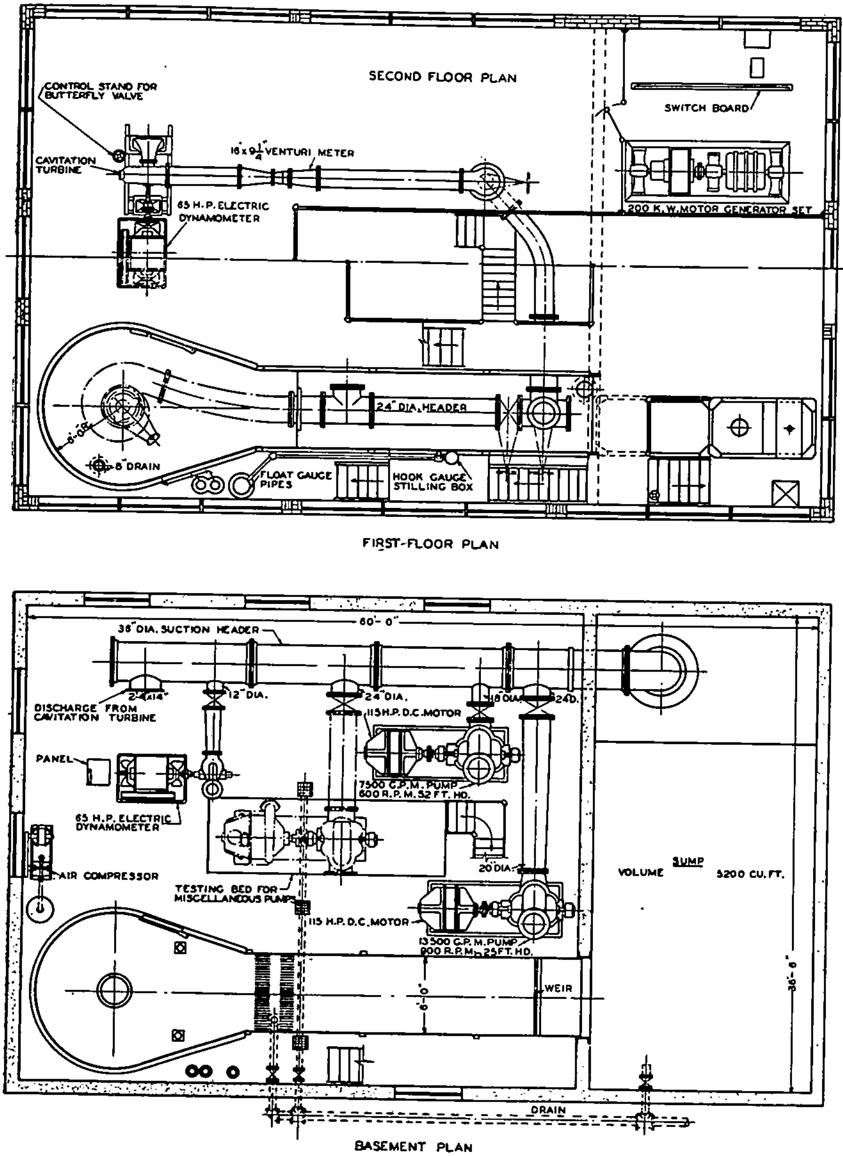

FIG. 32. — THE NEWPORT NEWS SHIPBUILDING AND DRY DOCK COMPANY, NEWPORT NEWS, VA. — PLAN OF LABORATORY

a scale, while the other, connected to the headrace flume or to the entrance to the scroll case, carries a pointer.

The head on the weir is measured by means of a float gage with a vernier allowing readings to be made to 0.001 foot.

The output of the water wheel is measured with a vertical 65 horsepower electric dynamometer which has a special double ball thrust bearing. The intermediate race of this bearing is rotated in either direction by a small electric motor, allowing the effect of friction in the stator thrust bearing to be eliminated.

A master clock, through a program machine, automatically sends out signals for timing the test runs, and through relays operates the revolution counter at the beginning and end of the run.

A 2,500 foot-pound Woodward governor is installed in connection with the water wheel testing flume, and is primarily used in testing propeller type turbine models with automatically adjustable vanes.

The cavitation equipment consists of a semi-closed circulating system. The water from the pump passes up to the second story through a diverging pipe to a converging elbow. In the horizontal run from this elbow there is a 16-inch by 9¼-inch Venturi meter, from which the water passes to the inlet of the 10-inch water wheel. The draft tube from the water wheel passes through a rectangular pressure-regulating butterfly valve to the 36-inch suction header about 25 feet beneath in the basement.

The inlet pressure is regulated by means of the pump speed. Inlet and discharge pressures are measured with mercury manometers. Flow is measured with the Venturi meter.

The output of the water wheel is measured in the same way as in the main water wheel test flume, except that a horizontal electric dynamometer is used.

The most interesting detail of this unit is the use of a 10-inch glass cylindrical connection extending from just below the runner to the top of the draft tube, which permits the observation of cavitation phenomena by means of a rotoscope or by stroboscopic light. Other draft tube models are provided with two or more observation windows.

Pump models, up to 10-inch eye diameter, are tested in the basement, using the 65 horsepower horizontal dynamometer, and the water is measured by 6-inch and 10-inch Venturi meters. This equipment is cross-connected with one of the permanent circulating pumps, so that special models may be tested both as pumps and as turbines.

In running each test only two men are employed ordinarily; one man handles all adjustments and controls which are conveniently

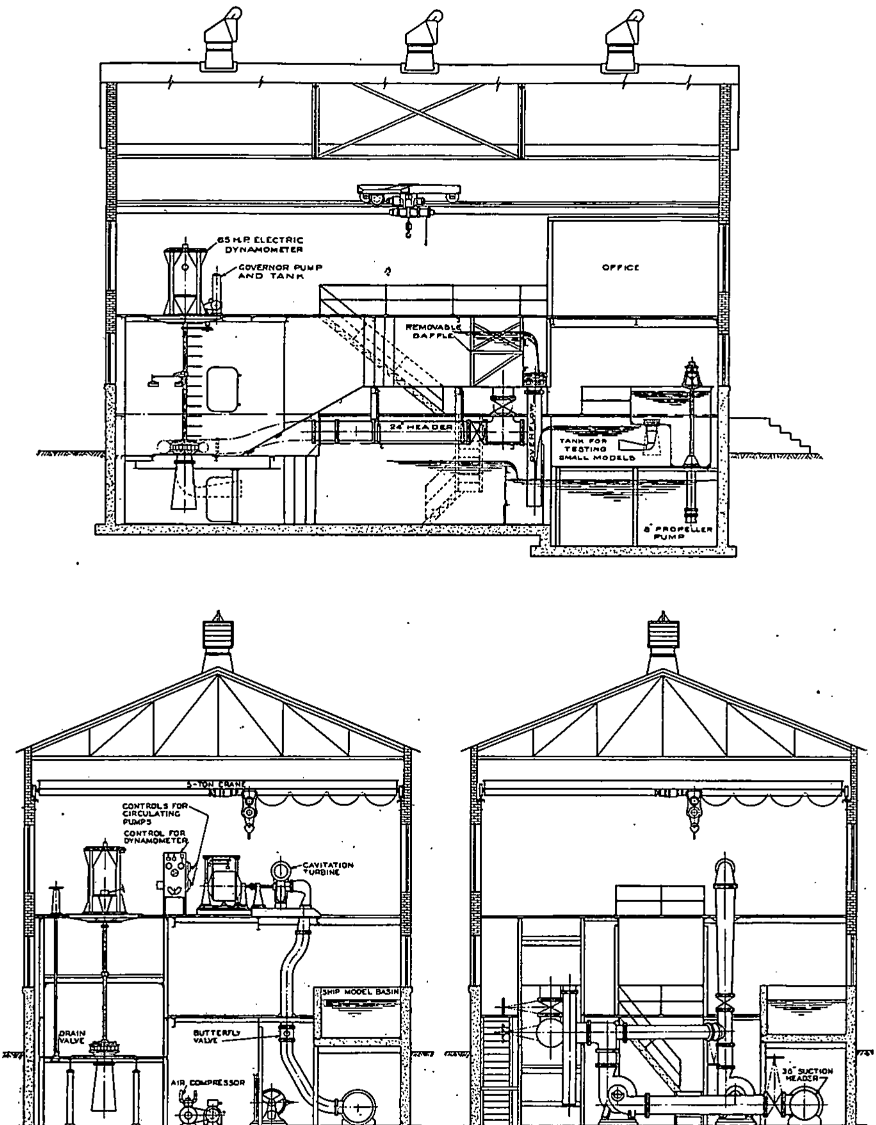

FIG. 33. — THE NEWPORT NEWS SHIPBUILDING AND DRY DOCK COMPANY, NEWPORT NEWS, VA. — SECTIONAL ELEVATIONS OF LABORATORY

grouped, while the other directs the test and computes and plots the results.

On the first floor a small steel flume 8 feet long, 4 feet wide and 4 feet deep is used for the testing of 4-inch draft tube models. A small motor-driven propeller type pump supplies 2.5 c. f. s. under a head of 4 feet for this work. The discharge from the model tube passes into a steel flume 4 feet wide, 4 feet deep and 12 feet long, with a 2-foot contracted weir at the far end. The model draft tube is tested with straight and swirling flow as a head regainer, pressure measurements being taken of the headwater, tailwater, and at the throat of the tube.

The ship model towing tank at the Newport News Shipbuilding and Dry Dock Company is 56 feet long, 8 feet wide and 4 feet deep. It is designed to accommodate a 4-foot ship model. The water in the tank is normally perfectly quiet, although at one end of the tank a wave-making apparatus has been installed which can produce waves of varying amplitude and frequency. Along one side of the tank pieces of 6-inch copper stove pipe are so mounted that the top of the pipe is just above the surface of the water. The purpose of these pieces of pipe is to damp out the waves caused by the passage of the ship model.

The model at the Newport News tank is towed by means of a gravity dynamometer mounted at one end of the flume. A weight attached to a drum by a cord causes a pulley ten times as large as the drum to revolve, pulling the towing cable and the attached model along in the tank. The construction of this dynamometer was most interesting because of its attention to the minute details of design. There are two weights attached to the driving drum. The heavier supplies the driving force while the other acts as a counterweight which supplies tension in the cord wrapped around the drum. Each weight is rectangular in form and is supported by two cords which wrap on the drum on either side of the driving pulley for the towing cable. This construction loads the bearings uniformly. In addition, the total weight on the cords is maintained constant by shifting small weights from the counterweight to the driving weight when an increased speed is required. This procedure maintains a constant load on the bearings.

The tension in the towing cable is adjusted to a standard value at the start of each day's work and checked frequently during the course of the tests to insure constant bearing forces from this source. The tension of the cable is checked by hanging a small weight on the towing cable at the center of the span and measuring the vertical deflection. The axle carrying the drum and driving pulley is about five sixteenths inch in diameter, and is carried on either side by two wheels about 5 inches in diameter. The axles of these bearing wheels are mounted in precision ball bearings. All the bearing surfaces are case-hardened and ground to a smooth, true finish. The end thrust of the main shaft is carried by hardened steel points bearing against a hardened flat plate. However, there is about one sixteenth inch of end play at each end of the shaft, and the dynamometer is set up so that neither thrust bearing is touching. This is checked from time to time during tests, and there is so little end thrust in the apparatus that the bearings rarely have to be adjusted.

The anchor pulley at the far end of the cable is constructed in the same fashion as the dynamometer, except that there are no weights. As a result of this care in the construction of the dynamometer, the friction force of the apparatus is constant throughout a run, and varies only slightly with the speed of the test. The calibration curve has been accurately determined and is very smooth. Calibration is regularly checked.

The speed of the model is obtained from the revolutions of the anchor pulley. The alternate sectors between the six arms are blanked off with aluminum plates. A light source throws a beam through the pulley to a photo-electric cell. The relay operated by the photo-electric cell provides a record of the pulley speed on the chronographic chart.

A time record is provided by a master clock which beats seconds. A pair of contacts are mounted near the upper end of the pendulum so that they do not affect its operation. The record of the data is kept by an Esterline Angus chronograph equipped with five recording pens. These data include the time in seconds, the speed of the model as given by the photo-electric cell, and the time of disengaging the accelerating weights.

These accelerating weights are hung on hooks projecting from each side of the main drive weight. The purpose of these weights is to bring the model up to speed quickly and smoothly. Then they must be disengaged so as not to disturb the model in any way, which is accomplished by floating them off the hooks in mercury cups. The amount of the acceleration is determined by the length of travel during which the weights are left connected to the driving weight of the dynamometer.

The models used in these tests are made of wood and are normally 4 feet long. The external shape of the model is finished to match metal section templates (about 20 in number) within .005 inch. The hull is finally carefully painted to provide as smooth an underwater surface as it is possible to attain.

The model ratio is determined from the water line lengths of the model and the ship, and the model displacement is calculated. The calculated water line is marked on the model. Before being tested the model is placed on a sensitive set of scales and the total weight adjusted to the calculated figure as closely as possible, in this case to about one part in four thousand.

The model is floated and the position of the ballast is adjusted to bring the actual water surface parallel with the computed water surface, both longitudinally and transversely. When this has been accomplished all the ballast is fastened down.

For convenience in the experiments the towing cord is parted, one end being attached at the bow and the other at the stern of the model, the two points of attachment being at the same elevation. After the towing cord has been attached to the model, measurements are taken from the cord to the water surface, and the elevation of the dynamometers is adjusted so that the towing force is applied in a direction parallel to the water surface.

In operation the model is held at the starting end of the tank by a trigger released by an electro-magnet. When the magnet is energized the model starts without any vibration or initial impulse. The apparatus is so wired that throwing one switch energizes the starting magnet, engages the chronograph clutch, and connects the timing circuit.

At the end of the run the model is stopped by a spring cable stretched across the tank, which engages a metal piece set on the bow of the model.

The procedure in conducting a series of tests on a model is as follows. Before the start of a test, the surface of the tank is swept clear of dust. This is important because this dirt would adhere to the model at the water surface and cause serious errors due to surface tension. Care must also be taken to insure that the under surface of the model is kept clear of bubbles. These bubbles appear on the model at certain times when the temperature of the water is changing, and any results obtained with bubbles adhering to the hull are valueless.

The first thing that is done with a new model is to find the proper accelerating distance for the weights. For instance, with a net towing weight of 0.5 pound a run is made with the accelerating weights attached during 6½ feet of the model travel. During the test run it is found that the model speed accelerated .036 knot during the test. The accelerating weights are connected for 7½ feet of travel, and it is found that the model decelerated .006 knot during the run. A final run is made with the accelerating weights connected for 8½ feet, and the results indicate that the model decelerated .048 knot during the run. The data are analyzed by plotting acceleration during a run against the accelerating distance. The proper accelerating distance for the 0.5-pound net towing weight is indicated at the point where the acceleration is zero during the run. This series of tests is repeated for net weights of 1 pound, 1.5 pounds and 2 pounds. From these data a curve may be drawn indicating the proper accelerating distance for any net towing weight. These preliminary tests are necessary when any new model is tested.

The next series of tests are made to determine the towing resistance of the hull at various velocities corresponding to useful ship speeds. These will be from 1.0 knot to 4.5 knots, which is the maximum speed possible in this towing tank. This set of runs is made with the model clean. Then another set of runs is taken with a ⅛-inch wire or strut located 1 inch ahead of the model and equal in depth to the draft of the model. The effect of this strut is to break up the laminar flow at the lower velocities and keep the model operating in the turbulent range. The resistance of this strut has been determined for various depths of submergence in an independent series of tests, and this resistance is subtracted from the towing force to obtain the net resistance of the model. The test of the model with a strut should indicate the same net hull resistance at the higher velocities, and may indicate considerably more resistance at the lower velocities, due to the fact that the strut induces turbulent resistance for the model. However, in a model having a bluff bow the water is pushed so far ahead of the model that the strut is operating in water which is traveling at a lower velocity than the measured speed of the model. If this is true the effect of the strut is over-corrected, and the specific resistance at the higher speeds will not check those values of the clean hull. When this is found to be the case, a third series of tests is made with a strut 4 inches ahead of the model. Usually this brings the values of specific resistance in agreement at the higher velocities. However, occasionally fourth and fifth sets of tests are made with the strut located 6 inches and 10 inches ahead of the model to insure the correctness of the results, particularly where the model test is important. In some cases the use of local roughness along the stem is used to induce turbulence.

Testing of Ship Models

The testing of ship models and the determination of the resistance of various bodies in water is known to have been attempted as early as

1607 in Italy by Crescenzio, and later by Pantera. In the next century experiments were made by many men, notably Franklin in America, Chapman in Sweden (about 1775), d'Alembert, Condorcet and Bossut in France (about 1777), Beaufoy and associates in England from 1793–98, and Lagerhjelm and associates in Sweden in the early part of the nineteenth century.

In 1832 Reech, in France, developed the mathematical demonstration of the basic law of similitude, based on Newton's enunciation of the principle. This formed the foundation for the successful use of ship models for the prediction of the resistance of full-sized ships, but it was not successfully used until 1872, when Froude, in England, was able to check the conclusions of his model tests by towing a full-sized ship. Since that time it has been the subject of ever-increasing interest and research. A study of a table of ship model testing basins, their size and the date of their installation, indicates that larger basins capable of operating at higher speeds are being constructed at an increasing rate, which would indicate that the subject at the present time is a very live one.

The total resistance to motion of a ship is composed of two parts. The first part comprises skin friction of the ship and is directly proportional to the wetted surface multiplied by a power of velocity which varies from about 1.82 to 2.0, depending on the length and roughness of the surface. The second portion of the resistance is made up of the wave-making and eddy effects. This part of the resistance is a function of the form of the ship, its size, and some power of the velocity which, in general, is slightly larger than the second power at operating speeds.

All model testing work on ships concerns itself with the reduction in the wave-making and form resistance of the ship, and no attempt is made to reduce the frictional drag of the hull. For low speed craft such as freighters, the frictional drag comprises over 70 per cent of the total resistance, so that the only improvements possible in this type of model have to do with a slight reduction of the remaining resistance which is only about 30 per cent of the total. In high speed hulls such as cruisers and destroyers the frictional drag is only about 40 per cent to 50 per cent of the total, so that improvements of form are relatively more important.

The method of making model tests and applying these results to the full scale prototype is briefly as follows:

1. Determine the total resistance of the model.
2. Compute the frictional drag of the model and subtract it from

the total towing resistance, leaving the residual resistance which is due to waves and eddies.

3. This residual resistance is stepped up to the prototype, using the customary model ratios.

4. The frictional drag computed for the hull of the prototype is added to the indicated residual resistance of the prototype to obtain the total resistance of this hull at the given speed.

Thus it becomes apparent that while the tests of ship models are concerned with the residual resistance which comprises the effects of wave-making and eddies, the great question in ship model tests is the computation of model friction and ship friction. For this reason, if a search is made of the literature, it will be found that there are a large number of formulæ which are designed to accurately estimate ship friction. The fact that these formulæ do not all agree merely indicates the complexity of this branch of the subject.

There are a number of reliable formulæ which have been developed from tests made under certain conditions, and a brief discussion of these formulæ is presented.

William Froude did the pioneer work in connection with the resistance of ships. He towed planks of various lengths in water and finally induced the British Admiralty to make towing tests of a full-sized ship, the "Greyhound." From these results he developed the coefficients with various types and lengths of surface, ranging from a few feet to 50 feet, and it was found that the longer the plank the less the specific resistance. The term "specific resistance" is defined as the towing force divided by the density, the area of the wetted surface, and the square of the velocity. The reason for this decrease in the specific resistance is that there does not exist the same rubbing velocity between the plank and the water throughout the length of the plank. Due to the frictional effect of the plank, the water is moved in the direction of the plank, so that the true relative motion between the water and the plank is not the absolute velocity of the plank with respect to the earth.

The next formula to be presented in historical order was that of Tideman, a naval architect of the Danish Navy, who based his results on Froude's towing tests. The results of Tideman were substantially in agreement with those of Froude, the frictional resistance being slightly larger for a given condition. At the present time it is believed that the estimate of frictional resistance by either the Froude or Tideman formula indicates results which are probably larger than the truth. For this reason these two formulæ are in general use for the computation of the skin resistance of the ship, so that the final estimate of ship horsepower required will be conservative.

There has been a great deal of research work upon the subject of the skin friction of models. Nearly every towing tank has made a series of tests with friction planes to determine these coefficients. The outstanding work in this direction was done by Gebers in Europe. He made two complete sets of experiments to determine the frictional resistance of small planes. In his work the friction planes were parallel surfaces upon which standard brass end pieces were mounted to provide a suitable cutwater and trailing edge. These ends were placed together and towed separately to evaluate their towing resistance. His work comprises friction planes which varied from 3 feet to 31 feet in length and submergences which varied from 3 inches to 20 inches. As a result of these tests, Gebers states that frictional resistance of a test surface should be corrected for an edge effect. Imagine a surface with zero thickness immersed in water for any given depth, and arbitrarily assume that the frictional effect of this surface when it is moved disturbs the water to a distance of 1 inch from the surface. Obviously, the volume of water disturbed by the plate is equal to the submerged area of the plate multiplied by the thickness of the disturbance on both sides. But at the end of the plate it is obvious that any particle within a radius of 1 inch from the edge is probably disturbed. This bottom edge of the plate has no area, and yet there is a very definite volume of water which is disturbed. It is on this basis that Gebers argues that the edge effect or, in a broader sense, the curvature effect of a small model must be evaluated separately from the pure frictional resistance. It is felt that predictions of the frictional resistance of models by the Gebers formula give an answer which is probably slightly lower or smaller than the truth. For this reason the Gebers formula is frequently used in model test basins to compute the frictional resistance of the model, since it leaves the residual resistance too large, and the final answer as applied to the ship will be on the conservative side.

The most recent work which has been done in the determination of frictional resistance of ships and models is the work of Schoenherr. This work consisted in compiling the data of all other investigators and comparing the results. Then a very considerable amount of original experimental work was done in the towing tank of the Navy Yard at Washington. On the basis of all the accurate historical data and his own test data, another formula was proposed which, it is felt, probably presents the most accurate estimate of the frictional resistance in the present state of the art.

Before leaving the subject of towing tanks for ship models, a brief discussion of the proper size of a tank may be in order. For moderate speeds, a towing basin should have a depth equal to the length of the largest model which is to be tested, and the width of the tank should be equal to twice the length of the model. The shortest possible length for the tank is approximately 15 times the length of the model. The cross-section dimension given insures tests which duplicate open water conditions for the model. For high speed displacement vessels, all dimensions should be increased about 30 per cent. The length of the tank should be longer than the value indicated above rather than shorter, since where high speeds of operation are contemplated the problem of acceleration becomes more difficult, and longer tanks are desirable.

Ohio State University

The hydraulic laboratory at Ohio State University at Columbus is under the direction of the mechanical engineering department, with Prof. H. Judd directly in charge. There is a total floor space about 100 feet by 115 feet of which about one third is used by the hydraulic section. There are narrow balconies at the second floor level, but nearly all test equipment is installed on the ground floor.

Beneath the main floor of the laboratory are located a number of cisterns. The largest (at the far end) is 15 feet by 26 feet by 10 feet and serves as a sump for the 20-inch centrifugal pump and two smaller centrifugal pumps. There are six cisterns 8 feet by 15 feet by 10 feet which are used as volumetric tanks or as weir tanks, since the walls between these tanks terminate in steel diaphragms in which weirs can be mounted. There is one other cistern located at the end (in the foreground) which is 15 feet square and 10 feet deep and serves as a suction bay for the general service pumps of the laboratory, but is also used as a volumetric tank. A concrete flume (covered by grating) 3 feet by 4.5 feet by 63 feet is located along one side of the cisterns and can be used as a return channel to the main pump, as well as for current meter measurements. These cisterns have a combined storage capacity of 18,000 cubic feet. The 15-inch and 20-inch pipe lines are suspended over the middle and right side of the section, and the whole system is interconnected by suction and discharge lines to the various pumps. These pumps may be used for general service supply, or may be isolated for special laboratory and research tests.

The cisterns are connected to a centrally located observation well, fitted with water level gages, 10 feet high, and hook-gage wells, both connected to each cistern by 2-inch pipe lines.

There is no gravity water supply at the laboratory. Hence, the following pumps are utilized for general service demands, for research, and for student tests:

20-inch centrifugal pump	10,000 g. p. m. under 50-foot head
6-inch centrifugal pump	2,000 g. p. m. under 160-foot head
4-inch centrifugal pump	500 g. p. m. under 100-foot head
3-inch centrifugal pump	250 g. p. m. under 90-foot head
Duplex reciprocating pump	1,000 g. p. m. under 100-foot head
Simplex reciprocating pump	150 g. p. m. under 250-foot head
Quimby screw pump	40 g. p. m. under 230-foot head

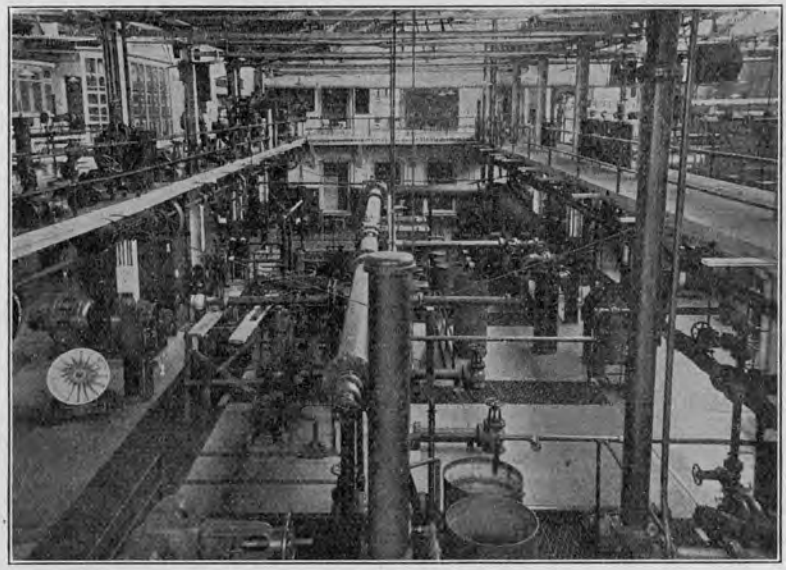

FIG. 34. — VIEW OF THE HYDRAULIC SECTION OF THE LABORATORIES OF OHIO STATE UNIVERSITY

Many of the pumps are equipped with standard flow metering devices in the discharge lines — either a Venturi meter, an orifice meter, a flow-nozzle or a Pitot traverse. To a limited extent direct volumetric measurements of the flow may be made. For the largest sized pumps the weir or the current meter placed in the flume may be used. These pumps, in turn, are also available for scheduled laboratory studies of pumping machinery. For the centrifugal pumps the input horsepower is, for the most part, determined by the cradle form of electric dynamometer. The exceptions to this method are the steam turbo-centrifugal driven units and the belted motor-driven unit.

The 20-inch centrifugal pump supplies the 42-horsepower S. Morgan Smith reaction water wheel, equipped with a Prony brake. The head is measured by a mercury column; the speed is regulated by a relay-valve oil pressure governor. The discharge is checked by flow over a weir, by a Pitot traverse, or, if desired, by a current meter.

A 4-horsepower Hoppes propeller type of water wheel, 25-foot head, is also supplied from the 20-inch line.

The impulse type of water wheel is represented by a 12-inch Pelton-Doble wheel housed in a glass case for observation. The output horsepower is measured by means of a Prony brake. The head, up to a maximum of 250 feet, is measured by a calibrated Bourdon tube gage.

For student instruction in fluid flow there are:

1. For standard types of orifices (the sharp edge, the standard tube, the rounded entrance and the nozzle) two standpipes, each 16 feet high, 6-inch diameter, are fitted with standard orifices of ½-inch diameter. The discharge is weighed in tanks and the diameter of the jet is calipered. The spouting velocity is found by a Pitot tube.

2. Two weir boxes are provided, 6 feet long, 4 feet wide, 18 inches deep, properly baffled and provided with hook gages in stilling boxes. The discharge is weighed in double weighing tanks for continuous record. Capacities up to 15/100 second-feet may be measured. Rectangular, triangular and trapezoidal weirs with end contractions are used in these weir studies.

3. There are three sets of Venturi meter installations, each 1.6 inch by 0.75 inch, connected to the piping system. The differential head is read on a one-tube mercury manometer, 32-inch scale reading, and the discharge is weighed in tanks placed on scales.

There is a small hydraulic ram arranged for tests with a 2-inch drive pipe 30 feet long and a 1-inch discharge pipe. The discharge is weighed in small tanks.

On one of the galleries a section of glass pipe 40 feet long has been installed. The majority of the pipe is 3 inches in diameter, but near the center of the line there is a 5-foot section 6 inches in diameter. The purpose of this pipe is to demonstrate the actual flow conditions existing in straight pipes, with expansions and contractions by means of dye or suspended particles. At the same time the hydraulic gradient is portrayed by means of suitable piezometers and open ended manometer tubes.

Much valuable research has been carried on and is now being conducted on fluid flow of water and steam under the supervision of Prof. S. R. Beitler.

Oregon State College

The hydraulic laboratory of Oregon State College at Corvallis is operated by the civil engineering department under the direction of Prof. C. A. Mockmore. The laboratory, designed primarily for student instruction, is located in the engineering laboratory building. This building is 40 feet by 120 feet in plan and includes the materials testing, the hydraulics, and the steam and gas engine laboratories. The part devoted to hydraulics is about 40 feet by 40 feet in plan and located in the center of the building. In addition to the space on the first floor there is a mezzanine above that floor as well as a basement beneath which adds to the available space. A 5-ton electric crane serves the entire building.

There are three motor-driven centrifugal pumps available for experimental use. They are all located in the basement with the suction pipes communicating with the sump which is beneath the basement floor and has a storage capacity of about 3,000 cubic feet of water. Two of these pumps can deliver 2.7 c. f. s. against a head of 80 feet when operating at 1,750 r. p. m. These pumps, which can be connected either in series or in parallel, normally discharge into the vertical steel pressure tank on the first floor. The third pump, which is driven by a variable speed motor, and is rated at 1.1 c. f. s. under 80-foot head, is normally connected to the pipe distribution system around the laboratory and can be used for any of the less demanding experiments.

The principal hydraulic equipment is located on the first floor. Two concrete flumes, which are 5 feet square in section and located side by side, form a pedestal upon which the water wheels and some other equipment are mounted. These flumes can be used for volumetric tanks, or weirs mounted at one end can be used to check discharge measurements. The discharge from the weirs passes through a switchway and thence either to a pair of 16,000-pound weighing tanks or to the sump. The weighing tanks are so arranged that they can be used consecutively so as to make measurements of moderate discharges of indefinite length.

At the upstream end of the flumes there is located a vertical pressure tank 5 feet in diameter and 18 feet high. While it is a closed tank and normally used for equalizing flow conditions, there is a 4-inch pipe connected near the top so that a practically constant head of about 15 feet above the ground floor can be maintained when desired. In the side of this tank there is located a 12-inch flange and quick-opening gate valve in which orifices, nozzles and short tubes can be mounted for testing. In connection with this equipment there is a jet dynamometer to measure the reaction of the jet under test. The dynamometer consists of a 4-inch pipe curved in such a way as to form a bell crank with a nozzle on one end and so arranged that the other end rests on a set of platform scales. The water of the jet is allowed to drop into one of the concrete flumes to measure rate of flow and thus establish the velocity of the jet.

The water wheels are mounted upon the flume near the center of the floor. There were two permanent wheels installed at the time of the inspection, each being of 30-horsepower capacity and built by the

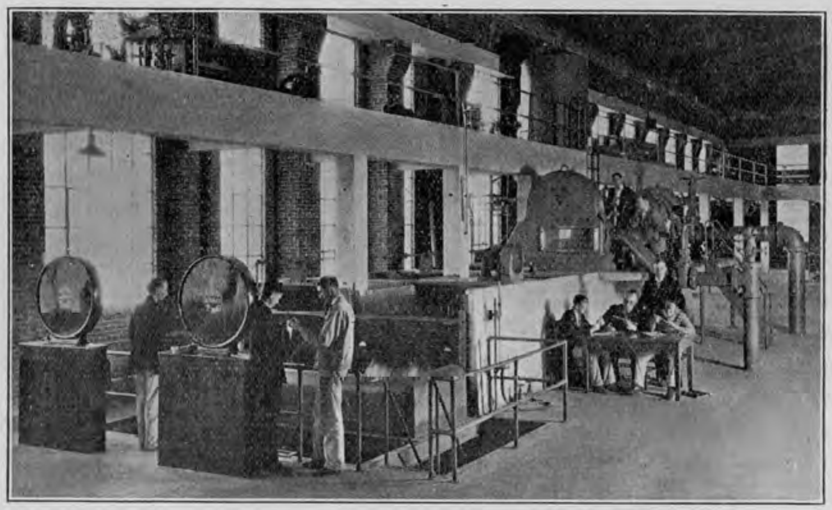

Fig. 35. — View of the Hydraulic Laboratory of Oregon State College

Pelton Water Wheel Company. One of the wheels is of the impulse type, while the other is of the Francis reaction type. Both of these turbines are equipped with Pelton governors. For the operation of these wheels, the pumps are connected so as to provide 2.7 c. f. s. at 160-foot head for the impulse wheel, and 5.4 c. f. s. at 80-foot head for the reaction wheel. Both wheels discharge into the concrete flume beneath.

In addition to the two permanent wheels there were two experimental wheels at the time of the visit. One is a 10-horsepower propeller turbine which was designed and built as an experimental project in conjunction with the students. Further experimental work is being done on this turbine in an endeavor to establish a new method of gating the turbine. The other experimental project was a 3-horsepower Banki water wheel. This wheel was found to have a characteristic speed between that for a Pelton and that for a reaction turbine, and had remarkably high efficiency at part gate. This turbine has been installed at a farm home power site since 1935, and has given remarkably good service.

In addition to the pumps there are several smaller tests set up in the basement. These include a 4-inch Venturi meter, a pipe equipped with taps and piezometers for a Pitot tube traverse, and a pipe friction rack. This latter test is made on 20-foot length of pipe of ¾-inch to 4-inch diameters, including pipes of brass, wrought iron, and transit pipe made of asbestos and cement by the Johns-Manville Company.

In connection with his study for the degree of doctor, Professor Mockmore made some interesting studies of the flow of water in elbows and draft tubes. Elbows of different designs and elbow draft tubes were made of pyralin to fit a 6-inch pipe. Velocity traverses and loss of head tests were made, and still and moving pictures were taken of the flow under various conditions. The results of this work were published in the February, 1937, issue of American Society of Civil Engineers Proceedings.

The most interesting part of this work was the technique evolved in forming the pyralin elbows. Wooden forms were made for the outside and inside surfaces of the finished elbow, sufficient space being left between for the thickness of the material. The sheet pyralin was then slowly heated in an oven until a temperature of 270° F. was reached when the pyralin became flabby. Then the sheet was placed between the forms which were clamped tightly in place. After the material had cooled the excess was trimmed off around the edges and then the forms removed. Flanges, piezometer connections, fins and similar joints were made by gluing the surfaces together, using an adhesive made of pyralin chips dissolved in acetone. The bends and draft tubes made by this process were strong, smooth, self-supporting and transparent, and it would seem that this material would have great possibilities of use in the study of the flow of fluids.

At present an experimental study of "Flow Around Bends in Open Channels," sponsored by Engineering Foundation and the Committee on Hydraulic Research of the American Society of Civil Engineers, is in progress. A rectangular channel 10 inches by 18 inches has been constructed of wood and transparent pyralin. The bends in the channel are made in sections to permit the making of various combinations of right and left turns and tangents. The flow may be measured by weir or by volume.

The Pelton Water Wheel Company

In 1925 the Pelton Water Wheel Company of San Francisco established in their new head office building a complete hydraulics laboratory for the purpose of testing special forms of impulse turbines and pumps. The original series of tests proved to be so valuable, and indicated so many possibilities of improving the art, that the laboratory has been greatly extended and is now in continuous service in the testing of model impulse turbines, pumps and special valves. Tests of reaction turbines and other special forms of hydraulic apparatus are carried on concurrently by the I. P. Morris Department of the Baldwin Southwark Corporation, Philadelphia, with which the Pelton Water Wheel Company is associated. These joint efforts make available to both organizations the results of all tests.

The present laboratory occupies a floor space of approximately 45 feet by 100 feet, and is served by two electrically operated traveling cranes. Field conditions are set up on a small scale for various special problems, and complete studies are made of the performance being investigated.

The pressure supply is provided by two modern electric motor operated pumps, one being of the centrifugal type capable of delivering about 7 c. f. s. against 100-foot head, while the other is of the deep well turbine type, having an equal capacity at a head of about 50 feet. Water quantity is determined by volumetrically calibrated Venturi meters constructed of cast bronze. A carefully calibrated weir with adjustable opening is also available for measuring quantities beyond the range of the Venturi meters.

The input to pumps under test may be measured either by knowing the efficiency of the driving motor, or by the use of a transmission dynamometer arranged for vertical shaft use.

With water wheel tests, the output is measured by an Alden dynamometer in combination with a Toledo scale with direct reading dial.

Speed of operation for water wheel testing may be taken direct with a speed counter, or electrically by means of a Weston magneto with accurately calibrated voltmeter indicator.

Constant head is maintained during water wheel tests by means of a Larner Johnson type pressure regulator connected in the discharge line of the pump downstream from the Venturi meter.

The laboratory is fully equipped with a bank of differential manometers, using mercury or other suitable fluids depending upon the magnitude of the pressures being observed.

The laboratory now operates continuously with a permanent staff on a definitely budgeted development engineering program. The work is under the general supervision of the chief engineer, Mr. Ray S. Quick, while the direct operation of the laboratory is in charge of Mr. Bernard F. Sharpley, with one or more assistants.

The Pennsylvania State College

The hydraulic laboratory at the Pennsylvania State College at State College was established in 1929 and operates under the direction of Prof. Elton D. Walker. It was designed and is used almost entirely for student instruction and some student experimental work. The student laboratory is 48 feet wide and 91 feet long with a mezzanine floor 20 feet by 91 feet.

Water used in the laboratory is stored in a sump below the level of the basement floor, having a capacity of 2,250 cubic feet. The water is circulated by three motor-driven centrifugal pumps having capacities of (1) 1 c. f. s. at 25-foot head; (2) 1.65 c. f. s. at 200-foot head; and (3) 2.3 c. f. s. at 35-foot head. These pumps discharge either into a head tank or a standpipe in order to obtain uniform pressure conditions for the experiments. The head tank is 5 feet in diameter and 18 feet high. It can be operated at atmospheric pressure with the low head pump, or, by closing a valve at the top, as a pressure tank with an air cushion when higher pressures are to be used. The standpipe is 12 inches in diameter and 65 feet high. Overflow weirs are built into the standpipe by means of special castings. The weirs are installed on 2.5 foot centers for the first 10 feet and on 5-foot centers thereafter, so that any desired head in the range of the standpipe can be maintained. The discharge from each of these overflow weirs passes through a 2-inch pipe which is equipped with a remotely controlled gate valve. All the controls are located near the pumps in the basement. A system of 6-inch standard pipe carries the water from the head tank or standpipe to the various experiments.

The discharge is usually measured volumetrically or by weighing. In general, the smaller discharges are weighed with 600 pound portable Fairbanks scales and convenient sized tanks. The larger discharges are measured in two concrete volumetric tanks, each 3 feet wide, 6 feet deep and 50 feet long, and having a capacity of 650 cubic feet. The discharge valves from the tanks are 14 inches in diameter and operated by hydraulic servo-motors. This enables the tanks to be drained rapidly so that flow measurements can be made over extended periods of time by using the two tanks alternately. The water elevation in the tanks is measured either with hook gages or water columns in open ¾-inch gage glass.

The remainder of the apparatus in the student laboratory is used with single experiments, and the description of the experiment and the apparatus follows.

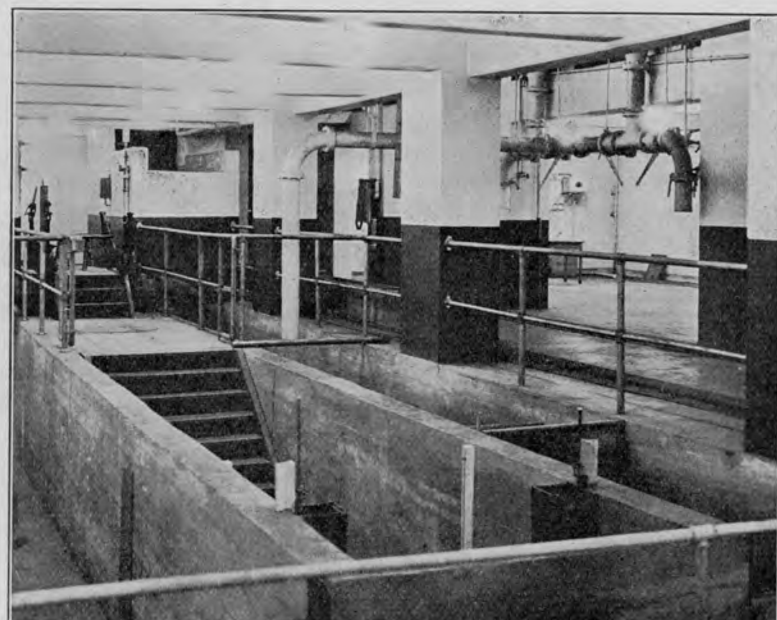

FIG. 36. PENNSYLVANIA STATE COLLEGE VIEW OF THE VOLUMETRIC MEASURING TANKS

Two water wheels are set up for test over one end of the volumetric tanks. One of these wheels is a Trump 9½-inch reaction water wheel, while the other is a 24-inch impulse wheel made by the Pelton Water Wheel Company. The water supply for both wheels is taken from the 6-inch main. The head is measured with a calibrated Bourdon tube gage. The discharge from each wheel falls into a short concrete channel about 12 feet long equipped with racks and a 3 foot suppressed weir at the end. The discharge from either weir can flow into either volumetric tank or to the sump, depending upon the manual operation of 14-inch quick acting valves in the 14-inch pipe system below the weirs. The output of the water wheels is determined by a Prony brake, scales and a hand counter.

On the mezzanine floor there are two vertical tanks, 18 inches in diameter and 6 feet high, which are used for sharp-edged orifice and short tube experiments. The test orifice is mounted about 1 foot above the bottom of the tank in a screw connection which allows various orifices to be readily interchanged. A number of standard sharp-edged orifices and a standard short tube are available for test. The elevation of the water surface in the tanks is measured by means of a gage glass. The discharge is determined with a small weighing tank on the floor below.

There are four small flumes available for weir tests. Two flumes are 3 feet wide, 30 inches deep and 8 feet long and accommodate contracted weirs having adjustable crests. The other two flumes are 30 inches wide, 2 feet deep, and 5 feet long with 6-inch weirs mounted at one end. All the weirs tested in these flumes are contracted in form and may be rectangular, Cipolletti, or "V" notch in form. In the two larger flumes and in one of the smaller, the head is measured with hook gages, while a float gage is used in the other small flume. Small discharges are measured in portable weighing tanks set up on the lower floor. The higher discharges from the 12-inch weirs are measured in the large volumetric tanks.

A small hydraulic ram is set up for test in the basement. A 1-inch drive pipe takes water from a small supply tank on the mezzanine. The water wasted and the water pumped are caught and weighed in separate tanks. The discharge pressure is determined with a Bourdon tube gage.

An experiment to determine the friction loss in pipes has been installed in the basement under the mezzanine. Sixteen different pipes to be tested are installed between two manifolds about 42 feet apart. The test length of each section is just 16 feet, and the test sections terminate in special brass piezometer fittings. Each 16-foot section includes one standard pipe joint. The loss in head is measured with differential manometers, using mercury, water and air, or carbon tetrachloride, depending on the magnitude of the loss. Pipes of four sizes and four materials are tested. The pipe sizes are ½ inch, ¾ inch, 1 inch and 2 inches, and the pipe materials are brass, copper, lead and galvanized iron. The data on these tests are being kept as gathered from year to year in order to obtain information on the effect of age on the friction losses.

Adjoining the student laboratory is another room about 40 feet by 48 feet, which is designed for student and staff research in hydraulics. There are three steel flumes available for model tests and open channel work. Two of these flumes are 3 feet square in section and 23 feet long. The third is 5 feet wide, 4 feet deep and 42 feet long. The walls and floor of the central 15-foot portion of this flume are formed of glass plates ¾-inch thick. The panels are 5 feet long and there are no supplementary supporting beams, so that the visibility is unusually good. The design of the glass portion of the flume is based upon the recommendations of the director of the aquarium at the Battery in New York City. The glass plates have a 45° bevel along the inner edges. A beveled steel strip bolted to the tank at about 6-inch

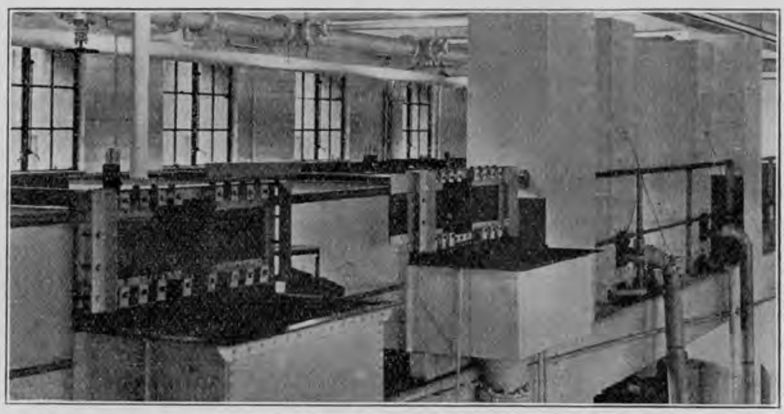

FIG. 37. — PENNSYLVANIA STATE COLLEGE — WEIR AND ORIFICE TANKS

intervals bears against the edge of the glass plate so that the edge is under continual uniform pressure rather than localized pressures as caused by individual clips. The glass sheets are bedded on single strips of rubber 1/16-inch thick.

These flumes are supplied by a 12-inch line from the constant level tank, but as yet there is insufficient pump capacity to properly supply the flumes. In this 12-inch line there is a 12-inch by 5-inch Venturi meter which is used to measure the flow to the flumes. At the time of the inspection it had not been calibrated, as all the piping was not installed. A concrete model spillway was located in the large flume. The transverse center line of the model contained a large number of piezometers for pressure studies.

University of Pennsylvania

The hydraulic laboratory of the University of Pennsylvania, located at Philadelphia, Pennsylvania, is a part of the civil engineering department operated under the direction of Prof. W. S. Pardoe. The apparatus is designed for student instruction and for precise commercial calibration of Venturi meters, flow nozzles, orifice meters, weirs, Pitot tubes and centrifugal pumps.

The laboratory occupies a part of the first floor and basement of the engineering building, having a floor space 50 feet by 75 feet in plan. Water for experimental use is supplied by centrifugal pumps which are connected to a sump of 4,000 cubic feet capacity located below the basement floor level. Several motor-driven centrifugal pumps are available. One 5-inch and two 8-inch pumps are connected so as to discharge either into a standpipe or a head tank, both located at one end of the room. The head tank is 5½ feet in diameter and 30 feet high, and is equipped with two overflows so that the head may be held constant at either of two levels. The standpipe is 12 inches in diameter and 50 feet high. Overflows are connected at 5-foot intervals. The combined discharge of the pumps is 14 c. f. s. at 40-foot head when working into the head tank, and 10 c. f. s. at 60-foot head as obtained with the standpipe.

There are, in addition, two 2-stage, 4-inch centrifugal pumps which can supply 1 c. f. s. each at 165-foot head. These pumps are normally used with the impulse water wheels and fire hose tests.

The weighing tanks, which constitute the primary method of water measurement at this laboratory, are located at the opposite end of the room from the head tank and standpipe. The two tanks are mounted on sets of Fairbanks scales each of 16,000 pounds' capacity, installed in the basement so that the tops of the tanks are about 5 feet below the first floor level. A rectangular enclosed steel channel is located over the tanks and equipped with collecting troughs and discharge valves. The discharge valves are operated by hydraulic servo-motors, allowing the water to be discharged into either weighing tank or directly into the sump. The emptying valves of the weighing tanks are also hydraulically operated. All controls are located beside the weighing apparatus which is on the first floor. Using the tanks consecutively, flow determinations are made with an accuracy of less than one tenth of 1 per cent for discharges up to 5½ c. f. s. Discharges up to 8 c. f. s. are measured, using the tanks together with some slight decrease in accuracy.

An 18-inch flange connection to the head tank is provided about 5 feet above the first floor level. A number of conical reducers are available so that any commercial size of pipe may be fitted to the head tank and run lengthwise of the room in a straight line discharging into the weighing tanks at the downstream end. It is customary to install Venturi meters and Pitot tubes for commercial calibration in this section of pipe. A crane rail and four hand-operated hoists are located directly over the center of the calibration pipe system which facilitates the handling of heavy pieces of apparatus.

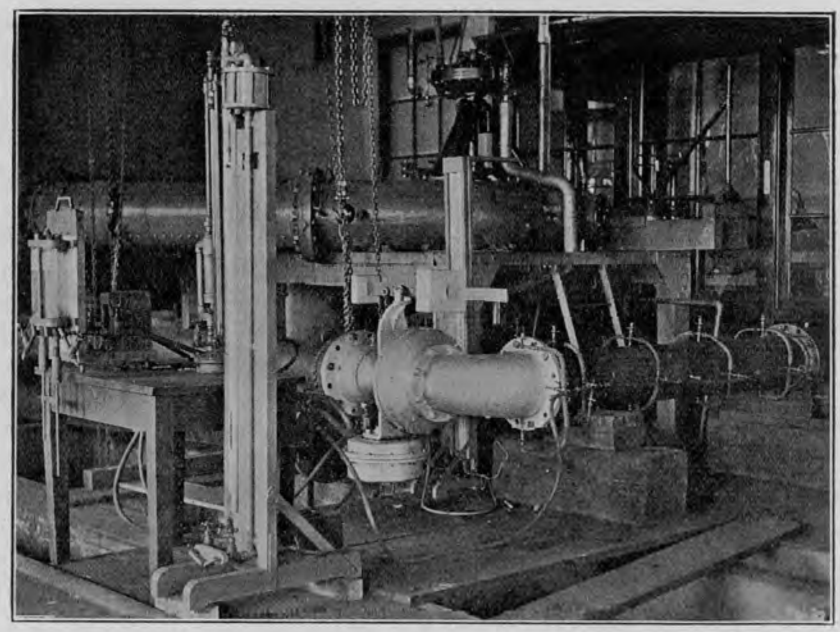

FIG. 38. — UNIVERSITY OF PENNSYLVANIA — VENTURI CONTROLLER INSTALLED FOR TEST WITH MANOMETERS IN FOREGROUND; 14½″ WATER WHEEL IN BACKGROUND

Three sets of manometers are installed for the measurement of Venturi and Pitot tube deflections. For very low differentials a pair of hook gates operating in enclosed glass tubes 3 inches in diameter are used. The scales of the hook gages may be read by the vernier to 0.001 foot and easily estimated to 0.0002 foot. For deflections between 1 foot and 4 feet of water, a water and air differential manometer is used. One leg of this manometer is a pot 6 inches in diameter, while the other is formed three quarters I. D. of gage glass. A short ¾-inch gage glass is mounted on the side of the steel pot, allowing the water level in this leg of the manometer to be determined, and eliminating errors due to capillarity. The third manometer is constructed in the same manner as the second, except that mercury is used as the indicating fluid.

In the center of the floor and parallel to the calibration piping there are located two concrete flumes 5 feet square in section and 34 feet long. One of the flumes is located directly under the pipe. Provision has been made at the downstream end of the flumes to discharge into the collector channel of the weighing tank. The flume directly under the pipe may be used for volumetric measurements, while the other is equipped with a 5-foot suppressed weir, or 3-foot and 2-foot contracted weirs.

There are two reaction water wheels which are used for student instruction. Both wheels are located near the head tank. A 14½-inch S. Morgan Smith wheel installed in a cast iron scroll case takes its water supply from the head tank and discharges directly into the 5-foot weir flume. The output of the wheel is determined with a single-disc 14-inch Alden dynamometer and a portable counter. The water elevation in the head tank is read in a gage glass. The tailrace water elevation is determined with a float gage.

There is also a 10-inch cylinder gate Smith water wheel installed in a cylindrical pressure case which may be used for a student test. Its water supply is taken from the 12-inch standpipe, and the draft tube discharges into the weir flume. A rope brake is used in the determination of the output.

There are two impulse wheels which are available for student test and which are supplied by the high head centrifugal pumps mentioned previously. The larger of the two wheels is 24 inches in diameter and mounted in a cast iron case. The discharge of the wheel is measured by the weighing tanks. The pressure at the nozzle is determined with a calibrated Bourdon tube gage and a mercury column. The output of the wheel is measured with a rope brake and the speed by means of an electric tachometer.

A 16-inch impulse wheel is installed in a glass-sided case and is mounted over a steel weir flume about 24 inches deep, 30 inches wide and 10 feet long. A 15-inch contracted weir is mounted in a diaphragm near the downstream end of the flume. The pressure head on the wheel and the output are measured in the same manner as for the first impulse wheel.

The 4-inch by 2-inch Venturi meter, which is located in a 4-inch flanged cast iron pipe running across the end and down one side of the laboratory, is calibrated by the students. The discharge is measured in the large weighing tanks. In addition, there is a 2-inch by 1-inch Venturi meter installed in a 2-inch line which is connected to the main head tank and discharges into a trough in the floor which, in turn, may discharge into the large weighing tanks.

A steel tank 2 feet square in section and 4 feet high supplies water for a test illustrating the hydraulic gradient. Water is taken out near the bottom of the tank in a 1¼-inch pipe which tapers to seven eighths inch in diameter and then makes a vertical bend of about 30°. In the sloping section, the pipe expands to 2 inches in diameter and then contracts to seven eighths inch again. Following the contraction there is located a small Venturi meter, and finally, another vertical bend to bring the pipe horizontal. Piezometers are connected to show the gradient as affected by entrance, bends, contraction and expansion losses. Finally, the use of the sloping pipe demonstrates that the hydraulic gradient is independent of the pipe location.

In addition to the above equipment there is a considerable amount of auxiliary apparatus used, principally for student demonstration and tests. A Crosby dead weight gage tester is used for the calibration of Bourdon tube gages, and various differential manometers are available for student instruction. House type water meters and various designs of Pitot tubes are also available.

The Holtwood Laboratory, Pennsylvania Water and Power Company

The water wheel testing laboratory of the Pennsylvania Water and Power Company is located at the Holtwood Hydro-Electric Development, Holtwood, Pennsylvania. This laboratory is operated under the direction of Mr. L. M. Davis.

Water is taken from the forebay of the Holtwood plant by a motor-driven centrifugal pump which can supply a discharge of 56 c. f. s. at a head of 35 feet. The discharge from the pumps, which is practically a constant quantity varying only slightly with the head on the pump, flows into a head tank provided with suitable racks and a sluice gate for discharging the excess water not required in the laboratory into the forebay. This gate is operated by an electric motor and is remotely controlled from the laboratory, allowing the head in this forebay tank to be varied over a range of about 20 feet. A bell-mouthed

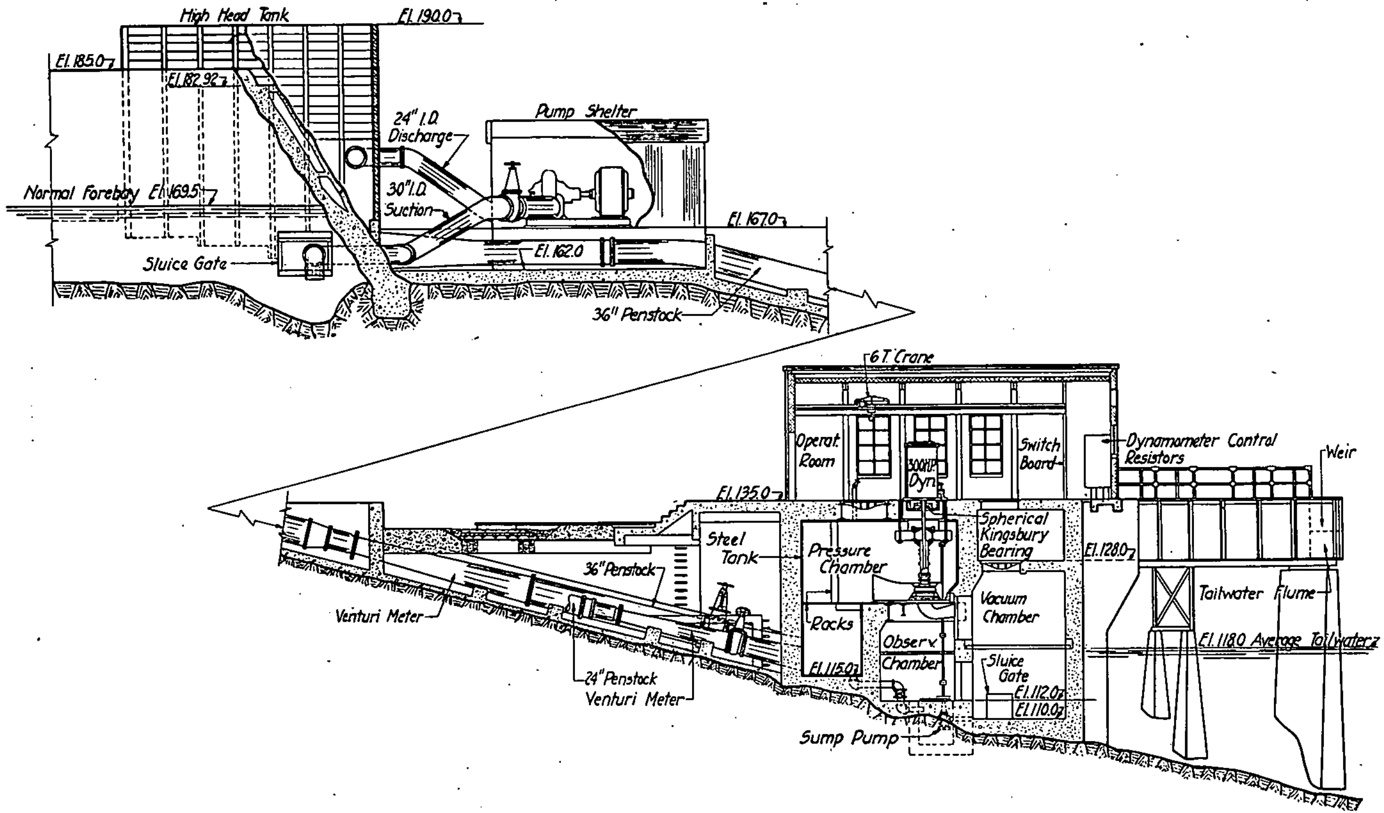

FIG. 39. — THE HOLTWOOD HYDRAULIC LABORATORY OF THE PENNSYLVANIA WATER AND POWER COMPANY, HOLTWOOD, PENNSYLVANIA

intake, 52 inches in diameter, connects with a 36-inch penstock, which delivers the water through a 36-inch by 15-inch Venturi meter to the rectangular pressure chamber at the laboratory. This pressure chamber serves as the wheel pit and is 12 feet by 18 feet in plan and 9 feet high, allowing ample room for the installation of model scroll cases and intakes. Directly below the wheel there is an observation chamber in which elbow, spreading and conical draft tubes of the shape desired may be installed. The draft tube under test at the time of the visit was fitted with small windows which allowed the inspection of the wheel and of the draft-tube flow while the unit was in operation. This feature has been particularly useful in studying cavitation with the aid of steady and stroboscopic light. The draft tubes discharge into a closed chamber which has a regulating gate at the bottom and a vacuum pump taking off at the high point. This makes it possible to keep the draft tubes sealed, and yet, by proper manipulation of the gate, the pressure in the chamber may be dropped to a very low equivalent water surface. By varying the pressure in the forebay tank and in the draft-tube chamber, tests can be run with a range of heads from 70 feet to 30 feet. For cavitation tests σ can be varied from 0.4 to 1.5. Tests at heads under 12 feet may be made through use of the low-head tank, which receives its water from a by-pass in the 36-inch penstock, and delivers it to the pressure chamber of the laboratory through a 24-inch by 10-inch Venturi meter.

The pressure head on the wheel is measured with a barometric type of mercury manometer. The tailrace elevation is read by means of a counterweighted float gage. These two gages are set close together allowing one observer to take both readings which, when subtracted, give the pressure head on the wheel. The discharge is measured by the 36-inch by 15-inch Venturi meter, which was calibrated by the Allen salt-velocity method.

The output of the water wheel is measured by a vertical 300-horsepower electric dynamometer, which is equipped with a special thrust bearing, allowing friction effects to be evaluated. The dynamometer will deliver 225 horsepower as a motor in making pump tests for which the laboratory is also adapted. The speed of the wheel is counted by a Leeds and Northrup synchronous timer driven by a small A. C. generator which, in turn, is gear-driven from the dynamometer shaft. The clutch of the timer is operated automatically by contacts on an electrically wound International time clock, which also controls the warning and reading bells.

During the formal cavitation tests, the phi of the wheel, the blade angle, and the gate opening are held constant while sigma is varied. Sigma curves are run for at least three gate openings to permit cross plotting. The horsepower, discharge and efficiency are determined. Where possible during these tests the total head and the actual r. p. m. are also held constant, but for extreme values of sigma this is not possible. The horsepower, discharge and efficiency are all plotted against sigma, and from the "breaks" in the curves the cavitation limit is determined. It is not always easy to do this, and all three sets of curves are studied to get more conclusive evidence. The tests by Professor Spannhake at Karlsruhe indicate that the "breaks" in the curves occur with the start of visible cavitation. Pitting, however, does not start immediately, because a certain unit strain must be set up before the metal begins to disintegrate. Therefore the cavitation limit determined from the "breaks" in the curves of efficiency, horsepower and discharge plotted against sigma are on the conservative side as regards actual pitting. From the cavitation test results, curves are worked up for the operating department which show the limits of load which can be carried under various head conditions at the plant. For a more complete description of these cavitation tests and results, reference should be made to a paper presented by Mr. L. M. Davis before the National Hydraulic Power Committee, May 28, 1934, entitled "Model Testing at the Holtwood Laboratory," also a paper presented at the December, 1935, meeting of the American Society of Mechanical Engineers, entitled "Cavitation Testing of Model Hydraulic Turbines and Its Bearing on Design and Operation," in the "Transactions of the American Society of Mechanical Engineers, November, 1935." Copies of the former paper may be obtained from the Pennsylvania Water and Power Company.

The Holtwood laboratory was used initially to determine the characteristics of water wheels for the Safe Harbor power plant, both from the design viewpoint and finally from the operation viewpoint, when the power output as limited by cavitation was determined for various head conditions. The laboratory has been used also by various manufacturers for their experimental work in cavitation.

Cavitation Tests of Materials

A cavitation stand has been built at Holtwood to determine the comparative resistance of metals to pitting by cavitation. The water is supplied under 500 pounds per square inch pressure, a discharge of about 0.4 c. f. s. being used. The water passage at the entrance to the apparatus is 4 inches in diameter and it gradually tapers down until at the throat the cross section is 1 inch by ¼ inch and the velocity about 265 feet per second. Beyond the throat there is a sudden expansion in the size of the passage, and one side of the throat is continued in a curve so as to throw the jet with its cavitation effects into direct contact with the samples of material to be tested. The sudden expansion beyond the throat into a passage of which the walls are parallel tends to give severe concentrated cavitation effects.

Three pieces of material are used for each test. Two pieces 4 inches by 1¼ inches by ¼ inch of the material to be tested are located on each side of the parallel passage beyond the throat of the test apparatus. The top plate of the passage is formed by a piece of standard material 4 inches by 1 inch by ¼ inch. The standard material used in these tests is stainless steel with a composition of 18 per cent nickel and 8 per cent chrome.

It is of the utmost importance that the working face of the sample pieces be ground to a standard finish so as to insure uniformity in the test results. The surface condition has a very important effect upon the start of pitting. As soon as the surface is roughened, the pitting proceeds much more rapidly. Pitting is accelerated where cracks or holes are found, as evidenced by the rapid attack of the samples at the joints between the specimens.

The tests are continued for a period of sixteen hours, which length of time was selected after making a study of pitting of the various materials over various test times. With soft materials a longer test time would have resulted in the complete disintegration of the test specimen, and with the very hard materials a shorter test time would not have allowed sufficient pitting to afford an accurate result. While the rate of pitting is still increasing rapidly after this test time, still the results as found are reliable. The severity of cavitation is judged by accurately determining the loss in weight of the test specimen.

Their tests have included a wide range of materials. The runner for Safe Harbor unit No. 2 was prewelded before installation with materials having a high resistance to pitting at those spots where pitting was most apt to occur. For that reason their first tests were concerned with the proper welding methods and material to be used for this process. Most of these tests were made upon various types of stainless steels, but other materials suggested by manufacturers were tried. The effect of electric arc welding and gas welding on the materials was determined. The best material was selected upon the basis of its resistance to pitting and also with respect to machinability. The next series of tests determined the characteristics of various cast materials, such as iron, steel, bronzes, brasses and alloyed steels. Finally, a series of tests were made upon forged and rolled specimens of steel and steel alloys.

For a more detailed account of these tests and the results obtained, see "Pitting Resistance of Metals under Cavitation Conditions," by J. M. Mousson, published in the "American Society of Mechanical Engineers Transactions for July, 1937."

Princeton University

The hydraulic laboratory of Princeton University at Princeton, New Jersey, is operated in the mechanical engineering department under the direction of Prof. L. F. Moody assisted by Prof. A. E. Sorenson. The equipment is installed on the first floor of the engineering building and occupies a floor space of 45 feet by 75 feet in plan, exclusive of the rating flume which has a length of 140 feet. This laboratory is designed primarily for undergraduate and graduate instruction, but its facilities are also adapted to a wide range of research.

The water supply is kept in a sump below the main floor having a capacity of about 5,000 gallons. The three centrifugal pumps which supply the various student experiments take their water from this sump. The first of these pumps can supply a discharge of 0.55 c. f. s. against a head of 23 feet, the second, 0.22 c. f. s. against a head of 50 feet, and the third, 1.25 c. f. s. against 45-foot head. There are two tanks equipped with overflows which are used to provide constant head for the experimental work. The first is a closed cylindrical steel tank 3 feet in diameter and 7 feet long, which is strapped to the ceiling and provides a head of about 23 feet to the laboratory floor. The second somewhat smaller tank is located on the roof and provides a head of about 50 feet.

There are two experimental flumes which are devoted entirely to graduate research work. The first is a glass-sided flume with a square cross section 12 inches on a side and about 8 feet long. Water supplied to this flume through a 5-inch line discharges into an open box about 5 feet long, 4 feet wide and 30 inches deep, equipped with suitable racks to provide quiet entrance conditions to the glass-sided flume. The discharge from this flume falls into a rectangular steel tank about 4 feet wide, 20 feet long and 30 inches deep, which is used as a volumetric tank. This flume is used for investigations of the flow in open channels, the loss of head due to sudden enlargement, and studies of the hydraulic jump.

The other flume is designed to test diffuser cones such as conical draft tubes. The pressure box is about 30 inches wide, 2 feet high and 4 feet long. The conical tubes are mounted in the front face of this tank and discharge horizontally into a rectangular steel tank about 40 inches wide, 6 feet long and with a variable depth of water. The water flows from this rectangular tank into the same volumetric tank which measures the discharge for the glass-sided flume. The water for both of these flumes is supplied by a 1.25 c. f. s. motor-driven centrifu-

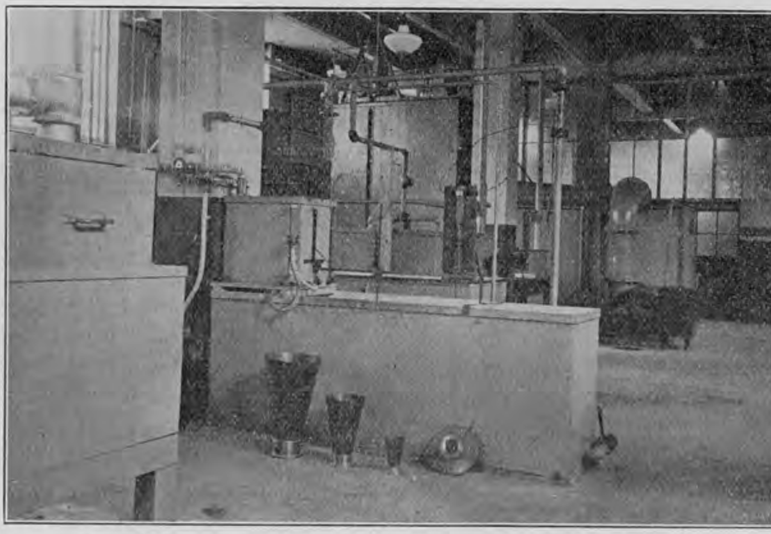

FIG. 40.—PRINCETON UNIVERSITY—GENERAL VIEW. ORIFICE TANK IN FOREGROUND AND WATER WHEEL FLUME IN BACKGROUND

gal pump. In the line to these flumes is located a calibrated Venturi meter of special design having a rounded entrance section to the meter.

A device for measuring the hydraulic gradient in a converging and diverging tube has been added recently to the laboratory equipment. It consistes of headwater and tailwater tanks 2 feet wide, 3 feet long and 4 feet deep. The converging section is attached to the headwater tank with a bell-mouth nozzle protruding into the tank. This section runs from 4 inches in diameter at the entrance to 2 inches at the throat. The diverging section has a total angle of flare of 12 degrees, and is about 6¼ inches in diameter where it discharges into the tailwater tank. Eleven piezometer openings with gage glasses are distributed along the sections in order to measure the gradient. This apparatus may be supplied by either the 0.55 c. f. s. or the 1.25 c. f. s. pumps.

Another piece of equipment which is used for research work is a rating tank for the tests of current meters and towing tests on models. This tank is 140 feet long, 5 feet wide and 5 feet deep. A car, mounted on four cast iron wheels, is driven along the tracks by a variable speed D. C. motor. The car speed is controlled by regulating the voltage applied to the armature of the motor. Suitable contacts record the passage of the car along the track on an Esterline Angus chronograph. This chronograph is equipped with four pens so that the revolutions of current meters and similar devices may be recorded simultaneously. A time record is provided by operating one of the chronograph pens through relays by a photo-electric cell and a pendulum clock.

The remainder of the apparatus is used in the student experiments. A reaction water wheel test is performed in an open flume setting. Two types of wheels are available, one being a medium speed Francis runner and the other a Moody diagonal flow runner. Water for the test is supplied by a 20-horsepower D. C. variable speed motor-driven Moody spiral pump discharging against a 10-foot head. The discharge is measured by a 4.5-foot suppressed weir. The speed is determined with a counter designed by I. P. Morris division of Baldwin Southwark Corporation. The load is measured with a Prony brake and a set of platform scales. The head is measured by floats in wells connected to the headrace and the tailrace, respectively. These floats carry a steel tape over a ball-bearing pulley so that one reading gives the head on the unit.

The operating characteristics of a glass-enclosed impulse wheel built by the Pelton Water Wheel Company are determined. The water supply is separate from the laboratory pressure system. A 10-horsepower motor-driven pump supplies water under a pressure of 145 feet for the test. This head is measured by a Bourdon tube gage located just upstream from the nozzle. The discharge is measured by a 2-inch by 1-inch Venturi meter which has been calibrated by weighing tanks. The wheel discharges into a tank which contains a 10-inch suppressed weir which is also used to measure the discharge. The output is determined by a portable counter and a Prony brake.

A 1-inch by ½-inch Venturi meter is calibrated by means of a pair of weighing tanks. The deflections are measured in water and mercury differential manometers. The water supply is taken from a motor-driven pump capable of furnishing 0.22 c. f. s. against a head of 50 feet. One detail of this experiment is different from the ordinary procedure. In addition to the difference in pressure between the inlet and the throat, the difference in pressure between the throat and the exit end of the Venturi meter is read. This second differential pressure represents the velocity head which has been regained in the meter. The regain in velocity head divided by the total change in velocity head is a measure of the efficiency of the regainer. This ratio is plotted against the absolute pressure at the throat of the meter. When the curve deviates from a horizontal line it can be shown that the absolute pressure at the throat is at the vapor pressure of the water, and cavitation is starting.

At the present time cavitation tests are being made on a new Venturi having a rounded entrance section and a glass throat. This instrument has a 6-inch entrance section and a 2.5-inch throat, and is supplied with water from the 1.25 c. f. s. pump through the calibrated Venturi meter mentioned formerly. The meter is set in the room above the hydraulic laboratory, in order to have a long return pipe to the sump, which will produce a low pressure at the throat of the Venturi. Ten piezometer taps are provided to measure the pressure at various points along the meter. Pressures are recorded on mercury pot vacuum gages equipped with a steel point at the zero of the scale, which in turn is attached to a flash-light bulb through dry cells. The scales are adjustable and are moved until the light just blinks. When this happens the zero of the scale is at the mercury level of the pot, and only one reading is necessary.

The pressure tank for an orifice test is a cube about 18 inches on a side, with the outlet for the orifices about 4 inches above the bottom. The diameter of the orifices or short tubes used is about one half inch. A constant head is maintained on the orifice by means of an overflow dam in one side of the tank. The head is measured with a gage glass. The velocity of the jet is determined by the trajectory method, using a ring of wire mounted on a hook gage which travels on a horizontal boom. The discharge is measured in a rectangular volumetric tank 2 feet wide, 2.5 feet deep and 7 feet long. During the experiment the coefficients of velocity, area and discharge are determined for a sharp-edged orifice and for a standard rounded entrance orifice.

Weir tests are conducted on either rectangular or "V" notch weirs, and in the latter type several angles of opening are available. In each shape there is one crest which is sharpened to a knife edge and another which has an edge one sixteenth inch wide. The experiments are performed in a steel tank 3 feet wide, 4 feet deep and about 15 feet long, divided into two sections by two transverse diaphragms separated about 1 foot. These diaphragms divide the tank into two tanks 7 feet long, one of which is the weir flume and the other the volumetric tank to check the discharge. The space between the diaphragms is connected to the sump and discharges the water to waste. The weir is mounted in one of the diaphragms, and the water is introduced at the far end of the tank from the weir. Suitable baffles provide quiet flow conditions in the channel of approach. The discharge from the weir is thrown by a suitable switchway, either into the volumetric tank or to waste. The volumetric tank has been calibrated by weighing tank measurement.

Pipe friction losses are determined in ¼-inch, ½-inch and 1-inch pipe, using a test section 100 feet long between piezometers. The pipes are laid along the end wall of the building and along the wall of the current meter rating flume, so that there is one elbow in each test section. At the far end of the test section the three pipes flow into a 1¼-inch return pipe which discharges into a pair of weighing tanks near the upstream piezometer and differential gages. The pressure connections from the downstream piezometers are piped back to the differential gages which are located near the upstream piezometer. Head losses are measured in differential gages, using mercury deflections for the larger losses and water deflections for the smaller losses.

The water supply to a Rife hydraulic ram is piped from three 10-inch standpipes which are located about 25 feet, 100 feet and 120 feet, respectively, from the ram. This enables the ram to be tested with three lengths of drive pipe by operating valves. The water wasted and the water pumped by the ram are measured in weighing tanks. The discharge pressure is measured in weighing tanks. The discharge pressure is measured with a steam indicator so that the mean pressure may be determined from the diagram obtained.

At the present time (June, 1937) a device for determining the critical velocity of flow is being added to the laboratory equipment. It is made up of headwater and tailwater tanks 2 feet wide, 3 feet long and 4 feet deep. A brass bell-mouthed orifice opens from the head tank to a horizontal glass tube 5 feet long and about 1½ inches in diameter, which discharges into the tailwater tank. Colored dyes are introduced at the bell mouth to show the stream lines. Connections between glass and metal have been made by using rubber stoppers drilled out to permit the tube to go through them and compressing the stoppers into a stuffing box. This apparatus has been set up, but is not complete as yet.

Purdue University, Schools of Engineering

The hydraulic laboratory of Purdue University at Lafayette, Indiana, is under the direction of Prof. F. W. Greve of the school of civil engineering. The main floor is about 140 feet by 50 feet in plan, and the floor space is supplemented by a balcony covering about one half of the floor area.

Water is kept in a sump below the main floor from which it is pumped by several centrifugal and displacement pumps.

The largest pump in the laboratory, discharging 22 c. f. s. against a head of 38 feet, is a direct motor-driven centrifugal unit supplying a 14-inch Trump reaction water wheel and two concrete channels. The larger of the two concrete flumes is 5 feet and 8 feet wide, 6 feet deep and 80 feet long. At the end is located a 5-foot suppressed weir, the discharge of which can be caught in a weighing tank of 20 tons' capacity. The smaller of the two concrete flumes is 120 feet long, 3 feet wide and 3 feet deep. It is provided with a light track and car for the calibration of current meters. A bulkhead at one end can be replaced by a weir, water being supplied by any or all of the several pumps to the other end of the channel.

The supply piping throughout the laboratory is 6 inches in diameter, and all the student experimental equipment is connected into this system. Water is supplied by any one or combination of pumps. One unit is a motor-driven, two-stage 6-inch centrifugal pump which can supply 2.2 c. f. s. at a head of 230 feet. The second is a 4-inch single stage, motor-driven centrifugal pump which delivers 1 c. f. s. at a head of 100 feet. Other pumps include a 2-inch triplex, a 2-inch centrifugal and a 2-inch rotary.

A 14-inch glass-enclosed impulse wheel is set up on the mezzanine, taking water from the 6-inch supply system. The head is measured with a calibrated Bourdon tube gage. The discharge is measured with a volumetric tank located on the main floor. The output of the wheel is determined with a Prony brake and a hand counter.

There are two weir and two orifice tanks on the mezzanine floor. Experiments are conducted on a 6-inch and 3.57-inch contracted weir, and on circular orifices of maximal 1.50 inches diameter. Two of the tanks are constructed of steel and two of wood and they are similar in size and arrangement of details. The flume in which the 6-inch contracted weir is tested, for instance, is 3 feet long, 28 inches wide and 18 inches deep. It is fitted with a rock-filled screen for quiet-flow conditions. The head is measured with a Gurley hook gage placed in a still box. Piezometers are used to measure the head on orifices. The discharge is measured with small weighing tanks located on the main floor.

There are two hydraulic rams mounted on a concrete waste tank on the main floor. Two small supply tanks, about 24 inches in diameter and 30 inches high, are installed on the mezzanine allowing about 25 feet of 2-inch drive pipe to each ram. The discharges are measured in weighing tanks. The discharge head is determined with a Bourdon tube gage, and the supply head is measured in a piezometer.

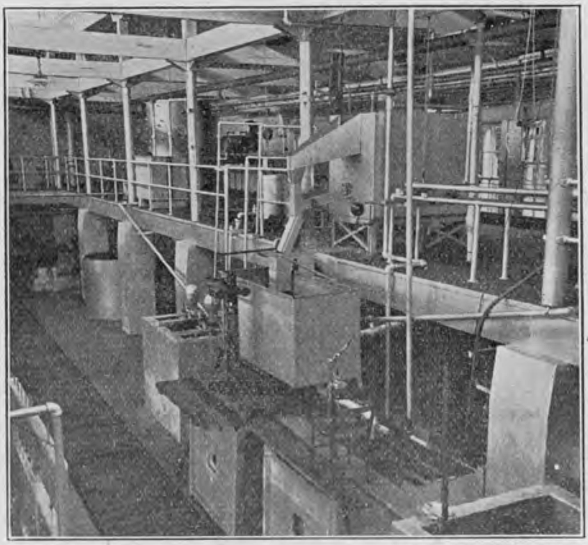

FIG. 41.—PURDUE UNIVERSITY—GENERAL VIEW OF LABORATORY

A small triplex pump is tested by the students to determine slip, efficiency, etc. It is belt-driven and the input is equal to the known motor output. The output is measured with a Bourdon tube gage and a small weighing tank. The revolutions of the pump are counted with a hand counter.

A pipe loss experiment is performed in a loop of 2-inch pipe. The loss in head is determined with a differential mercury gage and the flow with a small weighing tank.

A Venturi meter experiment is set up in the 6-inch line. A 6-inch by 3-inch meter is tested, using Bourdon tube gages to determine the difference in heads, and the large weighing tank to measure the discharge. Current meters are rated in the smaller concrete channel.

There were two experiments in progress in the nature of advanced research. The first was being performed by Prof. W. E. Howland. It was a scheme to simplify the study of pipe net works, using water as a fluid in an "equivalent circuit" arrangement. Junction points in the system were represented by 2-quart pails in the model. Each connecting pipe was made up of a ¾-inch return bend with two 8-inch nipples. One of these nipples was left open while the other was partly closed with a rubber stopper containing a short copper tube about five sixteenths inch in diameter. This "U"-shaped unit became a siphon in the model connecting two 2-quart pails or junction points. The flow through this system was a function of the head to about the 1.9 power, which was the same approximate law which friction follows in a pipe line. The constant in the equation which represented the amount of water flowing for a given head difference was adjusted by squeezing the copper tube to constrict the opening the proper amount while measuring the head and discharge. Thus each pipe in a system could be replaced in the model with its hydraulic equivalent. In operation the water was run backwards in the model because of the greater ease of operation. Thus the point of inflow in the pipe system became the discharge point of the model, and vice versa. This system provided a simple and inexpensive way of checking computations in the design or analysis of complicated pipe networks.

The other research work in progress was a series of tests on three triangular weirs and several sharp-edged circular orifices, ¼ inch, ½ inch, 1 inch and 2 inches in diameter. These were mounted in a steel tank 30 inches wide, 6 feet long and 6 feet deep. A rock screen provided quiet flow conditions. The flow from the orifice or weir was passed either to a weighing tank or to the separate sump for this test. A motor-driven 2-inch centrifugal pump took the water from the sump and forced it up to an elevated tank which provided constant head. The head on an orifice was measured with a piezometer, and that on a weir with a hook gage located in a still box.

The underlying object of these experiments was an endeavor to derive a fundamental flow relation which could be expressed in terms of density, surface tension and viscosity. To this end the temperature of the water was controlled and the density, surface tension and viscosity were frequently determined. When the initial experiments with water are completed, it is hoped to continue the tests with soap solutions in order to vary the surface tension, and with sucrose or glucose solutions to vary the viscosity. This work is in progress at the present time.

Queen's University

The hydraulic laboratory of Queen's University, located at Kingston, Ontario, is operated by Prof. D. S. Ellis of the department of civil engineering. At this college the field of hydraulics has been extended to include air flow and aërodynamics. For this reason there are essentially two laboratories, one for the study of the flow of water and similar liquids and the other for the study of the flow of air. Both of these laboratories are designed primarily for undergraduate use.

The two laboratories are housed in a building formerly used as a gymnasium, whose interior dimensions are 56 feet by 100 feet, the hydraulic section occupying the basement and the air-flow section about one half of the first floor. The remainder of this floor is used for classrooms and offices.

Hydraulic Laboratory

The original swimming pool of the gymnasium is used as the main sump or reservoir. It is 24 feet by 40 feet in plan and lies at the east end of the basement floor. To extend the sump capacity and also permit experiments on channels of some size, a rectangular channel 4 feet by 4 feet by 3 feet deep was carried westerly along the center of the floor and about 70 feet to the west end, and a loop about the south part of the floor was made by cutting a channel 3 feet by 3 feet along the west and south walls and back to the center channel.

In designing the laboratory, as many independent sources of water supply as possible were sought, in order that each party of students might, if possible, be independent of the others.

The first and principal water supply for experimental use is provided by a 6-inch centrifugal pump placed at the corner of the pool in the basement. It is driven by a direct connected D. C. motor, and can discharge 2.2 c. f. s. into a constant level tank located about 25 feet above the basement floor. An 8-inch pipe is connected into this tank to supply the equipment in the basement.

A 6-inch New American water wheel is tested for efficiency. Water is supplied from the constant level tank to the wheel pit which is a cylindrical steel tank 5 feet high and 4.5 feet in diameter. The draft tube of the wheel discharges into the 3-foot-square return channel. The discharge is measured with four Pitot tubes permanently installed at the centers of equal area in the supply pipe. The impact and pressure heads are measured in a differential manometer bank. The head on the wheel is determined by measuring from a horizontal reference line to the water surface in the flume and in the channel. The output of the wheel is obtained with a Prony brake and a tachometer.

Toward the center of the floor is located a steel flume 2 feet wide, 3 feet deep and 25 feet long, which is used for tests of suppressed and contracted weirs and for studies of spillway models. Glass-side panels are provided to facilitate observation of the flow conditions. The head on the weir or model is measured with a hook gage, and the discharge is checked in a calibrated steel volumetric tank.

A tilting steel flume carried on two screw jacks is located near by and is used for the calibration of model sluice gates as well as tests of standing waves and open channel phenomena. The flume is 12 inches wide, 15 inches deep and 20 feet long. A steel head box 3 feet by 3 feet in plan, and 24 inches deep and equipped with baffles provides smooth flow conditions in the channel. The discharge is measured with four Pitot tubes permanently installed at the centers of areas of quadrants in the 6-inch supply pipe.

A rack of pipes is installed for the determination of pipe and elbow losses. The pipe sizes tested are ½ inch, ¾ inch, 1½ inches and 2 inches. A 2-inch by ¾-inch Venturi meter is also connected in this rack. Differential pressures are measured in air and water manometers or in mercury manometers, depending upon the range required. The discharge is checked in a volumetric tank.

A 2-inch pipe is installed with provision for connecting 1-inch orifices at the end. A board is set up behind the jet so that the trajectory can be traced. The discharge is caught in a small volumetric tank.

The discharge from the 2-inch by ¾-inch Venturi meter can be sent tangentially into a special circular tank 4 feet in diameter and 2 feet deep to study vortex flow. There is a 2-inch orifice in the center of the bottom of the tank. A portable Pitot tube is used to measure the velocities at various radial distances, and the velocities and velocity heads are compared with the surface curve. The whirl formula for a centrifugal pump is thus demonstrated and checked.

At one side of the sump there is installed a motor-driven 2-inch centrifugal pump which is tested for efficiency. The discharge pressure is measured with a Bourdon tube gage. The discharge passes through a throttling valve and falls into a wooden weir flume 18 inches square in section and 8 feet long. Suitable racks provide quiet approach conditions to the "V" notch weir located at the downstream end of the flume. The driving motor has been calibrated and the input is measured electrically.

This pump is also connected to a cylindrical head tank 30 inches in diameter and 6 feet high, which supplies an orifice test. The 1-inch sharp-edged orifice is installed in a 2-inch line. A number of piezometers connected to a bank of open water manometers show the hydraulic gradient of the system.

A 12-inch Pelton water wheel is provided for test. The city water service provides the necessary high pressure supply. The pressure at the nozzle is read with a Bourdon tube gage, and the discharge is measured with a small volumetric tank. The output is determined with a Prony brake and a tachometer.

The fourth water supply is provided by a small portable sump pump which can discharge about 20 g. p. m. against 20-foot head. It can be taken easily to any part of the laboratory, the suction of the pump being placed in the concrete channels in the floor. At present, this pump is being used to supply the orifice demonstration apparatus which consists of a vertical tube or tank about 8 inches in diameter and 5 feet high, on which are mounted five sets of orifices at various elevations. Three types of orifices are mounted on a slide at each station. The discharge falls into a small trough which connects with the sump.

A glass-sided tank 2 feet by 2 feet by 4 feet is used for Reynolds' experiment on viscous and turbulent flow and other similar problems.

Air-Flow Laboratory

Due to the broadening influence of aërodynamics, mine ventilation and similar flow problems upon the study of hydraulics, it has been found desirable at this college to operate an air-flow laboratory in conjunction with the hydraulic laboratory.

The first wind tunnel in this air-flow laboratory was designed to be used primarily as a demonstration unit. It had an enclosed jet and an open return path. The throat section is only 8 inches by 12 inches, with a maximum air speed of about 30 feet per second. Small as it is the unit performed very successfully, and it is still used for experiments demonstrating flow lines and similar problems.

Two years ago an open jet, closed return tunnel was built having a 24-inch diameter jet or test section and a return channel 48 inches in diameter. Miter joints were made at the bends of the return channel and deflectors were placed along the joint to reduce the bend losses. The air is moved by a 36 inch diameter propeller fan situated below the test section and driven by a 5 horsepower direct connected motor. The air speed at the test section may be varied from 30 to 90 feet per second. The balance in use at present is of the fulcrum type and measures three components. The airfoil is mounted on a steel rod which in turn is gripped by a chuck in the balance. This method of attachment is not suitable for velocities in excess of 50 feet per second, and a new balance is being constructed. Besides measuring the lift and drag of model airfoils, some work has been done in this tunnel in determining the wind pressures on model buildings and trusses.

There are available for testing and study the following fans: No. 0 Sturtevant blower with motor; No. 4½ Sirocco fan with an interchangeable high speed rotor; 24-inch Buffalo steel plate fan.

The discharge lines of the Sirocco and Buffalo fans are formed of circular galvanized conduit in which Pitot tube velocity measurements are made. Model mine passages are being constructed to provide means of illustrating and testing ventilation problems.

Pressure measurements in this laboratory are made with a variety of manometers. High pressures are measured directly with water columns. For lower pressures a two fluid differential manometer having a multiplying factor of about 25 is used. For the lowest pressures, either a Chattock gage or a micrometer point gage is used. The instant of contact is indicated in the latter type of manometer with a sensitive vacuum tube circuit.

Bureau of Reclamation

The materials, testing and control division of the design office of the United States Bureau of Reclamation was created to handle all selection, investigation and control of construction materials and investigation of the hydraulic, architectural and stress features of the proposed designs. The activities of the three hydraulic laboratories of the Bureau are included in the latter category.

The main hydraulic laboratory, used principally for detailed studies requiring close co-ordination with the design departments, is located in the recently completed addition to the customhouse at 19th and Stout streets, in Denver, Colorado. A second laboratory, utilized mainly for model studies requiring considerable space and less co-ordination with the design department, is on the campus of Colorado State College, Fort Collins, Colorado. A third laboratory is operated near Montrose, Colorado, where water in considerable quantities can be diverted from the South Canal of the Uncompahgre irrigation project, allowed to flow through the models and returned to the canal approximately 40 feet in elevation below the entrance. Being an outdoor laboratory subject to inclement weather during the winter months, and being rather large in expanse, the laboratory is expensive to operate and is used only to study the final or semi-final designs of structures on which the preliminary studies have been made on a smaller scale in either the Denver or Fort Collins laboratories.

Denver Laboratory

The main hydraulic laboratory in Denver is located in the basement of the recently completed addition to the customhouse and contains the equipment formerly used in the basement of the old customhouse. The total floor space is about 50 feet by 150 feet in plan, with 15 feet of clear head room, broken only by an elevator shaft at one end and center columns. A clear run of 125 feet can be obtained.

At the present time there are three centrifugal pumps installed, and a fourth will be placed in the near future. A 12-inch pump, direct-connected to a variable speed, 75-horsepower motor, can be regulated to furnish a flow from 12 second-feet against a 30-foot head through a constant head tank to 5 second-feet against a 100-foot head through a pressure tank. An 8-inch pump, belt-connected to a constant speed motor, delivers about 4 second-feet of water to a constant-head tank near the ceiling, from which it can be piped to the different models it is to serve. A second 8-inch pump, belt-connected to a constant speed motor, delivers about 4 second-feet of water to a pressure tank connected to a turbine model test arrangement. A 6-inch pump, direct-connected to a constant-speed motor and capable of handling 3 second-feet against 10 feet of head, will be installed in the near future. It is anticipated that the flow in the latter installation will be measured by a Venturi meter rather than by weirs, as has been the practice formerly. In fact, serious consideration is being given to a more general use of Venturi meters as measuring devices so as to maintain a more flexible arrangement of equipment and greater utilization of space.

A return and storage channel 5 feet wide by 5 feet deep extends lengthwise of the center of the laboratory beneath the floor. A rating flume, 8 feet wide and 5 feet deep, extends the entire length of the laboratory and is connected by cross-channels to the return channel.

The rating flume can be isolated by control gates in the end of the cross-channels. Lateral channels, 5 feet by 3 feet, extend in the opposite direction to act as feeders to the return channel. The discharge of the 12-inch pump is measured by a modified "V" notch weir placed across the return channel where it joins the pump sump. The discharge of the 8-inch pump connected to the constant head tank is measured by a "V" notch weir in an adjacent tank.

The model ratios in use in the Denver laboratory at the present time range from 1:6 to 1:60. The spillway sections of the models are most frequently made of galvanized sheet iron mounted on wooden

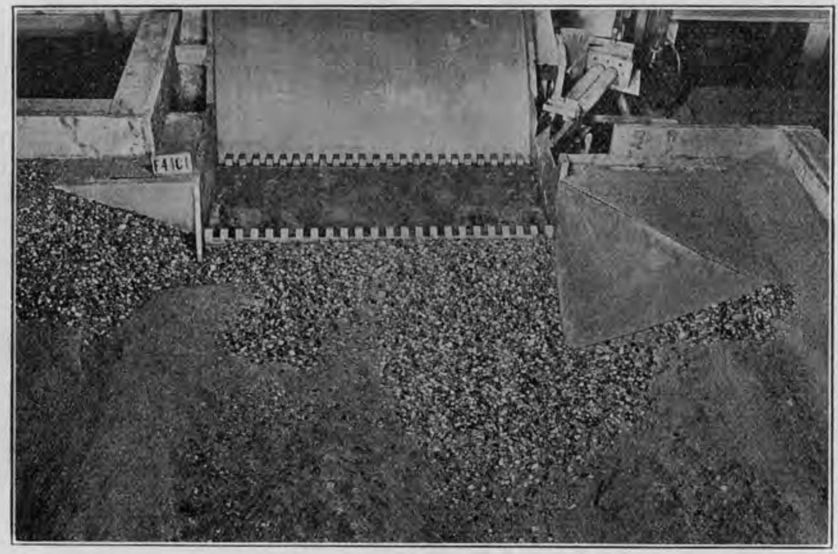

Fig. 42. — Bureau of Reclamation — Spillway and Outlet Works, Stilling Pool for Fresno Dam, Milk River Project, Montana. Scale 1:60

framing. The necessary forebay is usually made of galvanized sheet iron mounted on wooden framing. The forebay is constructed for each model to meet the individual requirements. Here again the tanks are made of wood and lined with galvanized iron.

At the present time studies are in progress on the power-drop structures being constructed in the All-American Canal; on the outlet works and stilling pool for the Seminoe Dam on the Casper-Alcova project; on the draft tubes for the Grand Coulee power house; on the ejectors for evacuating the seepage water under the Imperial Dam; on the discharge channel for the spillway and outlet works on the Vallecito Dam of the Pine River project; and on the performance of a float-controlled automatic gate to be installed on several control structures of the All-American Canal. Of these studies, the latter perhaps is the most interesting at the present time. A complete model on the scale of 1:6, built according to design drawings when first operated, showed excessive "hunting" and very poor control of the water level in the forebay. Several points affecting the functioning of this gate could not be determined accurately without testing. Among these were the dimensions and specific gravity of the float; the shape, size and capacity of the control weir; and the size of the bleeder pipe. Preliminary tests eliminated a large percentage of the difficulty, and final tests are now in progress to perfect the design.

Studies have been in progress for several months in connection with the Grand Coulee draft tube design. In that connection a model to a scale of 1:24, consisting of the penstock, scroll case, turbine runner and draft tube, has been so constructed that visual studies are made as an aid in determining the characteristics of the draft tube. The penstock, scroll case and draft tube assembly is constructed of pyralin pressed into shape from sheets one tenth inch thick. The turbine runner was cast in one piece from bearing metal. The movable gate vanes and the speed rings were cast from the same material. The turbine shaft was connected through a flexible coupling and change-gear box to a synchronous motor used as a constant-speed dynamometer. This dynamometer was suspended on ball bearings so as to rotate freely. The torque exerted on the dynamometer by the turbine was transmitted to a delicately balanced scale beam, where its value was determined by a system of movable weights.

Designs are being prepared of models and apparatus with which to study the proposed designs of the twelve hydraulic pumps to be installed to lift 1,600 cubic feet per second per unit, with a normal head of 295 feet, from the Grand Coulee Reservoir into the Grand Coulee Irrigation Reservoir. It is expected that those studies will require at least two years to complete.

Fort Collins Laboratory

The hydraulic laboratory at Colorado State College was established in 1913 as a part of the Colorado Agricultural Experiment Station by co-operation of the Bureau of Agricultural Engineering of the United States Department of Agriculture. During the past seven years the laboratory has been operated co-operatively with the United States Bureau of Reclamation.

In 1936 the old laboratory was practically dismantled and a new and larger building erected on the same site, utilizing the channels and tanks already in place. One additional tank was added in the extended area. The new building, 95 feet by 118 feet in plan, has a clear headroom of at least 20 feet. Rooms along one side of the building provide space for offices and workshop.

Water for use in the laboratory is stored in a high level, copper-lined, concrete circular pool 72 feet in diameter and $6\frac{1}{2}$ feet deep. Three 12-inch valves, one of which is remotely controlled, regulates the

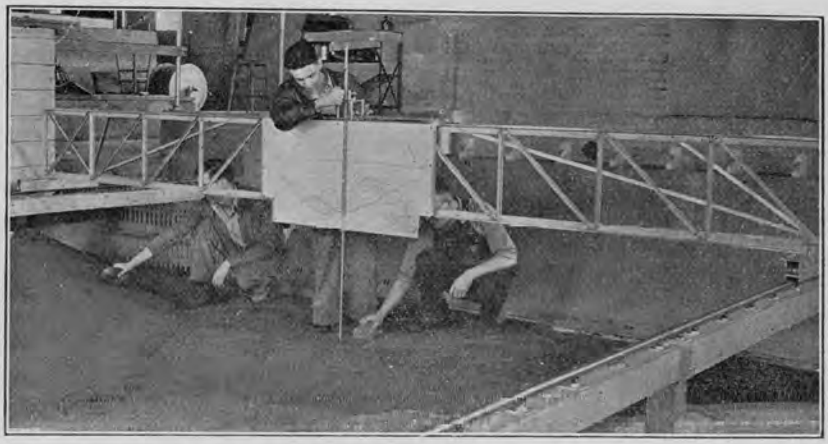

FIG. 43. — BUREAU OF RECLAMATION — PROFILOGRAPH USED IN THE RIVER BED OF THE 1:120 MODEL OF THE ULTIMATE DEVELOPMENT OF THE GRAND COULEE DAM. MEASUREMENTS OF EROSION WERE RECORDED ON PROFILOGRAPH IN PROTOTYPE TERMS

discharge into a concrete channel 10 feet by 10 feet in section, which passes under the road by the building. After the water has been used, it is returned to the pool from the low level sump by a 12-inch belt-connected centrifugal pump capable of delivering 9 second-feet at a head of 20 feet. This discharge is therefore the maximum discharge for long-continued tests. When tests can be made of very short duration, a maximum discharge of 17 second-feet can be maintained utilizing the storage of the upper basin.

At the laboratory end of the 10-foot concrete flume there is located a weir diaphragm in which various sizes and shapes of weirs can be mounted. These weir plates range from 12 to 48 inches in length and are available in both the rectangular-contracted and Cipolletti types. In addition there are available 90 degree and 120 degree "V" notch weirs. Every weir has been calibrated in place, using the volumetric tank beneath the floor for that purpose. The discharge from the weir can be diverted to any part of the building through conduits beneath the floor.

Provision was made during the reconstruction of the laboratory for an additional pumping unit and sump if and when there is urgent need for it. When installed the laboratory can be divided into two distinct sections and each operated independently.

At the present time the Fort Collins laboratory is primarily occupied by the studies in progress on the Grand Coulee Dam, being built in the Columbia River near Spokane, Washington, and on the Marshall Ford Dam, being built in the Lower Colorado River, near Austin, Texas. In the case of the former, three models are active: (1) a 1:120 model of the ultimate development; (2) a 1:20 model of the initial development; and (3) a 1:40 model of a single crest pier with one half of a drum gate on each side.

The model of the ultimate development was constructed for the purpose of determining the performance of the various sluices and the spillway, and especially to determine a suitable apron and bucket design for the protection of the stream bed. The bucket design was completed about two years ago, and the model has since been used for the solution of such problems as arise from time to time.

Water is brought to this model in a concrete conduit 24 inches in diameter. A double wire screen baffle filled with coarse gravel distributes the flow uniformly to the spillway crest. The model is mounted on two steel I-beams supported on steel plates fastened to the concrete floor of the tank to provide a very firm foundation. The dam itself is made almost entirely of steel and galvanized iron. The latter material is used as a cover, while the framework is made of 1½ inch angle iron formed to the correct shape. The very rapidly curving section of the crest itself is made of redwood. Thus a finished model was obtained which is unaffected by the presence of moisture or the pressure of water on the various parts.

All of the sluiceway and spillway details are faithfully reproduced to scale. The model drum gates are mounted between the piers and operated by means of a collar on a threaded pull rod located beneath the model. The sluices, both of high level and low level design, are duplicated. Even the draft tubes of the power houses are represented, and a flow corresponding to full load can be passed through each unit.

The bed of the river below the model was made of a fine sand in order to show the erosive action of the water. The final design of the apron consisted of a reversing bucket with a radius of 50 feet placed at a very low elevation. A more complete description of the result of these studies can be had by reference to an article in the November, 1936, issue of "Civil Engineering," entitled "Experiments Aid in Design at Grand Coulee."

The river bed was molded to the original cross section at the start of the test, and the final grades determined after the tests with the aid of a profilograph. It consists of a point gage with the upper section telescoping within the lower section. The two sections are controlled through a train of gears so that when the lower point is raised vertically 0.1 foot the upper section is raised 1 inch. This upper section carries a tracing point which moves over a small drawing board mounted on the instrument. The whole instrument is carried on a horizontal track traversing the model bed. The instrument is driven along the track, and at the same time the gage point is moved horizontally relative to the drawing board by operating one handwheel. The ratio of the gear trains is such that the point moves over the model five times as fast as the tracing point moves on the drawing board. The horizontal rail of the instrument is a part of the aluminum carriage which spans the model flume, and is carried on wheels and rails at each end of the frame. The instrument has been found very useful in the model test work, because it not only facilitates the molding of the bed at the start of the test, but also provides the complete transverse section of the stream bed after the tests recorded directly upon cross-section paper in prototype terms to a proper scale, thus eliminating considerable conversion of values and consequent computations.

A portion of the 1: 120 model of the initial development of the Grand Coulee Dam was originally built to study the proposed scheme of diversion of the Columbia River through the west cofferdam area during construction. The model was later extended to include the entire initial development, and studies have since been made of the flow conditions over it for various anticipated floods to determine the necessity of river-bed and bank protection.

Water is brought to this model in a concrete channel 6 feet wide and 10 feet deep, located between two of the large calibration tanks. The model is mounted with the heel on the free side wall of the concrete flume, so that the water enters at right angles to the direction of flow through the model. This right-angle turn in the flow of the water is accomplished by erecting a vertical steel diaphragm across the concrete channel a few feet upstream from the model, with an opening at the bottom for the water to pass through. Then a series of deflectors similar in action to those used in wind tunnel practice for right-angle bends were installed to give the entering water a uniform upward velocity. Since the cross-sectional flow in this direction is 6 feet by about 20 feet, and the maximum discharge 9 second-feet, the resulting velocity of approach is very low and very well distributed.

As stated above, the heel of the dam is carried on the concrete wall of the flume. The toe of the dam is supported on a beam and the whole weight carried through to the concrete floor of the tank on steel posts providing a very firm foundation. The dam itself is made almost entirely of concrete and galvanized iron, which provides a finished model very much unaffected by the presence of moisture or the pressure of water.

Practically all of the model construction is done in the laboratory. For this purpose an adequate shop has been provided in one corner of the building. The power tools available include a lathe, drill press, grinder, planer and a saw. In addition, there are tools for working thin sheet metal, such as is frequently used in the model work.

Near the hydraulic laboratory there is a current meter-rating flume. The channel is 5 feet wide, 4½ feet deep and 250 feet long. A motor-driven towing car upon which the instrument is mounted is carried on steel rails which are set on either side of the concrete channel. Power is supplied to the motor through a single-wire cable and the track. A 3-wire conductor attached to the car and allowed to drag along the side of the channel transmits indications of meter contact and distance traveled to the chronograph in the control house. The car can be driven at constant speed between 3/10 and 12 feet per second.

Montrose Laboratory

This hydraulic laboratory of the Bureau of Reclamation is located in the western part of Colorado, about eight miles southeast of Montrose. Only large models requiring large and continued discharges are tested here.

The laboratory is entirely an outdoor installation and cannot be operated during the winter, both because of the inclement weather and the lack of water. It is situated near a chute in the South Canal of the Uncompahgre Irrigation District. A discharge as large as 120 second-feet can be diverted from the canal, used for the desired tests, and returned to the canal below the chute. A maximum fall of about 40 feet is available.

One of the largest models that has been studied at the laboratory was a 1:15 model of a section of the Grand Coulee Dam. The purpose of the test was to determine pressures on the face of the dam, particularly in the region of the bucket for various operating heads and drum gate positions. Water is taken from the canal through two 48-inch valves into a weir flume. This flume is about 12 feet wide, 10 feet deep

FIG. 44. — BUREAU OF RECLAMATION — GILA VALLEY CANAL INTAKE AND SLUICE GATE STRUCTURE, IMPERIAL DAM. SCALE 1:40

and about 50 feet long. The weir is suppressed in form, with the crest formed by a machined steel angle 4 inches by 6 inches in section. Since it is not possible to calibrate this weir, the crest edge was made very carefully and is installed only when tests are in progress. The remainder of the time it is greased and stored in a protective case. The velocity of approach to the weir has been carefully equalized as determined by current meter measurements while the racks and baffles were being adjusted.

The discharge from the weir falls into a cross-channel connecting with the head box of the Grand Coulee model. This cross-channel was so constructed that another flume or model test can be installed readily.

The head box for the Grand Coulee model was 8 feet wide, 10 feet deep and 35 feet long. The crest of the model dam was set about 4 feet above the channel bottom, at one end of the flume. Suitable baffles and racks provide good flow conditions. The model spillway discharges into the tailrace box, from which the water is taken back into the irrigation flume by a wooden conduit about 4 feet by 3 feet in section. This same flume had been used for the final check tests of the side-spillway of Boulder Dam. That model was built with a ratio of 1:20.

A complete model of the Imperial Dam and its appurtenant structures, including about three miles of the Colorado River, has been constructed to a scale of 1:40 on the opposite side of the South Canal. The purpose of this model was to investigate the silting effects of the river at the control dam and intake structures.

Water for this model was taken from the aforementioned weir box through a 20-inch steel pipe to a supplemental weir flume. This weir flume is 6 feet wide, 30 feet long, with a suppressed weir located 4 feet above the bottom. The discharge from the weir falls into a basin and was taken into a 24-inch square wooden trough to the upper end of the model 200 feet away. Considerable difficulty was experienced in the approach to this problem because of the viscosity effects. In studies made with movable bed models, two ends may be accomplished: a quantitative analysis of the problem is attained which may or may not include data relative to the basic principles of transportation of solid matter by running water; or a qualitative or comparative analysis is obtained. In the latter case, such of the variables as it is possible to eliminate from the problems are deleted by maintaining certain conditions constant throughout the period of test.

In this particular case it was decided to attack the problem with the view of obtaining a qualitative or comparative analysis. Numerous factors governed this decision. The primary reason was the urgent need for the results at the earliest possible date, modified, of course, by the factor of economy in conducting the tests. The necessity for a detailed quantitative analysis of the problem was questioned. Practically all hydraulic designs are solved in this manner, and since a study of the basic principles of hydraulics by research was not imperative in the solution of this specific problem, the qualitative analysis was considered sufficient.

A study was made to determine the model scale and type of silt that could be used so that reasonably correct deductions might be made from the results obtained. It was considered probable, in view of the experience of others with small scale models, that in case a too great reduction in scale was used, it would be necessary to employ a material having a specific gravity less than that of silt and sand found in nature. The use of coal dust was considered, but the cost was found to be prohibitive.

The possibility of a distorted model scale would have made it possible to use a smaller scale. That type of model has been used to some extent for the study of river problems, but the verification on

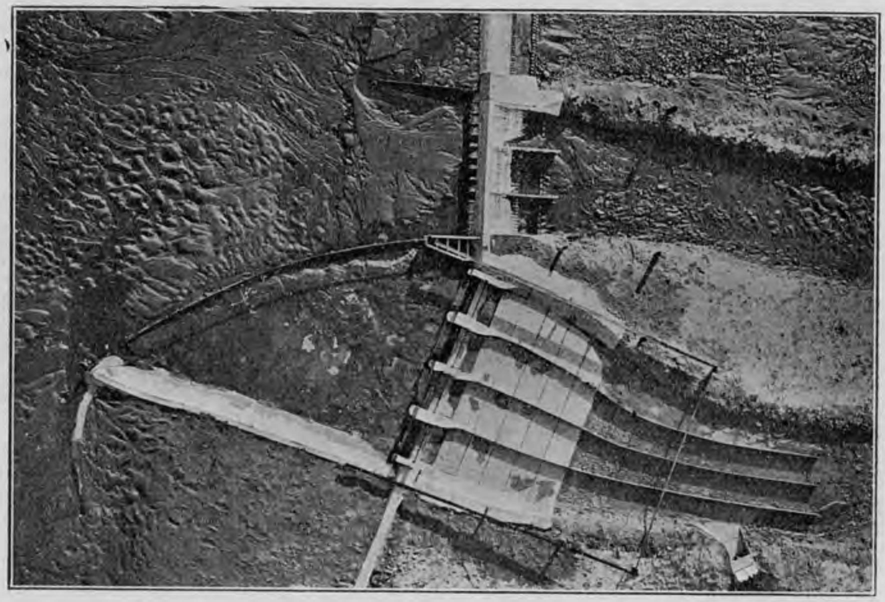

FIG. 45. — BUREAU OF RECLAMATION — ALL-AMERICAN CANAL INTAKE, IMPERIAL DAM. SCALE 1:40

prototype structures of results obtained in this manner are believed to be insufficient at the present time to justify complete confidence in the method. It was decided to make a model as large as the physical conditions at the site would permit, and to use a silt as fine as could be obtained at reasonable cost in the immediate vicinity of the model.

The material actually used was dredged from the South Canal adjacent to the laboratory where it had been deposited by the irrigation water diverted from the Gunnison River. The size of a typical sample of Colorado River silt, such as that which will be handled through the headworks at Imperial, ranges from 0.05 to 0.6 millimeters in diameter. To have reduced that by the scale ratio of 1:40 would have required a material in the model ranging in size from 0.001 to 0.011 millimeters. Such material in the model would have been impractical, since it would have been so small in size that it would have remained in suspension and been carried through the model, or if it would have settled, the rate would have been so slow as to require a test period too long to be practical. And then the cost of a material of those proportions would have been uneconomical to provide. Consideration was given to shipping a supply of the actual Colorado River silt to the model, but it would have been out of scale to practically the same degree as the material actually used which ranged in size from 0.08 to 2.0 millimeters. It was concluded that the indications of the formation of silt bars in the model were much more severe than will be experienced on the prototype, due to the use of silt as much out of proportion as the materials actually used. Since the size of material was held constant in so far as possible throughout the entire set of tests, it served well as a basis of comparison, and allowed a particular arrangement of headworks to be tested in approximately six hours.

The major problem in connection with the design of the All-American Canal intake structure were: (1) a distribution of trashrack flow as nearly uniform as possible along the length of the rack; (2) a minimum of silt carried through the racks and a minimum deposition of silt within the forebay of the gates; (3) a maximum of silt carried into the sluice gates and through the sluiceways to the river; (4) good hydraulic conditions of discharge through the sluice gates and head gates; (5) protection of the upstream apron of the dam from removal of the silt which will naturally deposit there and which it is desired to retain as an additional element of stability of the dam.

The solution of these different problems has been accomplished by the use of five major supplemental structures:

1. A trashrack curved in plan.

2. A wing-wall or abutment at the downstream end of the trashrack, separating the sluice gate forebay from the head-gate forebay so that flow from the former to the latter will not upset the balanced flow conditions below the gates.

3. A dike extending from the west end of the head-gate structure at a right angle to the structure for a distance of about 560 feet, the outer end forming the upstream terminal for the trashrack.

4. A training wall or groin at the east end of the sluiceway gate structure normal to the dam and extending across the upstream apron of the dam.

5. A submerged training wall extending upstream to the left of the sluiceway gates, to eliminate any tendency toward high velocities along the face of the spillway which might have a tendency toward disrupting good hydraulic conditions through the sluiceways and prevent the erosion of the silt deposition on the upstream apron.

During the course of the tests, several forms of the submerged training wall referred to in item 5 were tried, all with the thought of controlling and distributing the flow in the river as it approaches the trashracks. While the need of this particular structure was definitely indicated on the model, it was felt that no final solution of this particular problem could be reached by model studies, and that the construction of this feature should be postponed until its most desirable character, location and dimensions could be determined by experience with the river itself. In fact, it was concluded that the final operating program on these various features affecting flow control, and all like conditions affecting the operation of the discharge structures of the dam, must depend on actual experience with the river.

Simultaneous with the test program on the All-American Canal headworks, the model of one of the desilting basins and its appurtenances in the Gila Valley headworks was installed in the Arizona end of the Imperial Dam model.

At the time the model was constructed, certain features of the structure had not been detailed by the design department, but had been intentionally delayed until some model could be completed. Preliminary operation of the model brought out the fact that the sluicing of the desilting basin should be effected by controlling the inlet gates to maintain shooting velocity along the bottom of the basin with a small volume of water rather than by flushing with a large volume admitted at low velocity. Subsequent tests resulted in a change of the design of the crest under the inlet gates at the upstream end of the desilting basin to improve the flow conditions when the gates are open only a small amount and the water level in the basin is low. Material improvements of the flow conditions through the sluice gates were effected by altering the pier shape both upstream and downstream. The curved downstream ends of the piers for the head gates to the canal were studied until a design was evolved which changed the direction of the flow through an angle of 90 degrees with little disturbance. It was determined that the water into the canal could be admitted over the control gates with considerably less disturbance than that present when the water was admitted under the gates.

Rensselaer Polytechnic Institute

The hydraulic laboratory of Rensselaer Polytechnic Institute at Troy, New York, is operated under the direction of Prof. Grant K. Palsgrove of the mechanical engineering department. The laboratory occupies a floor space about 50 feet by 50 feet in plan, and is located in the basement of the mechanical engineering building. The equipment is arranged primarily for undergraduate instruction.

All the water used for experimental purposes is pumped from a cistern located below the laboratory floor and having a capacity of 2,000 cubic feet. A number of pumps are available, some being used to supply laboratory needs while others are more often the subject of individual tests. For low head work there are a Fairbanks-Morse duplex steam pump and a motor-driven Lawrence centrifugal pump, each of which can supply 2.2 c. f. s. at 18-foot head. The discharge lines from these pumps are connected to a steel tank of 3,300 cubic feet capacity located on the floor above the laboratory. A Worthington tandem duplex steam pump can supply 1.1 c. f. s. against heads ranging from 100 feet to 300 feet, and it is used as a high pressure water supply. The discharge of this pump is connected into a steel pressure tank 40 inches in diameter and 7 feet high, which is used with an air cushion to remove pulsations from the laboratory lines. The pipe systems are interconnected so as to allow great freedom in the use of the pumps for various experimental purposes.

There are several other pumps in addition to those mentioned above which are more frequently used as the subject of test. Of the reciprocating type there are a Marsh Simplex steam pump (12 inches by 6 inches by 12 inches) and a motor-driven Dean triplex pump (4 inches by 6 inches). All of these pumps are arranged along one side of the laboratory space.

At one end of the room there are installed a Platt centrifugal pump capable of supplying 0.44 c. f. s. at 75-foot head, and a Worthington three-stage centrifugal pump designed to deliver .09 c. f. s. at 250-foot head. Both of these pumps are electric motor-driven.

The Lawrence single-stage pump is tested by the students. The input to the pump is determined electrically, the efficiency of the driving motor having been determined. The discharge is measured with an 8-inch by 4-inch Venturi meter installed in the discharge line. It is finally possible to pass the flow over the 30-inch suppressed weir which is used in the reaction water wheel test, thus securing a check on the Venturi meter calibration. The suction and discharge pressures of the pump are read with piezometer tube gages. The speed of the pump is determined with a portable counter.

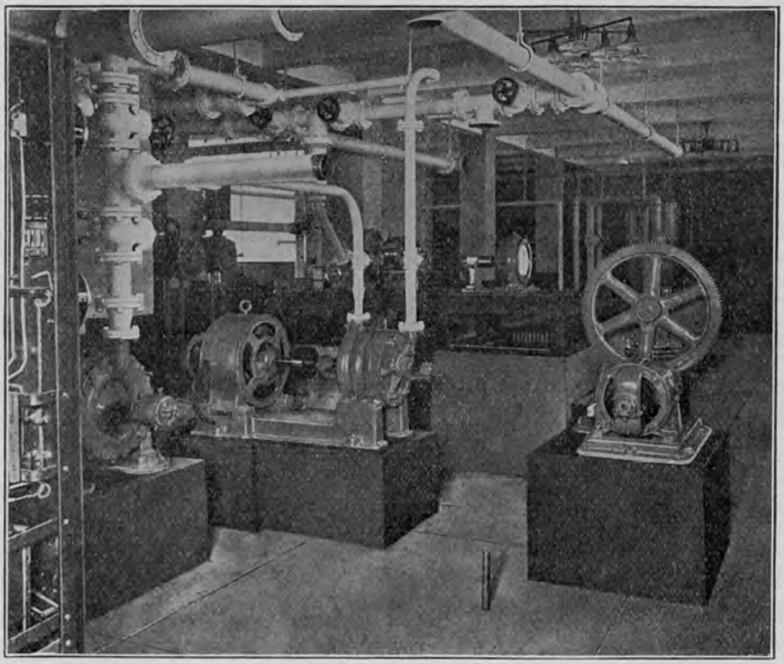

FIG. 46. — VIEW OF PART OF HYDRAULIC LABORATORY OF RENSSELAER POLYTECHNIC INSTITUTE

A reaction water turbine test is made on a 10-inch Leffel wheel installed in a globular casing. The water supply is taken from the steel head tank on the floor above, and the wheel discharges directly into a concrete weir flume. This flume is 30 inches square in section and about 45 feet long. Two sets of straightening racks are installed about 25 feet and 15 feet from the suppressed weir which is located at the end of the channel. The pressure head on the wheel is measured with a mercury manometer and the tailrace elevations with a float gage. The output of the wheel is determined with a Prony brake, spring scales and a portable counter.

Near the downstream end of the weir flume a pair of weighing tanks, each of 4,000 pounds' capacity, is installed. These tanks are used in series to determine the discharge from either a small single cylinder steam pump or from the triplex motor-driven pump.

Two pairs of concrete weir flumes are located near the center of the room and parallel to the water wheel weir flume. These pairs of flumes are set end to end and discharge through common central drains located at the center of the room. Each flume is about 15 feet long and 28 inches square in cross section.

An Escher-Wyss impulse water turbine complete with governor is set up over one of the flumes. It is used ordinarily as a demonstration unit. The weir in this flume is of the 90° "V" notch type.

Two 12-inch Pelton Doble glass-enclosed impulse turbines are mounted over two more weir flumes. The pressure at the nozzle is measured with a Bourdon tube gage. The output is determined with a Prony brake, scales and a portable hand counter. The discharge is measured in one case with a rectangular contracted weir, and in the other, with a semi-circular or parabolic weir. The fourth weir flume is equipped with a Parshall Venturi flume for investigations on open channel flow of liquids which are burdened with sand, sludge or other foreign material.

Over one of the flumes there is also installed a hydraulic gradient test. A supply tank 18 inches square in section and about 4 feet high supplies a diffusor, Venturi-shaped section, which tapers from 2 inches down to 1 inch at the throat and expands back to 2 inches again before discharging into the discharge standpipe which is about 8 inches square in section and 4 feet high. The quantity of water flowing is estimated from the Venturi equation applied to the diffusor. In the Venturi-shaped section there are about fifteen piezometers located at equal intervals and connected to open and gage glasses mounted on a permanent gage board. A plate type orifice may be substituted for the Venturi section, and the hydraulic gradient for both shapes of pipe section compared.

The equipment for performing the test on a nozzle and a Pitot tube is installed beside the weir flume. The nozzles used in the experiment are mounted on the end of a 4-inch pipe discharging vertically downwards through a switchway into a weighing tank of about 2,000 pounds' capacity. At the discharge from the nozzle a Pitot tube is inserted and arranged so that a complete traverse can be made of the jet in all four quadrants. Micrometer screws enable the diameter of the jet to be calipered, and the Pitot tube to be located.

A straight 2-inch line is mounted about 8 feet above the floor along the passageway through the middle of the laboratory. In this line are mounted a 2-inch by 1-inch Venturi meter, two plate type orifices, one small nozzle type orifice, a Pitot tube, a contraction in the pipe size to 1½ inches, and an expansion in section back to a 2-inch pipe. Permanent gage boards carry the water manometers which indicate the difference in pressures caused by the various pieces of equipment. At the contraction and the expansion of the pipe there are a large number of piezometers connected to suitable gages so that the hydraulic gradient is portrayed, and loss of pressure may be estimated. The discharge in the 2-inch line may be directed into the 28-inch flume, which is equipped with the 90° "V" notch weir, or into a weighing tank.

A current meter rating flume is situated in an open space adjoining the laboratory. The flume is 4 feet square in section and 90 feet long. The rating car, which carries the current meters, Pitot tubes or models for towing during calibration, travels on two steel rails mounted on either wall of the channel. The passage of the car along the flume, the time, and meter revolutions or towing resistance are recorded on a chronograph. The car, which is operated by hand, can attain speeds of about 10 feet per second.

Rodney Hunt Machine Company

The hydraulic laboratory of the Rodney Hunt Machine Company is designed for the determination of the operating characteristics of water wheels.

The laboratory is situated near Orange, Massachusetts, on a natural water privilege providing a test head of about 17 feet. Water for testing purposes is taken from Lake Rohunta which provides a storage of about 700 acre-feet with a 2-foot draw-down. This lake has a watershed of about forty-five square miles, and there are four other reservoirs upstream from Rohunta, providing about 1,000 acre-feet additional storage.

The building is of wood and brick mill construction. The main section is 26 feet wide, 24 feet long and 1½ stories in height. A single-story ell is added to this, 19 feet wide and 24 feet long.

Water is brought to the cast iron pressure box by a steel penstock, 4 feet in diameter and about 40 feet long. A motor-operated gate valve located just outside the building allows the wheel pit to be unwatered readily for inspection and alterations to the model.

The water wheel to be tested is mounted on the bottom plate of a closed cast iron pressure box 5 feet in diameter and 5 feet high. Various bottom plates are available for readily mounting any size or type of wheel within the capacity of the test flume. Wheels as large as 20 inches in diameter may be tested, but ordinarily 16-inch model runners are used. The shaft of the water wheel is hung vertically on two ball bearings, there being a guide bearing just above the runner, and a combined guide and thrust bearing at the upper end of the shaft. A plain stuffing box, lightly taken up, is used to make the shaft watertight where it passes through the top of the casing.

The water wheel discharges directly into the tailrace pit, where a space about 13 feet wide, 15 feet long and 6 feet deep is available for the installation of any desired form of draft tube. At the downstream end the pit tapers in width from 13 feet to 8 feet in connecting to the weir flume. This flume has parallel sides for a distance of about 20 feet. It is fitted with two sets of racks located about 10 feet and 20 feet, respectively, upstream from the downstream end of the flume. At this point an 8-foot brass-edged suppressed weir is installed 2½ feet above the floor of the flume. The head on this weir is read with a hook gage.

The head on the unit being tested is read in a small tower in the center of the building. The tail-water elevation is indicated by a float gage bearing a staff. The pressure in the wheel casing is read in an open end manometer. These gages are installed close together so that one observer takes both readings.

The wheel is loaded with a special form of water-cooled Prony brake. The upper shaft bearing is situated at the center of the brake pulley, so that the brake exerts practically no bending moment in the shaft. The scale beam, upon which dead weights are placed, operates a small piston valve, which, in turn, controls a servo-motor on the brake belt. Thus the brake automatically balances itself after the test load has been placed upon the scale beam. An oil dash pot connected to the scale beam assists materially in providing steady test conditions.

The revolution counter is driven directly from the shaft through a pair of beveled gears. The one pair of hands on the counter operates continuously with the shaft, one indicating the revolutions of the wheel and the other the hundreds of revolutions. The third hand is normally carried around with the revolution hand of the counter, but may be disengaged by means of a magnet. In operation, the magnetically controlled hand is operated automatically by a time clock, being disengaged at the end of each minute. This allows the operator to record the reading at that moment, and on the successive passage of the revolution hand the free hand is picked up again and carried along in synchronism. Thus it is possible for the operator to check the number of revolutions for each individual minute, and also for the whole three-minute test run. The time clock which operates the revolution counter also provides warning and signal bells used in synchronizing the readings of the test data.

There are four men on the test crew in normal operation. One reads the hook gage on the weir, a second takes the head readings, a third records the revolutions and computes the test results, while the fourth operates the dynamometer and insures the proper operation of all the test apparatus. The use of such a relatively large test crew is justified because the laboratory is at some distance from the factory and three of the men are customarily used in making alterations to the models under test.

This laboratory was installed in 1926 and has been in continuous operation since that time. Its use has been of great assistance in questions of design and operating details of water wheel runners together with their draft tubes and intakes, comparative values at varying gate openings being especially useful.

Experimental Turbine Testing Plant

This hydraulic laboratory was installed by the Shawinigan Water and Power Company, at Shawinigan Falls, Province of Quebec, and models of water turbines were first tested during the summer of 1924. This was at a time when high speed propeller turbines were beginning to supersede turbines of the Francis type under favorable operating conditions, the former type of wheel having been adopted for the company's plant at La Gabelle on the St. Maurice River. Comparatively little was known then of the causes and effects of cavitation in water turbines, and the decision to build such a laboratory — the first of its kind on the North American continent — was the outcome of the belief of the engineers of the company that tests of models under controlled operating conditions would be the basis of advances in the art of turbine building. The date of construction of the plant at La Gabelle, where four units of 30,000 horsepower each were installed initially at a head of 60 feet, was advanced owing to load conditions, so that delivery of power actually began about the same time as the experimental plant was ready for service. The testing season generally extends from May to November, work being suspended during the winter months. Dean Ernest Brown, professor of applied mechanics and hydraulics in McGill University, has been associated with the engineers of the company from the start of this project, and all testing has been done under his direction. The hydraulic engineers of the Dominion Engineering Works of Montreal have also been associated with many of the tests, and that company built all the experimental turbine equipment. The technical staff engaged in the tests has been drawn from the engineering division of the Shawinigan Water and Power Company, so that a large number have now had experience in such testing. While most of the work done has dealt with the Shawinigan Company's own problems, the facilities of the plant have been made available to other operating companies having special problems which the plant was equipped to handle.

The head at Shawinigan Falls, where the experimental plant is located, is about 145 feet, and a portion only of this is used. The building is a steel structure consisting of a cylindrical pressure tank in which the model is set. This tank is built integrally with the tailrace tank, in which the water level is controlled by stop logs and a movable baffle, and in which the draft-tube is placed. Water is supplied through a steel penstock 42 inches in diameter and about 150 feet long, from a forebay, near the headworks of the power plant, but separate from it. The headrace level is fairly constant, and the tailrace level can be varied by about 28 feet. The operating head ranges from about 53 feet to about 81 feet, giving a cavitation factor ranging from 0.73 to 0.15, a range which has proved sufficient for the work. The flow is measured by a Venturi meter calibrated by the volumetric method, using the tailrace tank as the collecting chamber, the Venturi head being read on a differential gage. Power is absorbed by a Heenan and Froude hydraulic brake. The head is measured by readings of a mercury pot gage connected to the pressure tank, and of a float gage in the tailrace tank. The tailrace level is recorded on a Bristol chart, throughout a test run of ninety seconds, the recording pen being operated by a relay in circuit with a standard clock, which also operates the magnetic clutch of a direct-revolution counter of the Veeder type, suitably geared with the turbine shaft.

All recording gages, brake equipment, office records and desk for computations are housed in a single-story wooden structure above the pressure and tailrace tanks. An operating staff of four is employed normally, three for recording observations and control of the brake,

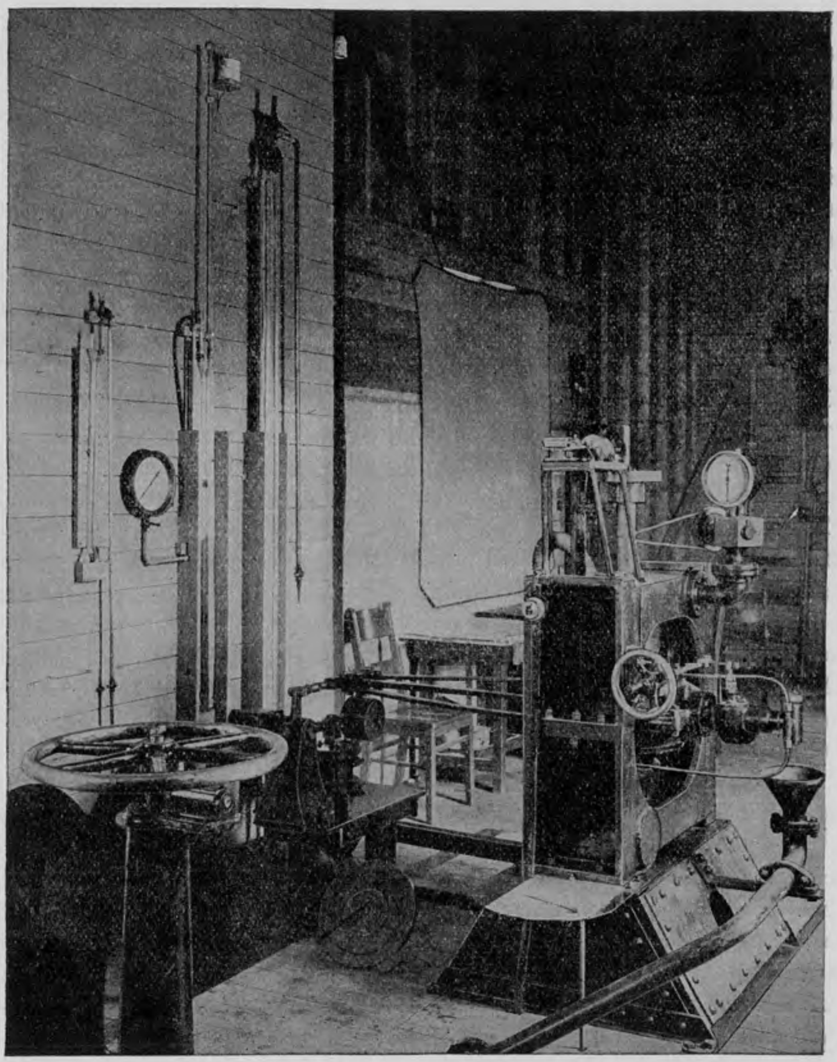

FIG. 47. — SHAWINIGAN FALLS — VIEW OF TEST ROOM, SHOWING VENTURI AND HEAD MANOMETERS AND FROUDE DYNAMOMETER

and one for computation and plotting of results. Approximately one day of eight nours is required for a complete power-efficiency test of a model with any given setting.

Early experience with the service units at La Gabelle provided many problems for the experimental plant. The draft-tubes are of the Moody type with central cones extending up to the runners. The cones, though reinforced, were broken off, and the concrete of the draft-tubes just below the runner was eroded in a band about 3 or 4 feet deep vertically and about 1 foot deep radially. The intensity of the destructive action was lessened as this erosion increased, the water in the eroded zone seeming to act as a buffer. The damage to the substructure had to be repaired, and heavy steel plate liners were installed and grouted in place. Severe pitting of the steel occurred in sixteen patches equally spaced circumferentially, and corresponding with the 16 guide vanes. Gradually the metal was eaten through and rivets were loosened. Despite the use of heavy plates and special anchorages, the liners were ultimately displaced and destroyed. Many lines of investigation were followed in the early stages of the experimental work on this problem. Specially designed pressure recorders of the diaphragm type, using high frequency currents in a differential electrical inductance bridge circuit, were installed in the throat of the draft-tube of one of the service units, where the destructive action was greatest. The variations of pressure on the diaphragms altered an air gap, and the unbalance in the inductive circuits was recorded by an oscillograph. No directly useful results were obtained beyond the establishing of the existence of variable pressures having a definite frequency of six cycles per revolution corresponding with the six blades of the runner. No measure of the pressures was obtained. In fact, the steel diaphragms of the recorders were quickly destroyed. Attempts were made to use this method, and also the piezometric effect of quartz crystals to measure pressure variations in the experimental unit, but in these tests, as in those on the service units, no cathode ray oscillograph, such as has been used successfully and more recently in other laboratories, was available at the date of the tests, and no directly useful results were obtained.

The conditions of flow in the runner and draft-tube of the experimental model have been explored in many different ways, such as (1) by using a Pitot tube of rugged design; (2) by illuminating the interior of the draft-tube and using direction recording vanes observed through glass portholes; (3) by sampling the gases in the draft-tube at eroded zones, and at zones of no erosion — distinct differences being obtained;

(4) by attempting to measure the pressure on rotating runner blades; and (5) by injecting small streams of sodium sulphide at different points to trace the path of the water by the blackening of paint.

In addition, tests have been made of the relative resistances of different metals to pitting, (1) by exposing them in the draft-tube to the severe action which occurs at a given head at some definite gate opening and speed; (2) by prolonged exposure under high vacuum in a Venturi throat, or at an elbow in a pipe line, or to high vacuum accompanied by vibration. Such tests can be classified as being of a research nature, and the aggregate results have been helpful. The greater part of the work, however, and by far the most productive from the standpoint of remedying the troubles in the service units, has been the systematic, patient testing of a large number of small models to determine the effect of changes in design. The upper section of the draft-tube, on which pitting or erosion took place, was cast separately to provide a readily removable piece about 18 inches high. This was painted with red Duco, and then with white paint, and provided a simple means of observing quickly the beginning of pitting, as the paint and even the Duco would be removed in a run of thirty minutes under the right conditions. The pitting always occurred in spots equal in number to the number of guide vanes, and it seems clear that zones of relatively low pressure are established immediately below the guide vanes where they overhang the throat. These zones of low pressure probably travel through the runner and appear in the draft-tube as zones in which the pressure is definitely lower than the general or average pressure. Voids appear to form in these zones, and the destructive action known as pitting follows the collapse of these voids. This, briefly, is the generally accepted view of the mechanism of the phenomenon known as pitting.

The laboratory procedure apart from these paint tests consists in making power-efficiency tests of given models, using successively smaller cavitation factors. The evidences of cavitation show in the power and efficiency curves as plotted on a speed base for any given gate opening, these curves breaking somewhat abruptly when cavitation appears. The speeds at which the breaks occur depend on the cavitation factor. Experience shows that the painted surfaces show no erosion, even after prolonged exposure under operating conditions, if the conditions under which cavitation occurs are not approached too closely. A brief exposure under conditions at which cavitation occurs, or is about to occur, results in rapid erosion of the paint. By patient observation of such erosion effects at gradually increasing gate openings, and their relation to the form of the power and efficiency curves, a definite technique develops which enables one quickly to interpret the curves in respect of the liability to erosion under any given operating conditions. Paint tests of several hours' duration can then be made under these conditions to check the conclusions reached from inspection of the curves.

The effects of changes in form and area of blades and hub, in the number and shape of guide vanes and in the draft-tube itself, — both in respect of contour and shape of cones or diaphragms, — have been determined by the methods described. Practical results of great value have been attained; for example, No. 5 unit, completing the installation at La Gabelle, was installed and put into service in 1931, and has operated since that date with no pitting of the draft-tube liners, and only slight pitting of the runner blades. There are 20 guide vanes, much thinner than the 16 used in the first four units installed in 1924. The runner is of slightly greater diameter and output, is set lower and in a cylindrical throat, blade angles are changed, blade areas increased, and the efficiency is improved.

The experience gained in No. 5 unit bore out the results of tests of models, and in 1934, after further experiment, the original runner of No. 2 unit was replaced. The original number of 16 guide vanes was, however, retained, but the vanes were made thinner. To date (1937) there has been no pitting of the draft-tube liner, and only slight pitting on the runner blades.

Further tests demonstrated that it would be practicable, in No. 3 unit, to change the guide vanes as in No. 2 unit, and to set the blades more steeply, at the same time making them longer. This change which is now being made (1937) is expected to increase the output by about 5,500 horsepower, and no troubles from pitting are anticipated.

As the result of the experimental work all the units at La Gabelle will ultimately be reconditioned. Large maintenance costs incurred in repairing at regular intervals the damage to the substructure have been eliminated. The cost of welding the small pitted areas on the runner blades is insignificant. Repairs will probably be needed at intervals of one to two years, and can be made without involving any outage of the units.

In addition to the special work described above in connection with the plant at La Gabelle, a series of tests has been made, using propeller wheels with as many as eight blades, to obtain information regarding the adaptability of this type of unit for heads much greater than that at La Gabelle. Tests of Francis runners with elbow and Moody draft-tubes have also been made in connection with future development of other power sites.

Finally, it can be said that while fundamental theories of the conditions of flow in water turbines have been extended greatly in recent years, tests of small models form the ultimate criterion in deciding the limitations governing an installation in practice. Long experience of such testing, while at times disclosing unexpected and unexplained results, leads to cumulative knowledge on which new developments can be soundly based. This, in the last resort, is the justification of such work as has been carried out at the testing plant of the Shawinigan Water and Power Company.

S. Morgan Smith Company

The hydraulic laboratory of the S. Morgan Smith Company, at York, Pennsylvania, has been designed for the testing of impulse and reaction water wheels, pumps, ejectors, special valves and similar hydraulic equipment. It is operated under the direction of Mr. George A. Jessop.

The laboratory is housed in a two story brick and concrete building 24 feet by 72 feet in plan. The water used in testing is stored in a sump built into the basement of the building. Two pumps are located in the basement, taking the water from the sump under a slight positive head. The first of these pumps is driven by a 75-horsepower induction motor, and is capable of delivering 22 c. f. s. under a head of 12 feet for use in the main water wheel test flume. The second pump is also motor-driven and can supply 3 c. f. s. into a 30-inch standpipe 110 feet high for use in testing impulse wheels. The discharge is regulated by gate valves located in the discharge lines of the pumps.

The main testing flume is built of concrete and is about 10 feet wide, 13 feet long and 12 feet high. The water is discharged into one side of the flume where a baffle chamber 3 feet wide is formed by a partition in the flume. There is an overflow weir 3 feet long in this baffle chamber, which helps materially in maintaining constant head during tests.

The unit to be tested is mounted on an adapter plate in the floor of the wheel pit, with the draft-tube discharging directly into the tailrace flume. A space 10 feet square in plan and about 5 feet deep is available beneath the flume for the installation of conical diverging, elbow or any other modern type of draft-tube.

The 7-foot weir flume, about 30 feet long, is connected at one side of the tailrace pit. Three sets of wooden baffles in the form of "fences" are installed in the weir flume. Below the "fences" four sets of window screen racks are located on about 4-inch center spacing. After passing through these screens there is a run of about 8 feet to the 7-foot suppressed weir which discharges into a 4-foot concrete channel which, in turn, discharges into the sump.

The 7-foot brass weir crest is carefully leveled. The zero of the hook gage which is used in reading the head on the weir is determined daily before commencing any tests.

The output of the water wheel is absorbed by an Alden dynamometer which is located on the operating platform built over the flume.

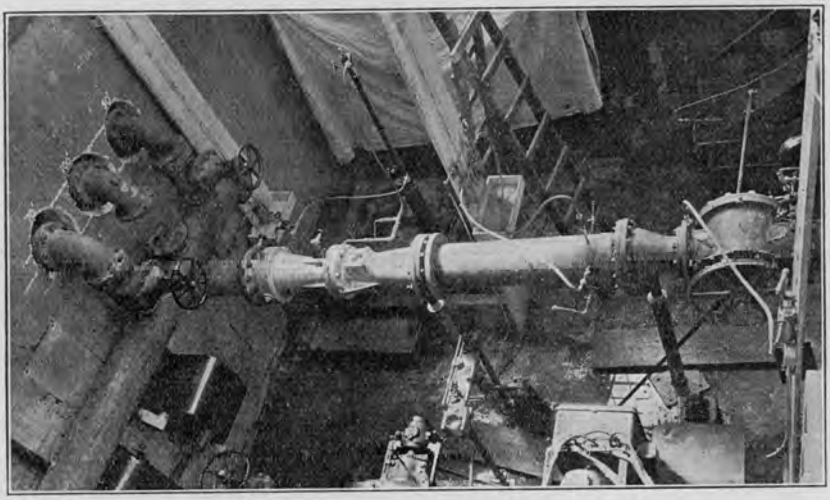

FIG. 48. — S. MORGAN SMITH COMPANY — TEST INSTALLATION OF A ROTOVALVE

The weight of the dynamometer is carried on ball bearings so that no added thrust is placed on the wheel bearings. The torque of the dynamometer is transmitted to a scale beam through a ball-bearing bell crank. The water supply for the brake is taken from a small standpipe mounted on the roof of the building so as to avoid the effect of any pressure pulsations upon the operation of the dynamometer. During a test the torque is held constant by an auxiliary discharge valve which is operated by the beam of the weighing system. As the beam deflects from the central position this valve is operated so as to bring the machine back into balance, resulting in very steady running conditions. The speed of the unit is determined with a large type Veeder counter which is driven by the wheel shaft through a magnetically operated clutch. This clutch is controlled by a time clock, thus eliminating personal error in the timing of the test runs. This same clock provides signals for the synchronization of the data which are taken during a test.

The head is measured directly by means of float gages. One carries a rod graduated in hundredths of feet, and its float chamber communicates with the tailrace of the wheel. The other float carries a pointer, and its chamber is connected to the head box. The pointer and scale are so arranged as to indicate the total head directly.

Three men are customarily used on a test. One reads the head on the weir. The second manipulates the weights on the scales, balances the dynamometer, and controls the timing of the test. The third man reads the head, computes and plots the test results. An electrically driven computing machine is used to facilitate the calculations of the results. As a further aid, reciprocal tables have been prepared of all quantities which normally are used as divisors, so that multiplication is the only computing operation.

The same apparatus and procedure is used as far as is possible in the test of impulse wheels. The water is brought to the nozzle in a pressure pipe, and the pressure head is measured with a mercury manometer. The same brake and counter are used in the power measurement, and the discharge is measured by the weir.

The entire floor space in the building is served by a ½-ton electric hoist which greatly facilitates the handling and placing of heavy pieces of equipment.

One runner and casing have been kept unchanged at the laboratory since 1922. Whenever any doubt arises as to the accuracy of performance of the equipment this calibrating runner is installed and tested. A composite curve showing the results of about ten such tests was exhibited, and the maximum spread of the points did not exceed one half of 1 per cent.

The facilities of this laboratory have recently been increased to allow the testing of pumps, valves, ejectors and similar hydraulic equipment. A 24-horsepower 3,600 r. p. m. electric dynamometer has been installed to measure the pump input during test. The pump discharge is measured by a 4-foot suppressed weir installed in the return channel connected to the sump. The headwater and tailwater levels are measured by means of differential float gages.

This laboratory has been used principally for water wheel tests since its construction, and has provided information required to materially improve the design of runners, intakes, draft-tubes and other turbine parts. In addition, research work on low head ejectors for use in vacuum flume settings has been conducted. Extensive tests of roto-valves have been made determining the losses through the valve and

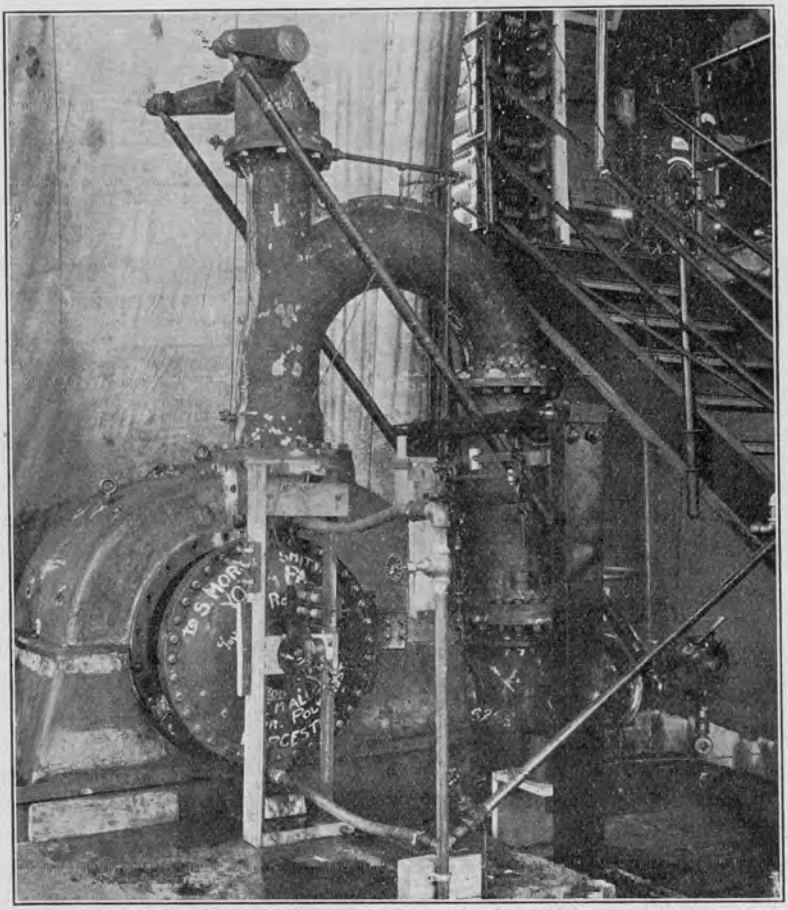

FIG. 49. — IMPULSE WATER WHEEL SET UP FOR TEST AT THE HYDRAULIC LABORATORY OF THE S. MORGAN SMITH COMPANY

the operating torque required. And finally turbine pressure regulators, or relief valves, have been tested to determine the coefficient of discharge and all the operating characteristics for hydraulic control and balance.

Stanford University

There are two laboratories for hydraulics at Stanford University, at Palo Alto, California. One, designed for the instruction of fundamental hydraulics, is operated by the civil engineering department of which Dean Samuel B. Morris is the head. The other, which is used in the study of hydraulic machinery, is used by the mechanical engineering department of which Prof. A. B. Domonoske is the head. Both laboratories are designed for undergraduate instruction.

The hydraulic laboratory of the civil engineering department of Stanford University is 50 feet by 140 feet in plan, with a ceiling height of 16 feet which allows the installation of a mezzanine floor along one side of the building. All of the water used is supplied by two motor-driven centrifugal pumps capable of supplying 4 c. f. s. under a head of 100 feet. Both pumps discharge into a 24 inch distribution pipe which supplies all the experimental equipment of the laboratory. After the water has been used in an experiment it is returned to the sump by means of rectangular channels in the concrete floor of the laboratory. These channels vary in width from 2 feet to 4 feet, and are used for a number of purposes. In the 4-foot channel are installed a 90° "V" notch weir and a 4-foot suppressed weir. One of the other channels is used for current meter work.

On the mezzanine floor there have been installed nine experiment stations which are very similar in construction and arrangement. Each station consists of a weir box and nozzle chamber which are supplied from the 24-inch main through a 4-inch line containing a Venturi meter. The steel plate weir boxes are 5 feet by 3.5 feet in plan, and 3 feet in depth. Racks and baffles provide quiet flow conditions in the tanks. The head on the weir is measured with a hook gage. The nozzle chambers are 24 inches in diameter and 6 feet in length, and operate with heads up to 100 feet of water. Various types of orifices, nozzles and short tubes are available for test. The discharge from the weir or nozzle is measured on the first floor. Four of the stations are equipped with pairs of volumetric tanks, each tank having a capacity of about 2,000 pounds. At two of the stations the discharge is measured by weighing tanks of 4,500 pounds' capacity. The other three stations are provided with a Kennicott water weigher, a Hammond meter and a Wilcox water weigher, respectively.

In addition to the above equipment there is a water meter testing stand and a pipe provided with suitable openings for a Pitot tube traverse.

Hydraulic machinery tests are made in the mechanical engineering department. The floor space occupied by this section of the laboratory is about 40 feet by 50 feet in plan. The water used in the experiments is stored in two sumps located in the concrete floor at opposite ends of the laboratory space. One of these sumps is 9 feet wide, 24 feet long and 16 feet deep, and is connected to the second sump by a tunnel 3 feet wide and 6 feet deep. The second sump is 9 feet wide, 24 feet long and 20 feet deep, and is divided into four sections by vertical steel diaphragms. Three of these sections are customarily used for volumetric measurements, while the fourth is connected to the sump tunnel. The suction connections of the various pumps are run into either sump or into the tunnel. Water may be discharged into the tunnel or into any of the sumps or volumetric tanks.

There are three experiments set up. The first is a test of a 12-inch Doble impulse water wheel. Water is supplied from the sump by a motor-driven, Byron-Jackson 2-inch, two-stage centrifugal pump capable of delivering 0.5 c. f. s. under a head of 200 feet. The water discharged by the impulse wheel falls into a steel tank 4 feet by 6 feet in plan, and 2.5 feet deep. Suitable baffles provide quiet approach conditions for a 9-inch contracted, brass-crested weir mounted in the end of the tank. The discharge from the weir is carried back to the sump by a concrete channel in the floor of the laboratory. The pressure at the nozzle of the water wheel is measured with a Bourdon tube gage. The output is measured with a cradled electric dynamometer and a hand counter.

A pump test is performed on a Peerless 3-stage, 6-inch turbine deep well pump which is also used as an additional source of supply for laboratory use. The power input to the pump is determined with an electric dynamometer and a revolution counter. The pump discharge is measured by one of the weirs or in a bank of measuring elements which include a 3-inch Venturi meter installed in a 3-inch line, and sharp-edged orifices installed in 3-inch, 4-inch and 6-inch pipes. These meters have been calibrated by weighing tank measurements. Pressure differences are determined either with mercury manometers or by a scale actuated by a sylphon bellows and calibrated by a dead weight tester. The suction and discharge pressures of the pump are read with calibrated Bourdon tube gages.

The third test given to the students is the reaction water wheel experiment. A motor-driven Pomona 12-inch centrifugal pump, capable of supplying 4.0 c. f. s. at 30-foot head, takes water from the sump and delivers it to a pressure tank about 4 feet in diameter and 20 feet high. This tank helps to provide steady flow conditions to the water wheel. A 14-inch supply pipe connects this tank with the 15-inch vertical Leffel water wheel installed in a globular pressure casing. The draft-tube of the wheel discharges into a plate steel tank 5 feet by 12.5 feet in plan, and 3 feet deep. Baffles and racks are used to provide quiet conditions of approach to an 18-inch contracted, brass-edged weir mounted in the end of the tank. The output of the water wheel is measured with a rope brake and a hand revolution counter.

There are several other pumps which are available for additional water supply or for test purposes. These include a 6-inch double suction, single-stage Fairbanks-Morse horizontal centrifugal pump direct-connected to an electric motor and capable of delivering 1.8 c. f. s. A Wesco 2½-inch centrifugal pump and a Viking 3-inch positive displacement pump are available without motors. In this same laboratory there is a Sprague dynamometer rated at 100 horsepower capacity at 2,000 r. p. m., and pumps may be attached at either end of this machine.

Stevens Institute of Technology

The hydraulic laboratory of the Stevens Institute of Technology at Hoboken, New Jersey, is part of the mechanical engineering laboratory, and is used primarily for undergraduate instruction.

Hydraulic experiment set-ups are located on both the first and second floors of the laboratory. On the first floor are tests of weirs, orifices, Venturi meters, as well as a test of an impulse water wheel.

A 10-inch Pelton water wheel is mounted directly over a vertical cylindrical plate steel volumetric tank 44 inches in diameter and 6 feet high. Water is supplied to the wheel from another large tank by a single cylinder reciprocating steam pump. A 1-foot by 5-foot tank is in the line between the wheel and the pump to smooth out the pressure pulsations. The water volume through the wheel is measured by a gage glass mounted on the outside of the receiving tank. The pressure at the water wheel is read with a Bourdon tube gage. The power output of the wheel is determined with a Prony brake and a portable counter.

In the flow calibration set-up a steel weir flume 12 inches square in cross section and about 8 feet long is suspended from the ceiling with the discharge end located over a pair of weighing tanks each of about 400 pounds' capacity. Various forms of weirs, "V" notch, rectangular and parabolic, may be located near the downstream end of the flume. A 2-inch by ¾-inch Venturi meter is installed in the supply line of the flume, the differential pressure being read with a mercury manometer. Both the Venturi meter and the weir are calibrated against the weighing tanks. A similar set-up is available for calibration of a submerged orifice.

A second impulse water wheel test is performed on the second floor of the laboratory. Two centrifugal pumps are available, either of which may be driven by an electric motor mounted between them. The first pump supplies 0.25 c. f. s. at a head of 115 feet, while the second supplies 2.7 c. f. s. at 23-foot head. The high pressure pump is connected to the impulse wheel by a 2-inch line containing a 2-inch by 1-inch Venturi meter. The low pressure pump supplies the upper weir flume directly through a 6-inch pipe.

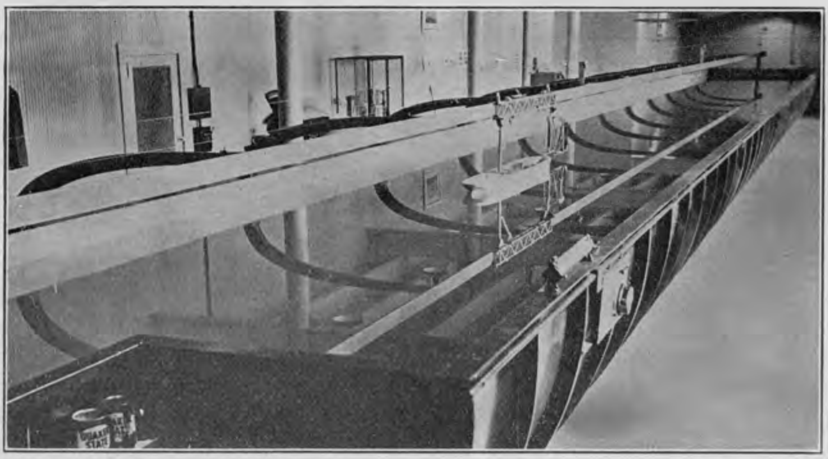

FIG. 50. — STEVENS INSTITUTE OF TECHNOLOGY — VIEW OF THE TOWING TANK AND EQUIPMENT

The 12-inch impulse water wheel is tested with a Prony brake, scales and a portable revolution counter. The discharge from the wheel falls into the upper steel weir flume which is about 3 feet wide, 3 feet high and 10 feet long. A 53° "V" notch weir is located at the downstream end of the tank. This tank is elevated on framing so that the bottom is about 5 feet above the floor level. The discharge of the "V" notch weir falls into a second flume which is of the same size but 2 feet lower in elevation. A rectangular suppressed weir is located at the end of this flume and discharges into a steel sump which is located on the floor and is about 4½ feet high, 4 feet wide and 5 feet long.

With this equipment the operating characteristics of the impulse water wheel are determined, and the indicated discharges of the Venturi meter and the two weirs are compared.

A test is made comparing the performance of metering elements with air as a fluid. A single-stage blower operating at about 4,000 r. p. m. supplies air under pressure to a 3 inch pipe in which are mounted a sharp-edged orifice plate, a 3-inch by 1½-inch Venturi meter, and a well-rounded discharge nozzle. Differential pressures are measured with vertical water manometers and slope gages. The electric motor driving the blower is cradled so that the operating characteristics of the blower may be determined.

In this same section of the laboratory, equipment for demonstration of viscous and turbulent flow has been installed. A head box about 18 inches square in section and about 3 feet long supplies water to a 1-inch horizontal glass pipe about 12 feet long. A bell-mouth entrance provides quiet entrance conditions, and dye may be injected quietly at this point. The discharge of the system is controlled by a throttling valve and a quick acting valve at the downstream end. Thus the effect of the sudden acceleration or deceleration of the flow may be demonstrated as well as steady flow conditions.

A towing tank for the testing of ship models has recently been installed under the direction of Prof. K. S. M. Davidson. The tank is built of plate steel and is semi-circular in form. It has a width of 9 feet, a depth of 4½ feet and a length of 101 feet, and is adapted for the testing of models up to about 7 feet long.

The models are towed by a small carriage traveling along a steel track which is mounted over the center of the tank. The towing carriage is operated by a cable which, in turn, is driven by a synchronous motor and a multi-step pulley. The speed of the carriage for each pulley size has been determined, and that value is used as the model velocity during test. Model speeds up to 13 feet per second are possible.

The resistance of the model to motion is measured with an indicating traction dynamometer attached between the carriage and the model. A maximum force of 4 pounds can be measured with this device. Similar dynamometers are available for the measurement of lateral forces on the model when desired.

Two details of the work which has been carried out in this tank are of particular interest:

First, to promote or to insure complete turbulence, the models are ordinarily tested with strips of coarse sand attached at the bow. It is the usual practice to test a given model with two or three different widths of strip and then to extrapolate to zero width a curve of resistance coefficient difference versus strip width. In this way the turbulent resistance of the clean hull can be determined. The change of resistance coefficient caused by changing the strip width has been found to be substantially independent of the speed-length ratio.

Second, special attention has been given to the resistances of sailing yacht forms. The resistances of the yacht form, when moving at various combinations of speed and heel angle, are important in design. Also, because a particular heel angle is associated with a particular lateral sail (or water) force, it must be associated with a particular curve of leeway versus speed. All of these factors have been duplicated in the model tests at the Stevens testing tank.

Tennessee Valley Authority, Engineering Data Division, Hydraulic Laboratory Section

The hydraulic laboratory of the Tennessee Valley Authority is located in the town of Norris, Tennessee, and operated under the supervision of George H. Hickox. It was designed and installed for the purpose of testing the hydraulic details of design in connection with the development of the rivers in the Tennessee Valley by the Federal government. The model work done at this laboratory falls into two classifications, — first, the test of hydraulic details, such as spillways and protective aprons, which are performed in a large glass-sided flume; and second, river model tests to check the performance of the whole structure in the river. Although the laboratory has been in service for less than two years it has well-equipped shops, drafting rooms and photographic apparatus, enabling the test work to be handled efficiently.

The hydraulic laboratory is housed in a single-story building 240 feet long and 60 feet wide in plan. There is a soil mechanics laboratory and a series of offices and a dark room along the side of the building which reduce the free width of the building to about 40 feet throughout most of its length. However, all of the floor space is not yet in use, so that there is no dearth of space for test purposes. The building is of the single monitor roof construction which provides good illumination for pictures.

The water supply for the experiments can be taken from two independent sources which are supplied from a common sump. There are three motor-driven centrifugal pumps which are housed in a separate building at one end of the laboratory. Two of these pumps can furnish a discharge of 8 c. f. s. to a constant head tank which is located on a mezzanine at the same end of the laboratory. This constant head tank is 10 feet by 14 feet in plan, and equipped with a large number of U-shaped troughs which constitute a spillway crest providing close control of head. A 12-inch pipe line distributes water from this tank to any experiments which might be set up in the laboratory.

The third centrifugal pump supplies 23 c. f. s. through a 20-inch pipe to the glass-sided flume. This flume is 8 feet square in cross section and 120 feet long. At the inlet end of the flume there is a constant head tank equipped with a long spillway which helps to keep the discharge into the flume constant. The water then flows through stilling

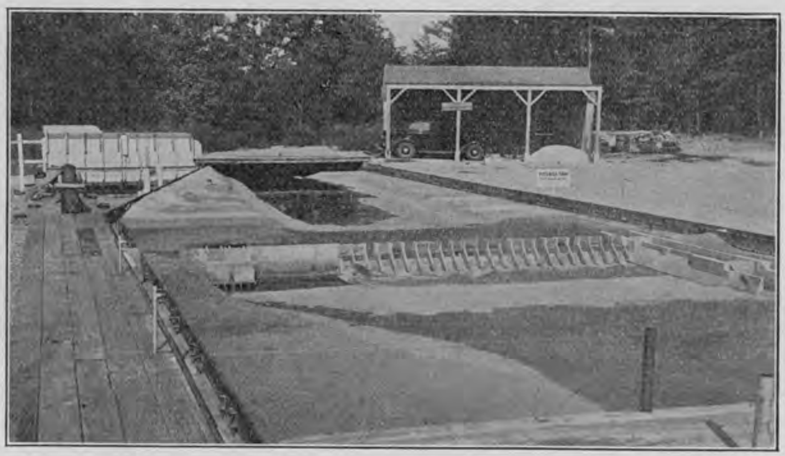

FIG. 51. — TENNESSEE VALLEY AUTHORITY — GENERAL MODEL OF PICKWICK LANDING DAM. MODEL RATIO 1: 100

racks to an 8-foot suppressed weir which has been calibrated by a volumetric tank at the further end of the flume. After passing over the weir and through stilling baffles, the water has a run of 40 feet before the glass-sided section of the tank is reached where the models are customarily located for test. Beyond the model there is a run of about 35 feet to the end of the steel flume where the water can be discharged into a volumetric tank having a capacity of 2,000 cubic feet, or else directly into the concrete return channel to the sump. The 8 c. f. s. delivered by the two smaller pumps can also be discharged into this flume ahead of the measuring weir, making a total available water supply of 31 c. f. s.

Typical of tests made in the glass-sided flume is a 1:25 model of the spillway for the Pickwick Landing Dam which has been tested for discharge and erosion characteristics. The outstanding feature of the test installation is the use of one pier made of pyralin where the model adjoins the glass side of the flume, thus allowing full visibility of the flow conditions between the piers. The dam itself is made entirely of metal so as to avoid trouble with swelling such as occurs with the use of wood. Changes are made in the bucket and apron with sheet metal forms bolted or soldered into place. Other models have been made of concrete, temporary features being reproduced in concrete, metal or wood as conditions required. The gravel in the tailrace which is used to indicate relative erosion is between one fourth inch to three eighths inch in diameter. It is believed at this laboratory that any larger size of gravel in the bed would not give a satisfactory indication of true conditions of erosion.

River models may be built inside the laboratory, and three dam sites have been modeled and investigation made. These are usually movable bed models, although the bed is paved for certain tests where movement of the bed is undesirable. The movable bed material selected is a uniform fine sand. The models are constructed in a basin formed by a wall of movable concrete blocks. Topography is reproduced with the aid of adjustable templates which are carried on horizontal rails located at each side of the model. The template consists of a stiff wooden rail supporting a number of adjustable vertical rods. These rods may be spaced at 3-inch intervals and are set so that their lower ends outline a section of the river bed. A suitable scale facilitates setting the rods. Paving is accomplished by sifting a thin layer of dry cement on the moistened river bed which has already been molded to shape. This layer hardens, forming a crust of neat cement about one sixteenth inch thick, which is entirely suitable where there is not excessive velocity or turbulence. The scale of these models is as large as 1:100.

Water for these tests is taken from the 12-inch distribution system which is connected to the constant head tank. The discharge is measured as it flows into the model from a steel head box containing a "V" notch weir which has been previously calibrated.

Smaller models are tested in a flume 3½ feet square in section and 65 feet long, which is also supplied with water from the constant head tank. It is provided with one glass side so that operation of the models under test may be observed. It has been used for preliminary testing of the spillway models on a small scale and for a 1:50 model of a head-increaser type of power house. This power house utilizes the excess water available during times of flood to increase the effective head on the turbine during these periods.

A general model of the Pickwick Landing Dam has been constructed and tested in an open space at one end of the laboratory near the pumping plant. The model ratio is 1:100. It is largely a fixed bed model having a small movable bed section near the dam. There are two things about this model test which are unique. In the first place,

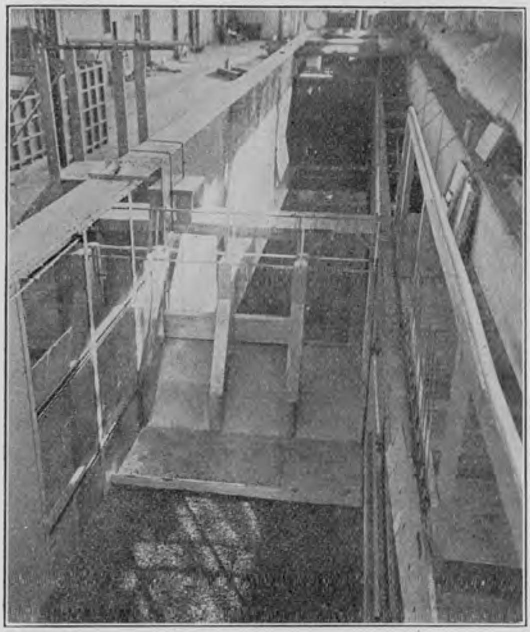

FIG. 52.—TENNESSEE VALLEY AUTHORITY—VIEW OF 1:25 MODEL OF PICKWICK LANDING DAM JUST INSTALLED IN THE 8-FOOT GLASS-SIDED TESTING FLUME. NOTE THE USE OF PYRALIN PIER NEXT TO GLASS WALL

the power-house structure and spillway were made of concrete cast in molds. Thus one spillway bay mold was constructed and a number of concrete sections cast. A spillway pier mold was similarly constructed, and so forth, for the other details of the hydraulic structure mentioned. This method of construction allows the complete model to be made quite cheaply and of a material which is not bothered by the absorption of water.

The other detail of importance is the manner of obtaining flow pictures. A plate camera is mounted on a light framework above the model and pointed vertically downward. The entire model is divided up into squares, each of which is covered by the field of the camera when it is mounted in the proper position for that square. With steady flow conditions, confetti is thrown upon the water and an exposure of a definite length of time, such as one second, for instance, is used in securing the picture of the flow directions and magnitudes as indicated by the confetti surface floats. Thus, knowing the time of exposure and the geometrical relations of the set-up, the actual surface velocities in the model can be measured in the photographs. These photographs of the individual squares of the model are properly trimmed and mounted so that a composite picture of the flow conditions throughout the model is presented in one illustration.

While this laboratory has been in existence only about two years, it has very good equipment for the construction and operation of models. The use of wood in the construction is avoided, metal and concrete being used wherever possible. The shops are well equipped for all types of model work. The machine tools available include three lathes, — a precision bench lathe, a speed lathe, and a 16-inch metal lathe, — bench drill press, 42-inch brake, 36-inch rolls, small shears, portable electric drills, and an oxyacetylene welding torch. Similarly, the photographic department is well taken care of. A large darkroom is provided with complete equipment for developing, printing and enlarging work. A good plate camera and an excellent moving picture camera are included in the equipment. In connection with their moving picture camera an interesting relay has been made. A contact wheel, rotating once a minute, was made which allowed from 1 to 60 impulses per minute to be used. This contact wheel operates two relay mercoid switches, one closing a little ahead of the other and continuing in contact a little longer. This first contact energizes the photoflood lights which might be necessary in the taking of the picture. The second contact operates the single frame release of the camera through a solenoid. In this way it is possible to get accelerated action pictures of such phenomena as erosion of the model bed during the course of a test without the waste of a great deal of film.

University of Toronto

The hydraulic laboratory at the University of Toronto, Toronto, Canada, is operated under the direction of Prof. Robert W. Angus, head of the department of mechanical engineering. This laboratory occupies two floors, each 40 feet by 112 feet. While designed primarily for undergraduate and graduate instruction, its facilities are also adapted to scientific and commercial research.

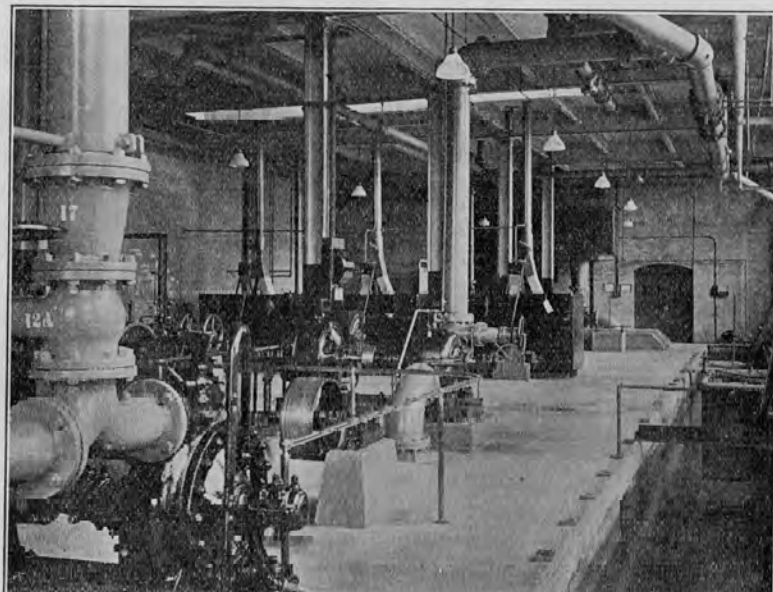

FIG. 53. — UNIVERSITY OF TORONTO — BASEMENT FLOOR, SHOWING PUMPING EQUIPMENT, VOLUMETRIC TANKS AND WATER WHEEL TESTING FLUME

All the water used for experimental work is pumped from a sump which is located below first floor level in one corner of the building. There are several pumps located on the first floor, of which two pumping units are belt connected to a 125-horsepower Belliss & Morcom steam engine. Each pumping unit consists of 2 two-stage pumps mounted on a single base and driven by a single pulley. Each two-stage pump is so constructed and connected that it may be driven and used separately, discharging 1 c. f. s. at 125-foot head. The piping is so arranged that all the units may be connected in series, series-parallel or parallel, depending on whether a large discharge or a high pressure is desired. The maximum working pressure is about 550 feet, with a discharge of 1 c. f. s. The maximum discharge of 4 c. f. s. is obtained at a head of 125 feet. In addition to this pump combination there is a motor-driven pump capable of delivering 6 c. f. s. at a head of 80 feet. These pumps are all connected into a plate steel pressure tank 5½ feet in diameter and 34 feet high, which is used with an air cushion to obtain quiet flow conditions. Several outlets are provided for various uses.

On the second floor, an Escher-Wyss reaction water wheel is directly connected to this pressure tank with a 14-inch pipe. The horsepower output of the wheel is measured with a rope brake bearing on a set of platform scales, and with a portable counter. The pressure at the wheel case is measured by mercury and water columns. The draft tube discharges into a steel weir flume 6 feet wide, 3 feet deep and 21 feet long. Racks provide quiet approach conditions to a 4½-foot contracted weir located at the downstream end of the flume. The weir discharge may flow either directly to the sump or else to a pair of weighing tanks which may be used in series, each holding 240 cubic feet. These tanks have been used for weir calibration and other direct weighing. All of the valves are operated by hydraulic servo-motors controlled at the weighing tanks.

A large flanged nozzle designed for the ready installation of sharp-edged orifices, and also for research and commercial tests, is mounted in the side of the pressure tank. The discharge falls directly into the weir flume described above, and may be weighed in the tanks if desired.

Two impulse water wheels are available, the larger being a Pelton wheel delivering about 10 horsepower under 160-foot head, and the smaller a Doble wheel delivering about 2 horsepower under the same conditions. The cases of both wheels have one complete glass side so that the actual operation of the jet on the buckets may be observed. Both wheels are equipped with hand-operated regulating nozzles. The discharge of each wheel is caught in the hollow steel base and flows into a steel weir tank 3 feet square in cross section and about 10 feet long. The output of each wheel is measured with a rope brake and a portable counter.

Beyond the impulse wheels there is installed a pipe line for Venturi and hydraulic gradient instruction. A 3-inch supply line connects with a 3-inch by 1¼-inch Venturi meter, which in turn discharges into a straight run of pipe which reduces to 2 inches and enlarges again to

3 inches. Thereafter, the pipe discharges in one of the weir flumes for measurement. Differential manometers, and also open-topped water piezometers, are provided to determine the hydraulic gradient and the losses. The laboratory also contains a Venturi meter flow recorder and integrator of commercial design.

Beyond this equipment there are located three steel tanks used for instruction on the coefficients of a 90° "V" notch weir, sharp-edged orifices and various mouthpieces, and a rectangular contracted

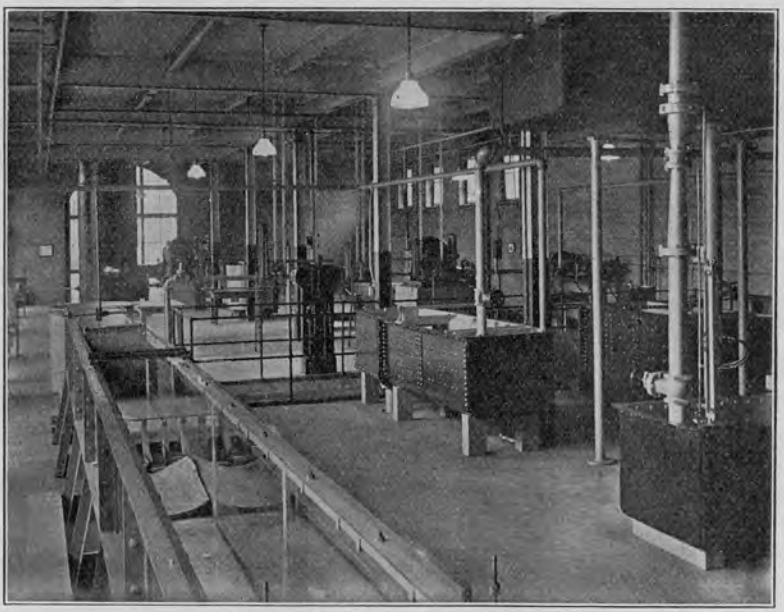

FIG. 54. — UNIVERSITY OF TORONTO — FIRST FLOOR, SHOWING GLASS-SIDED FLUME, WEIR AND ORIFICE TANKS, WITH REACTION AND IMPULSE WATER WHEELS IN THE BACKGROUND

weir. All of the tanks are about 12 feet long. The first two are about 3 feet high and 3 feet wide through most of the length, while the last is 3 feet square in cross section throughout. The water supply for these tests is taken from an open plate steel tank 5 feet by 3 feet in section and 15 feet long suspended near the ceiling of the second floor. The discharge of each test passes through the floor to a pair of volumetric tanks located on the first floor. Each of these tanks has a capacity of about 60 cubic feet. The drain valves and the switchway for each pair of volumetric tanks are operated by a single control lever.

Near these weir tanks there is installed an experimental motor-driven centrifugal pump which discharges through a 4-inch pressure line in which is installed a 4-inch by 2-inch Venturi meter. An open steel tank serves this pump as a sump.

On this same floor a glass-sided flume is available for tests of model spillways and studies of open channel flow. The flume is 18 inches wide, 24 inches deep and 30 feet long.

On the first floor of the laboratory there is located a complete reaction water wheel test flume. A motor-driven Moody spiral pump discharges up to 12 c. f. s. into a steel headrace tank about 3 feet by 4 feet in section and about 15 feet long. This channel connects with the concrete open flume, about 8 feet square in cross section, in which the water wheels are mounted. The draft-tube discharges directly into a 5-foot concrete weir flume about 25 feet long. Racks provide quiet flow conditions for the 5-foot suppressed weir. The head on the unit is measured with a combination of a manometer connected to the flume and a float gage in the tailrace. The output of the wheel is measured with an Alden dynamometer and a mechanically driven counter. The operating head is about 10 feet. Two runners, a reaction and a propeller type, are available for test and may be installed in the same setting. The laboratory also contains a complete Kaplan unit.

An open flume, 5 feet wide, 4 feet deep and 110 feet long, is constructed in the concrete of the first floor. Arrangement is made for a suppressed weir to be located at one end for the measurement of large discharges. Current meters are rated in this channel by the students under static conditions and used with water flowing.

Finally, there is a 2-inch hydraulic ram which is the subject of a student test. The water pumped and the water wasted are measured. The supply head is measured with a water manometer, and the discharge head with a calibrated Bourdon tube gage.

Tufts College

There are two hydraulic laboratories at Tufts College, Medford, Massachusetts, which are used for undergraduate instruction. These laboratories are operated under the direction of Prof. C. H. Holmberg of the civil engineering department.

The first of these laboratories is located in the basement of the main engineering building directly below the hydraulics classroom, and is used for class demonstrations as well as for student experiments after the primary hydraulics course. The room used for this purpose is 48 feet by 23 feet in plan, with about a 10-foot ceiling. Practically all of the apparatus is located along one side and one end of the room, leaving about one half of the floor space for tables, benches and storage.

The water used in this laboratory is kept in a channel 4 feet wide, 3 feet deep and 44 feet long. The channel is divided in two sections by a dam located near the center, in which is mounted a rectangular contracted weir.

Near one end of the flume is located a motor-driven pump supplying 1 c. f. s. at 20-foot head. The motor is equipped with a water-cooled pulley and flexible coupling which may be readily disconnected, allowing the motor to be calibrated in place.

This pump discharges into a 4-inch header to which two pipes are connected. The first expands from 4 inches to 6 inches for a run of 10 feet, contracts to 4 inches for a run of 6 feet, and discharges through a 4-inch by 2-inch Venturi meter to another 4-inch header at the downstream end. The second pipe is 3 inches in diameter throughout and connects both headers. Both of these pipes are carried on supports over the flume, and valves allow either pipe of the system to be used. The downstream header is connected to a small constant head tank mounted near the ceiling. It is 6 feet long, 24 inches wide and 20 inches deep, and equipped with one V-shaped trough spillway running the length of the tank.

A connection is also provided at the header for the installation of either a nozzle or a pipe discharging into a weighing tank beside the flume. When the nozzle is used the jet is caught in a deflecting hood, and the water discharged back into the flume. The steel weighing tank is 4 feet by 5 feet in plan, 28 inches deep and mounted on a set of 2,000-pound scales.

A 12-inch glass-encased Pelton water wheel is mounted over a small concrete weir flume which, in turn, is mounted over the main channel. The section of this channel above the dam has been calibrated volumetrically to permit determination of the coefficient for the Venturi meter and the nozzle precisely. The pressure at the nozzle is measured with a calibrated Bourdon tube gage. Nozzles of different diameters are available to vary the discharge characteristics. The discharge of the Pelton wheel falls into the weir flume which is 14 inches by 12 inches in cross section and 4 feet long. At the end of this flume is mounted a 6-inch "V" notch weir. The output of the wheel is determined with a Prony brake, scales and a portable counter.

The water supply for this Pelton wheel test may be taken from a 3-inch connection to the city water service, or provided by two motor-driven pumps in the laboratory. The first of these pumps is a 3-horsepower triplex pump capable of delivering 20 gallons per minute at 250 pounds per square inch pressure. This pump is also used to demonstrate the slip characteristics of this type of pump. The second pump is a 7½-horsepower, 3,450 r. p. m., motor-driven, single-stage centrifugal pump which delivers about 0.5 c. f. s. at a head of 50 pounds per square inch, and has a maximum or shut-off pressure of 75 pounds per square inch.

This centrifugal pump also delivers water through a 1½-inch pipe to a wooden channel, 8 inches wide, 6 inches deep and 20 feet long, located at the south end of the laboratory. A salt solution is forced from a small pressure tank into the upper end of the channel, and the time of its passage between two sets of electrical terminals is determined by a portable salt-velocity apparatus. There is also a cross connection between the city water supply and the low pressure laboratory system.

Over one end of the flume a small open concrete box was installed for the tests of an experimental reaction water wheel. The box is 40 inches square in section and 2 feet deep. This piece of equipment is about to be rebuilt. In the corner is a small head tank about 15 inches in diameter and 2 feet high. It is located about 8 feet above the floor and is connected by means of a 1-inch pipe to a 1-inch hydraulic ram. The head on the ram is measured with a water manometer, and the discharge head with a Bourdon tube gage. The water pumped and the water wasted are measured.

At this same end of the laboratory there is located an experiment upon viscous flow in glass pipe. Two wooden tanks 3 feet by 4 feet in section and 2 feet deep are connected by 8 feet of 1½-inch glass tube. The tube is provided with a bell mouth at the intake, and dye is injected to show the flow conditions existing. The downstream tank is provided with a ½-inch drain by which the discharge is regulated.

An experimental filter 12 inches square in cross section and 6 feet high is located at one end of the room. One side of this filter is made of plate glass so that the action may be readily observed. Four-inch hand holes are provided at 1-foot intervals. A small ¾-inch motor-driven centrifugal pump provides the water supply for this test.

On the floor beside this filter is located a model sedimentation box 3 feet by 4 feet in plan, and 2 feet deep.

The second hydraulic laboratory at this college is a general purpose low head laboratory primarily designed for student experimentation and thesis work in river hydraulics. It is located in a part of the basement of the music building of the college. The floor space available for this purpose is 50 feet by 38 feet, with an ell 12 feet long and 10 feet wide projecting on one side. Extension area is available for future staff research on commercial projects.

Water is supplied for test purposes by a 15-horsepower motor-driven single-stage centrifugal pump capable of supplying 4 c. f. s. under the created head of about 15 feet. The pump is mounted directly over the sump which is 5 feet wide, 12 feet long and 4 feet deep. A channel 42 inches wide and 33 inches deep is laid in the floor from this sump along one side of the room. Two side channels are led off from this main channel to serve as returns from the overflow of the constant head tank and from the various experiments. These two channels are 28 inches by 18 inches and 30 inches by 24 inches in cross section, respectively.

The 8-inch discharge of the pump contracts through a conical reducer to 6 inches in diameter and then expands to 10 inches. The conical reducer is fitted with piezometers and calibrated as a Venturi meter. The 10-inch pipe delivers the discharge of the pump into the constant head tank which is located near the center of one side wall of the room. Two Pitot tube stations are provided in the 10-inch discharge pipe for a check of the discharge. The constant head tank is 11 feet long, 5 feet wide and 42 inches deep, and is equipped with 72 linear feet of V-trough overflow weir crest providing constant head conditions. This tank is elevated on legs providing a head of about 8 feet to the operating floor. A number of independent 4-inch and 6-inch connections are provided in the tank so as to keep the various experiments as independent of each other as possible.

A number of small experimental and demonstration flumes are available. Near the pump is located a wooden flume 24 inches wide, 15 inches deep and 9½ feet long. It is provided with a 3-inch connection from the constant head tank. The bed of the flume is built up about 3 inches with sand, and the flume is used to demonstrate the erosion caused by various shapes of bridge piers located in a moving stream. The flume discharges into a weir box 3 feet wide, 4 feet long and 2 feet deep, which has a 15-inch "V" notch weir installed in the downstream end.

Along the side wall of the laboratory is located a tilting wooden flume 8½ inches wide, 5½ inches deep and 32 feet long. The head box is 32 inches long, 36 inches deep and 12 inches wide, and equipped with baffles to provide quiet entrance conditions into the flume. A broad-crested model weir 2 inches high and 13 inches long is now located near the middle of this flume. At the downstream end the water may discharge into the weighing tank or directly into the return channel.

The weighing tank, which is the primary standard of water measurement in this laboratory, is 8 feet by 12 feet in plan, 24 inches deep and mounted on a set of Fairbanks scales having a capacity of 14,000 pounds.

Two other flumes are installed along one side of the weighing tank and discharge into it. The first is 13 inches wide, 10 inches deep and 10 feet long. A concrete model of an ogee spillway is set up in this flume. Two glass panels are installed in the side walls of the flume, starting with the toe of the dam, allowing the flow conditions in this region to be demonstrated. The second flume is 12 feet long, 21 inches wide and 18 inches deep, and is equipped with a sharp-edged suppressed weir. A head box 3 feet square in plan and 46 inches deep helps to provide good entrance conditions to the flume, and Venturi-shaped racks are installed at the upstream end to improve the flow conditions. The head on the weir is measured with a hook gage, and the discharge checked in the weighing tank. The first of these flumes is supplied with a 3-inch pipe and the second with a 4-inch pipe having a common 4-inch connection to the constant head tank.

A third flume which discharges into one end of the weighing tank is the largest in the laboratory. A head box 4 feet long, 5½ feet wide and 4 feet deep is equipped with baffles and a raft to provide quiet flow conditions. A rack is also installed at the entrance to the flume for the same purpose. The flume is in two sections. The first and upper of these is 15 inches wide, 18 inches deep and 9½ feet long and contains a Parshall Venturi flume with a 6½-inch throat. This flume discharges into the second section at a somewhat lower level. This lower section, which is 24 inches wide, 33 inches deep and 11 feet long, contains a Herschel weir. The discharge from the flume passes through a switchway, either into the weighing tank or into the return channel. The heads in the Venturi flume and the head on the Herschel weir are measured with hook gages and point gages.

A second Parshall flume is available with a 12-inch throat, but this is not in use at the present time.

In the center of the floor just in front of the constant head tank there is located a pair of wooden flumes 22 inches wide, 24 inches deep and 10 feet long. In one of these flumes is located a 1:10 model of a stream gaging station. A 1½-inch pipe supplies water to the flume from the constant head tank. The discharge either falls directly into one of the return channels or may be caught in a copper-lined volumetric box 28 inches square in plan, and 15 inches deep.

Another demonstration in the laboratory is a pipe friction test, which is mounted on one end wall of the room. Pressure connections are tapped into the 2-inch city water supply pipe, and the differential pressures are measured in open and water manometers.

Stream gaging tests are made by the students at the Aberjona River in Winchester, which is located some five miles north of the college. The necessary equipment for the gaging, including current meters and floats, is kept in the low head laboratory.

Tulane University

The hydraulic laboratory of the engineering college of Tulane University at New Orleans, Louisiana, is housed in two rooms. The larger is 60 feet by 30 feet in plan, and the smaller 40 feet by 12 feet in plan. The ceiling height is about 17 feet, so that a mezzanine floor has been built into the laboratory nearly doubling the floor space. This laboratory was installed and is operated by Prof. W. B. Gregory.

All the water used in the experiments is pumped from a sump located below the first floor level. The sump consists of a number of concrete channels ranging from 2 feet to 4 feet in width by 3 feet deep, and having a capacity of about 2,100 cubic feet of water. Stop logs can be used to dam off sections for some types of work where a pool is required. The current meter practice experiment is performed in one of these flumes.

The largest pump in the laboratory is a 12-inch electric motor-driven Allis-Chalmers centrifugal pump capable of supplying 8 c. f. s. under a head of 16½ feet. This pump discharges directly into a constant head tank 4 feet by 7 feet in plan, and 5 feet deep. This tank is located just over the pump on the mezzanine floor and supplies two steel flumes on the same floor. The first flume is 24 inches wide, 30 inches deep and 15 feet long, with a brass suppressed weir 1 foot high at the downstream end. The second flume is 63 inches wide, 45 inches deep and 10 feet long, and has a 2-foot fully contracted weir at the downstream end. The discharge from these weirs falls either directly into the sump or else, through deflectors, into the 20,000-pound weighing tank on the first floor.

From the constant head tank a 10-inch pipe conveys water to be finally discharged into the 20,000-pound weighing tank. This pipe is available for work with Pitot tubes; both horizontal and vertical traverses are made at a point that is 28 feet from an elbow, so that there is but little distortion of the velocity curve.

Near the opposite wall of the main room from the large pump there is located a 10-horsepower motor-driven Allis-Chalmers centrifugal pump which delivers 0.5 c. f. s. under a head of 115 feet to three experiments on the mezzanine floor. In the 3-inch discharge line from the pump there is mounted an orifice meter equipped with a Cockrane flow indicator. On the wall there is located a 2-inch by ⅔-inch Venturi meter and a fire nozzle experiment. In the center of the mezzanine floor there is installed a 12-inch impulse water wheel equipped with a Prony brake. The discharge of these three experiments can be measured with a portable weighing tank of 2,000 pounds' capacity located on the first floor.

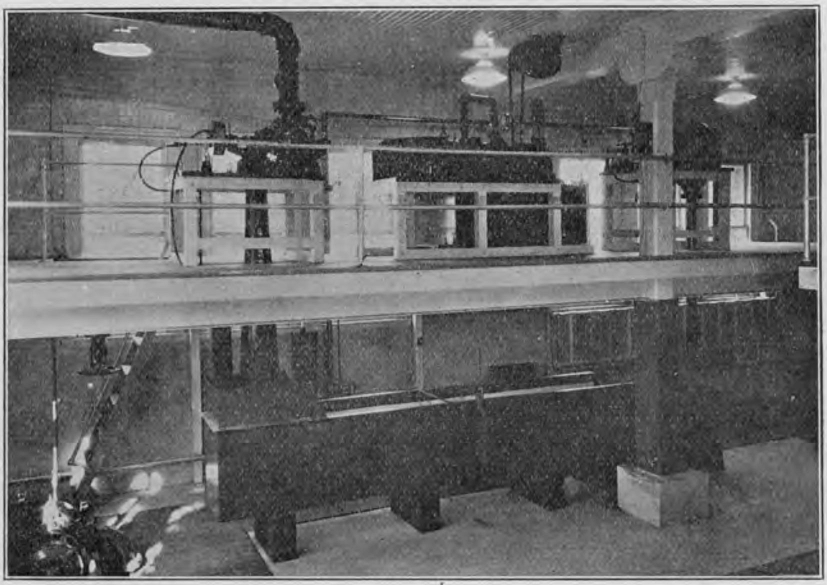

FIG. 55. — TULANE UNIVERSITY — MAIN LABORATORY 60° V-NOTCH WEIR FLUME AND 5-INCH CENTRIFUGAL PUMP ON FIRST FLOOR. WATER WHEEL AND CRADELED PUMP TESTS ON MEZZANINE

On the main floor of the laboratory there is located a steel flume 2 feet wide, 2½ feet deep and 14 feet long, with a calibrated 60° "V" notch weir at the downstream end. Several different types of pumps can discharge into this flume. There is a 5-horsepower model of the

Wood screw type pump which is used for the drainage of the city of New Orleans. The model pump is 9 inches in diameter and its capacity is 2 second-feet, while the large drainage pumps are 13 feet in diameter, with a capacity of 1,000 second-feet. A unique feature of this pump is the use of manually operated cutters to remove trash which might collect on the impeller blades of the pump. This pump is driven by a cradled electric motor. Near by there is a Lane vertical five-stage deep well pump which also discharges into this flume. Near the center of the floor there is a 3-inch Fairbanks-Morse trash pump which is driven by a 3-horsepower cradled electric motor. Beside the end wall

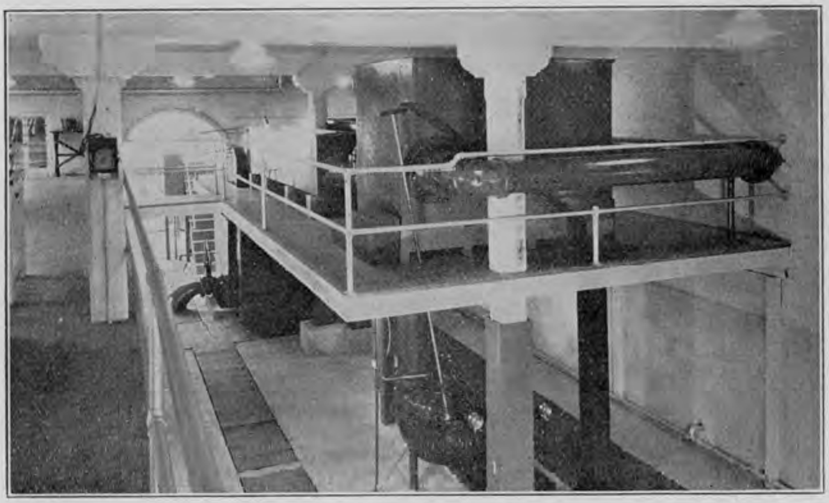

FIG. 56. — TULANE UNIVERSITY — HYDRAULIC LABORATORY, SHOWING 12-INCH PUMP, WEIR FLUMES AND WEIGHING TANK, LABORATORY ELL IN THE BACKGROUND

of the building there is a 5-inch motor-driven Allis-Chalmers pump which can supply either the "V" notch weir on the main floor or a reaction water wheel on the mezzanine. This reaction wheel is a 6-inch Trump turbine with a glass window in the pressure case. The output is measured with a rope brake. The draft-tube extends into the "V" notch weir flume. All of these pumps are connected to a vacuum pump which is used for priming purposes.

In the main laboratory room there are two other pieces of equipment which are practically independent of other piping systems. On the main floor near one wall there is a test stand for house type water meters. Discharges are measured in a portable 600-pound weighing tank, and the stand is supplied from the city service main. Provision is made in the piping to measure the pressure drop across the meter with differential manometers.

On the mezzanine floor there is another test of a centrifugal pump. In this case the pump, which is belt-driven by a 3-horsepower electric motor, is mounted in a cradle and the horsepower input to the pump thus measured. The intake and discharge connections are brought out parallel to the shaft, so as to allow complete freedom of the pump in its cradle. The base of this test stand is formed by a steel tank 5 feet long, 3 feet wide and 2 feet deep, which also acts as a sump. The discharge of the pump is measured by a 14-inch suppressed weir installed in a steel flume 12 inches deep and 6 feet long.

The remainder of the test equipment is installed in an ell, 40 feet by 12 feet in plan, leading off from the main laboratory. Along one wall there is installed a test of friction loss in 1-inch pipes. A test length between piezometers of 30 feet is provided. Tests are made in three pipes of different material, brass, wrought iron and galvanized iron being used. The head loss is measured with a differential manometer.

Near the other wall there has been installed a ¾-inch hydraulic ram which is supplied with water from a 10-inch standpipe at one end of the room. The head of supply and of discharge, the water pumped and the water wasted, are measured in this experiment.

A 6-inch brass flume has been installed for demonstration purposes. Various forms of dams and weirs can be mounted at a point where the side walls are made of glass, allowing easy observation. Beyond the weir is a Parshall Venturi flume; both weir and flume are calibrated at the same time. The water is supplied by a 1-horsepower vertical centrifugal pump and is measured by weighing in a tank on a scale of 600 pounds' capacity.

A test is performed upon orifices, using a steel tank 18 inches wide, 3 feet long and 3 feet deep. The orifices are mounted in the side of the tank about 6 inches from the bottom, and discharge just in front of a co-ordinate board, so that the trajectory of the jet is readily determined. This experiment is supplied with water by a separate 1½-horsepower centrifugal pump.

There are two experiments set up in this ell concerned with the flow of air. In the first, a centrifugal type of blower is given an efficiency test. In the second, air is forced through a variety of measuring devices, such as a sharp-edged and a round-edged orifice installed in the pipe, Venturi meter, Pitot tube in the pipe, and a discharge nozzle at the end of the pipe. The discharges indicated by these various metering elements are compared.

United States Waterways Experiment Station

Introduction

The principal hydraulic laboratory operated by the Army Engineers is called the Waterways Experiment Station and is located at Vicksburg, Mississippi. While this laboratory is equipped for studies in all branches of experimental hydraulics, the principal type of investigation has been the study of river and harbor control and improvements. In this direction more experience with such models has been obtained, in spite of the short existence of this laboratory, than in any other laboratory in this country. Finally, the location of the laboratory in the southern part of the country, where the winters are not severe, allows work outdoors the year around. This laboratory is operated under the direction of Lieut. Paul W. Thompson.

General

When this laboratory was first installed in 1930 it was felt that it would be possible to conduct the model tests under cover, and for that reason the main building was designed with a large testing room which was 50 feet wide and 150 feet long. In this respect the design followed the developments in Europe, where such procedure was common. The large volume of experimental work referred to the laboratory early in its existence quickly proved the facilities for housing models in the main building inadequate. At the same time, it became apparent that locating models outdoors offered such advantages as selection of model scales without regard for space limitations, and preservation of models until completion of the prototype projects ended their possible usefulness in further investigations. As a result, the main building houses only tilting flumes for transportation studies of bed load, glass-sided flume for dam studies, and calibrating flumes for the current meters and weirs.

The Experiment Station is located in a government reservation of 245 acres with a stream flowing through it. This stream has been dammed to provide a pond 64 acres in area when full and a storage of 436 acre-feet. This pond is used as a source of supply for those experiments which do not require clear water.

Fig. 57. — United States Waterways Experiment Station, Vicksburg, Mississippi — General View, April, 1936

For the outdoor model tests there are two level sections which have been used. The first and lower level is developed around the main laboratory building in the bed of the brook, where an area of 8 acres has been laid out in models. This section is supplied with two constant head tanks and two 20-inch lines from the lake. One of the constant head tanks has a capacity of 50 c. f. s. and is served by a centrifugal pump of 10 c. f. s. capacity, while the second tank has a capacity of 3 c. f. s.

Recently there were two very large model tests to be performed and it was necessary to develop the upper level. At this location, which may readily be seen in the aërial photograph, there is an area about 35 acres in extent of which about one half has been leveled for model use. A dam was thrown across a gully to provide a small pond of 2 acres area and 9 acre-feet storage. This pond serves as a sump for the upper level pumping plant which supplies a discharge of 25 c. f. s. to a constant head tank centrally located on the plateau. The water level in the small pond is kept at the proper elevation by a high head lift pump which can discharge 2 c. f. s. from the main pond into the small pond.

The main building of the Experiment Station consists of a well-lighted single-story room 50 feet by 150 feet, flanked by 2 two-story wings which are 35 feet wide and 110 feet long. The roof of the main hall is at the same elevation as that of the two-story wings, providing a very high ceiling and good illumination. The two wings are fitted as drafting rooms and offices which are used by the engineering staff and by the administrative staff of the organization.

The shops, storehouses and some field offices are scattered about the grounds in convenient locations. The soils mechanics laboratory is housed in a building about 35 feet wide by 70 feet long. This building is close to and to one side of the main building. Near by is located the carpenter shop which is about 35 feet by 60 feet in plan, and behind that is the tin shop which is similar in size. The paint shop is a unit 20 feet by 20 feet in plan, and it is situated well away from the rest of the shops, since it constitutes a greater fire risk. The storehouses are located on the other side of the valley from the main offices, the distance being nearly a quarter mile. One of the buildings is used for the new stores, while others are used for the storage of salvaged materials and working tools, etc. A small field office is also provided on the upper level for the use of the engineers on those projects. The distance between the main and the field offices is about a half mile by the road.

The extent of the testing program is such that the total personnel at the time of the visit numbered about 217 men. Of these, about 19 were men of professional grade, 75 of sub-professional grade, and the remainder were clerks, laborers, etc.

The main building is used for flume tests and for calibration work. As stated previously, the room available for test work is 150 feet by 50 feet in plan. Two complete independent circulating systems serve this part of the laboratory. In the smaller system the water supply is taken from a sump located beneath the main floor level and pumped into a constant level tank by two centrifugal pumps. The total discharge available is 5 c. f. s. acting under a head of about 11 feet. The return to the sump is by means of a concrete channel 4 feet by 2 feet in section set into the floor near the center of the building. This supply proved inadequate when the large spillway testing flume was installed, and a second constant level tank was constructed just outside the building at the rear of the room to supply the flume. Water is taken from a concrete sump having a capacity of about 10,000 cubic feet and lifted into a constant head tank by centrifugal pumps. At the time of the visit the maximum discharge was limited by the pump capacity to 15 c. f. s. The constant head tank is 22 feet by 21 feet in plan, and 6 feet deep. It is equipped with 400 feet of free crest spillway and is designed to handle 45 c. f. s. A 20-inch pipe supplies the spillway testing flume inside the laboratory, and a similar connection supplies an outdoor model test of the Possum Kingdom Dam near by.

The spillway testing flume is located in the center of the floor of the main laboratory building. It is built 5 feet above the laboratory floor to allow sufficient depth of water in the weir box for satisfactory flow conditions. The flume is 8 feet wide throughout its whole length. The head box is 10 feet long and 11 feet high, and it is equipped with straightening racks and baffles to insure quiet flow conditions of the water approaching the model. The test flume itself is 48 feet long with one glass side for about 30 feet of this length. The glass is laid out in 18-inch vertical panels and has internal wire mesh bracing. At the end of the testing flume the water passes over a motor-operated tail gate and into a weir flume 20 feet long which is set at a lower elevation so that the backwater of the weir cannot affect the tail-water conditions on the model being tested. The weir flume is provided with suitable board racks and baffles to insure proper velocity of approach conditions to the large "V" notch weir which is installed at the end of the flume.

At the time of the inspection there was a 1:50 model of the

Conchas Dam being tested. The problem was essentially that of protection of the river bed below the toe of the dam during floods. A satisfactory answer was found by creating a deflector or barrier, so that the high velocity water was diverted from the river bed to the surface of the tail-water, and scour was largely prevented. This model was built entirely of sheet metal.

At the rear of the main testing room of the laboratory there is located a long flume 3.5 feet wide, 3 feet deep and 165 feet long. It is straight throughout its length, reaching through the wall of the building at the downstream end and discharging water either into a sump return channel or into a volumetric tank for check measurements. This channel was not in use during the time of the inspection.

Between the long concrete channel and the dam testing flume there is located a tilting flume which has been used for an extensive series of tests upon the movement of sands as bed load at various velocities in an open channel. At the upstream end of the flume there is a weir box which does not move with the channel. A 2-foot "V" notch weir measures the discharge of the experiment before the water passes to the flume. Then there is a head box 4 feet wide, 4 feet deep and 6 feet long where the flow of the water is quieted before it enters the tilting portion of the flume. This test section is 16 inches deep, 28 inches wide and 48 feet long. At the downstream end of the flume the water is discharged into a sump return channel. This flume is fitted with brass rails for use with traveling point gages, Pitot tubes and similar instruments. At the upper end there is a shaking table which provides a uniform rate of addition of bed material to replace that moved along by the water during the test. A more complete description of this apparatus may be found in Paper No. 17 published by the United States Waterways Experiment Station.

At one end of this testing room there is located a new tilting flume in which an investigation of the bed-load movement of light materials, such as coal and gilsonite, is in progress. The head box of the flume contains a 3-foot "V" notch weir in a box 12 feet long, 4 feet wide and 5 feet deep. From this head box the water flows through a labyrinth and screens into the double glass-sided section which is tilted. This test section is 12 inches wide, 20 inches deep and 30 feet long. It is pivoted at the upstream end and carried on two screw jacks located at the center and downstream end of the flume, respectively. A single handwheel operates both jacks simultaneously, so that slopes of the flume bottom are readily set. The water elevation at the downstream end is regulated with a hand-operated tail gate in the form of a suppressed weir. Piezometers are installed in the side of the flume about 6 inches above the bottom. They are connected to a bank of stilling pots in which the water surface elevation is measured by a single multiple point hook gage. Thus the hydraulic gradient in the flume is readily determined. From the end of the flume the water is discharged into a return channel to the sump tank.

Near the new tilting flume there is located a revolvable circular tank which is used for the calibration of small current meters and Bentzel tubes. This tank is 4 feet in diameter and about 1.1 feet deep. There are projecting radial fins every 9 inches around the inside periphery of the tank to help keep the water revolving at the same speed as the walls of the tank. This tank is revolved by an electric motor through a variable speed drive which allows speeds ranging from near zero to 7 feet per second to be obtained at the rating diameter of the tank. At the higher speeds the water is caused to lag the speed of the tank due to the drag of the instrument. In this condition the relative backward motion of the water is determined by timing the revolutions of a chip on the surface of the water relative to the tank itself.

The photographic laboratory is located in this main building. Very complete equipment is available for the taking of still and moving pictures, developing, printing and enlarging. Three photographers are regularly employed on the laboratory work.

In this same building there is a small workroom equipped with a bench lathe and bench drill in addition to other small tools. Here the various special instruments demanded by the experiments are made to order.

Soils Mechanics Laboratory

This department is housed near one end of the main laboratory building in a separate single-story building. About one third of the floor space is used for offices and drafting room space, and the remainder is used for the work of the laboratory. The laboratory is equipped to make tests of the shear strength of soils under varying conditions of load, tests of permeability, consolidation and Atterburg limits in addition to the customary mechanical analyses and moisture content determinations. Their test work is performed with samples from 2 inches to 4 inches in size, as determined by the design of the testing machine. The "undisturbed" samples which are taken in the field are 5 inches in diameter and from 6 inches to 12 inches long. These are immediately encased in paraffin and shipped into the laboratory, where they are kept in a high humidity room until needed.

Shops

As mentioned above, the shops are also grouped about the main laboratory building. Both the carpenter and tin shops are well equipped for work in their respective lines. In the former the machine tools consist of a 36-inch band saw, a 15-inch jointer fitted with a cylinder planer attachment, router, 10-inch circular saw for general work, ½-inch bench drill press, bench lathe, power hack saw and a shaper. Finally, there is a DeWalt saw which is used for all model work requiring special cuts. It consists of a direct-connected motor and 12-inch saw in a pivoting mounting which is carried on a runway which in turn can be set at any angle from cross-cutting to ripping. Stops are provided for all the common angles encountered in the adjustments, but the motions can be clamped securely at any intermediate point when desired. This design of saw was the best adapted to model construction work of any seen during these inspections.

The tin shop is supplied with a 60-inch brake and a set of rolls, bench tool for crimping and beading, bench shear and the common hand tools used in this type of work. As will be seen later, a great deal of sheet metal work is done in connection with the construction of models.

Heavier machine operations are usually performed at a local machine shop which specializes in repairs to the tugs and river steamers of the Mississippi River Commission.

For the operation of this large laboratory there are also required a number of passenger cars and trucks which are available. In addition, they have their own automotive repair department, together with welding equipment. There is a caterpillar tractor and grading equipment for the heavier work of model building. A rock-crushing plant is available to smash up the concrete from old models to be used as aggregate in other building operations. There is also a cleaning and screening plant for gravel and coal, which is used in the preparation of bed materials for model use.

Model Tests in Progress during Inspection

There were a large number of model tests in progress at the time of the inspection of this laboratory, and a complete description of each test, its construction and test methods, and the results attained to date would be very long and tiresome. It is proposed, therefore, to substitute for such a description a brief outline of the tests that were observed, discuss briefly the effects of distortion and the principles of design of distorted models, and finally describe simply the model construction methods at the Waterways Experiment Station.

The following tests were found in progress at the United States Waterways Experiment Station in September, 1936:

Conchas Dam

In the 8-foot glass-sided testing flume in the main laboratory there was found a 1: 50 sized model dam. The purpose of the test was to determine the proper design of the protective apron at the toe of the dam. Many forms were tested and the final design was selected. It consisted of a flat apron for about 50 feet, with a deflector or barrier at the downstream end. A relatively fine gravel (about one fourth inch in diameter) and sand were used in the bed to portray the erosive forces below the toe of the dam.

Possum Kingdom Dam

This model was built and installed at the completion of the Conchas Dam tests. The model ratio was 1:70. The dam was built of wooden vertical ribs with a sheet copper facing. Some trouble was experienced with this form of construction in getting the sheet facing material to lie flat to the ribs without any buckles.

Helena–Donaldsonville Model

This was the largest and most spectacular model which was to be found at this laboratory. It represented about 600 miles of the Mississippi River, together with tributaries. The model was designed and built to study the movement and control of flood waves in the basin of the Mississippi River. The horizontal scale was 1: 2000, and the vertical scale 1: 100. The model had been in operation for about one and one half years, and test results were being obtained. The model was first adjusted for the proper hydraulic gradient for various conditions of steady flow. When this had been accomplished a flood hydrograph was made on the model, using the flood of 1929 for the purpose. It required a crew of about thirty-five men to operate the model, adjusting the flow of the main river and the tributaries to correspond to the data recorded, and taking readings of the gages (of which there were over 200) showing the hydraulic gradient throughout the model. A test was normally started about noon and completed about 2.30 the afternoon of the following day. When this 1929 flood hydrograph was

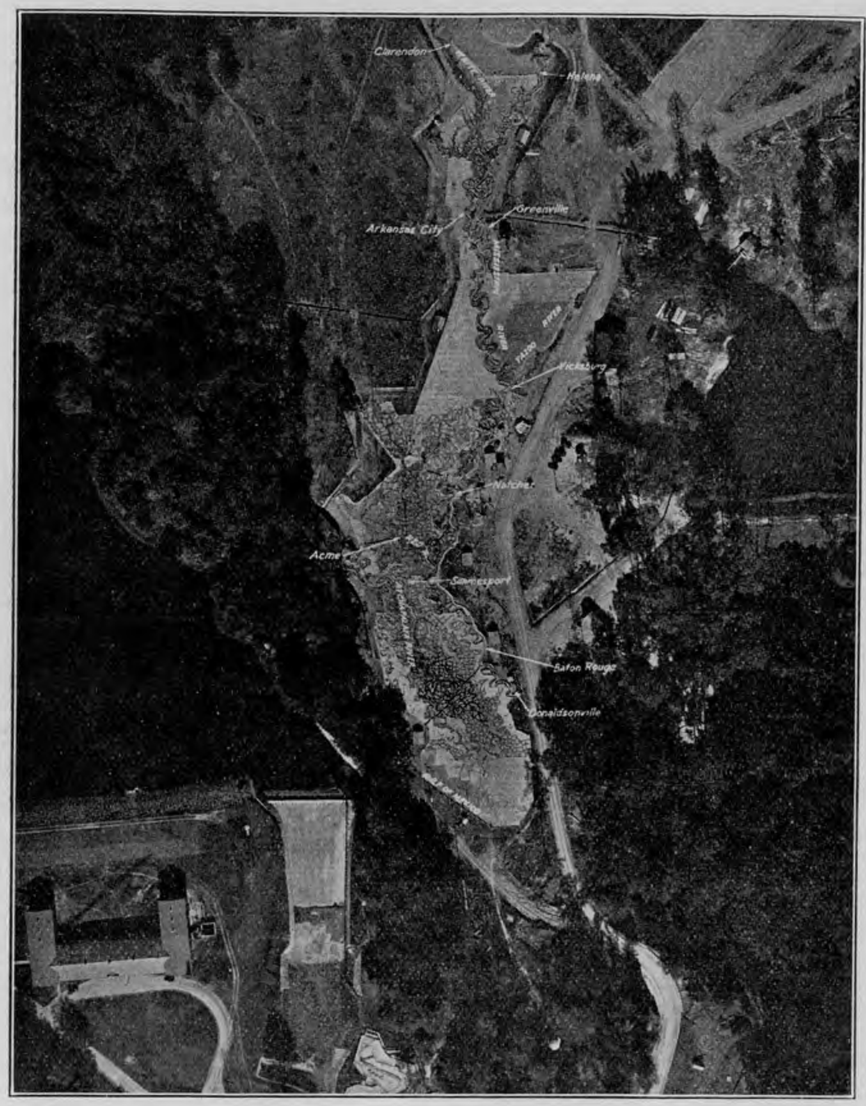

FIG. 58. — UNITED STATES WATERWAYS EXPERIMENT STATION — AERIAL VIEW OF THE HELENA–DONALDSONVILLE MODEL. RATIOS 1: 2000 AND 1: 100

run on the model it was found that the time and velocity factors, for the backwater areas in particular, were faulty, and these were corrected until the 1929 hydrograph was duplicated in the model. Having thus adjusted the model to operate correctly with one flood, the adjustment was verified by passing over the model a flood of entirely different characteristics as to magnitude and time. If the model was correctly constructed and adjusted this second flood was correctly indicated in all its detail on the model. At the time of the inspection the model had thus been verified as to its adjustment, and several variations as to the river channel arrangement had been tried.

The disastrous floods of the Mississippi River occur in the lower reaches in the region covered by this model. There are two obvious methods of alleviating a flood condition. In the first place, if the water coming down the various tributaries can be so delayed that it all does not combine with the maximum effect, then the peak can be reduced. In the second place, if other river channels can be provided to carry off the water, the peak in the main stream can be reduced. In the case of the Mississippi River, the volume of water is so great, and the length of time of the flood condition is so long, that the detention reservoir system is practically out of the question. One floodway at Bonnet Carre has already been built to reduce the flood danger to the city of New Orleans. Another was proposed, using the Atchafalaya River to reduce the flood peaks farther upstream. Other plans are under consideration, and this model study was providing a method of comparing the results obtained with the various plans, insuring the most economical answer to the problem.

Mare Island Straits Model

This model was constructed to determine the cause and possible remedy of the shoaling of the channel beside Mare Island in San Francisco Bay. The horizontal scale was 1 : 800 and the vertical scale 1 : 80. The shoaling phenomenon is the result of a number of complex relations. In the first place, the tides are not sinusoidal in that region but have a well-developed secondary hump in the curve. Thus the tidal phase passes from low low to low high to high low to high high and then to low low again. The Mare Island Channel communicates immediately with the bay at one end, and the other end is connected back to the bay at another point through several miles of tidal river channel. Finally, it had been determined in the field and in the preliminary model tests that the shoaling material came with the littoral drift when the flats in the bay had been stirred up by wave action. The material that lodged in the channel deposited when the tidal currents slackened, and afterwards the channel velocity was not sufficient to move the material again. Thus it was seen that the effects of the complicated tidal curve, the out-of-phase effects of the tides at the two ends of the channel, the littoral drift, wave action and the critical velocities at which bed material was started into motion and maintained in motion, were all combined in this problem. When the model was seen in operation it seemed that all except the last of these problems had been solved. However, since the inspection it has been found that gilsonite performed very satisfactorily as a movable bed material, and as a result the experiment has been entirely successful.

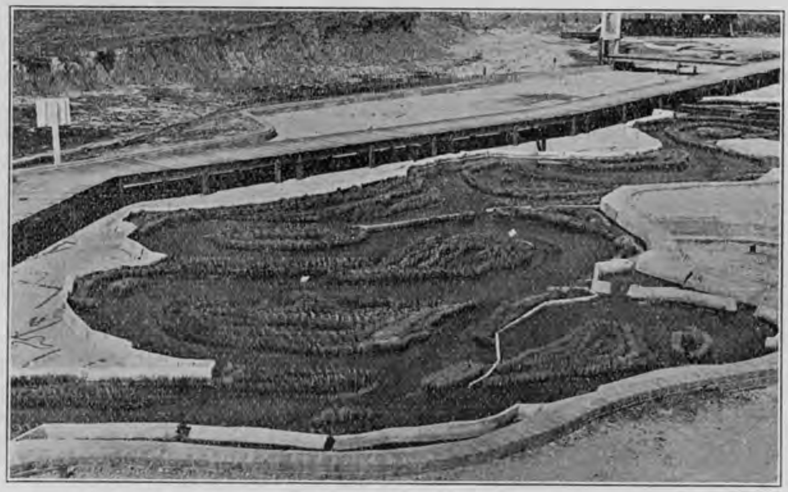

FIG. 59. — UNITED STATES WATERWAYS EXPERIMENT STATION — UPSTREAM VIEW OF THE GREENVILLE BENDS CUT-OFFS IN THE HELENA-DONALDSONVILLE MODEL. HORIZONTAL SCALE RATIO 1: 2000; VERTICAL 1: 100

Maracaibo Bay Model

This model was constructed with a horizontal scale ratio of 1: 300 and a vertical scale ratio of 1: 50 to try to determine a solution to the shoal condition at the entrance to the Bay of Maracaibo. The shoal was the result of the effects of the tides into the bay and the littoral drift at the entrance to the bay. This problem was complicated primarily by the fact that reliable and complete data for the construction and operation of the model were difficult to secure in nature. The model was 175 feet by 250 feet in plan, with a plunger type of wave-making machine along one of the long sides. Tides were caused by automatic control apparatus at each end of the model. Thus the water was admitted at one end of the model and drained at the other for a tide in one direction, and the procedure reversed when the tide was to flow in the other direction. The movable bed material which was being used to portray the shoaling effects was crushed and screened coal. At the time of the visit this model was in the adjustment stage. The distribution of velocities in the model and in the field checked very well. The difficulty at that moment was the proper adjustment of waves and bed material size, so that the erosion of the shore line and the movement of shoals would agree within themselves and also come out with some reasonable time scale.

Ballona Creek Model

This model was designed and built to study the effect of some proposed changes in the creek to adapt it as a flood way to the sea. The original creek outlet was more or less constricted by a bar, and it was hoped that some slight changes in the design might avoid this trouble for the larger channel where the backwater effect might be serious. The model was built with a horizontal scale ratio of 1: 100 and a vertical scale ratio of 1: 50. Sand was used as the movable bed material. The model was provided with the automatic control of the tides and a plunger type of wave-making machine. The verification tests which were in progress during the visit indicated that the field data provided were not sufficiently complete and accurate for the model work expected. Additional field data were later obtained which made it possible to carry this experiment to completion with gratifying results. The works partially completed in the prototype have furnished a field verification of the initial tests of the model.

Kansas City Flood Control

A study of the water levels of the Missouri and Kaw rivers was being made for Kansas City. Due to the nature of the river beds and the floods in them, it was not possible to make an exact model of all flood conditions. The model was designed with a fixed bed to duplicate the hydraulic gradients found for various floods. Then it was used to indicate the relative effects of levee locations, overbank clearing of trees, relocation of highway embankments and railroads, etc. The scale ratios of the model were 1:800 horizontal and 1:100 vertical. The tests were completed during the inspection, and were most satisfactory to the district office.

Pryor's Island Model

Horizontal scale ratio 1:600, vertical scale ratio 1:150.

Chain of Rocks Model

Horizontal scale ratio 1:600, vertical scale ratio 1:125.

Both of these models were designed to study reaches of the Ohio and the Mississippi rivers, respectively, with regard to the problem of maintaining suitable channels for navigation at all flow stages. Crushed, screened and washed coal was being used as a bed material. However, both of the models had only reached the preliminary adjustment stages, so that there was little to report upon them.

Dogtooth Bend Model

Horizontal scale 1:600, vertical scale 1:100.

Swift Sure Towhead

Horizontal scale 1:600, vertical scale 1:120.

These models were in the design and construction stage while this laboratory inspection was in progress. These two tests therefore afforded an opportunity to gain an insight into the design and construction methods of the Experiment Station in regard to movable bed models.

Pipe Line Mixer Tests

These tests were made in 4-inch pipe carrying a mixture of sand and water. It was the purpose of the tests to find out if it were possible to increase the carrying power of a given stream of water without increasing the actual power input. Velocity traverses of actual dredge pipe under operating conditions indicated that the sand tended to settle toward the bottom of the pipe, resulting in very low velocities in that portion and high velocities near the top of the pipe where there was little sand in the mixture. It was felt that some form of efficient mixing device would effect considerable economy in power requirements. A system of interrupted wall rifling was developed which was very successful in the laboratory tests, increasing the carrying capacity of a given stream and the maximum carrying capacity of a given pipe. It was hoped to have field tests of this development in the near future.

Port Washington Model

This model, built with an undistorted scale of 1:50, was designed to study the effect of waves in the harbor of Port Washington on Lake Michigan. Two extensive breakwaters had been built to form the harbor, and it was found after completion that under certain storm conditions waves built up inside the harbor to very damaging proportions. A plan of modification had been drawn up, but it was decided to test it in the model form first. This modification was found to be no more satisfactory than the original design. Various shapes of breakwater were tried out with no success. By that time those working on the model had determined that the troublesome waves were caused by wave reflection and surging in the harbor itself. With this in mind, cribs filled with loose rock were placed at strategic points in the model, to act as energy absorbers or dissipators, with entire success. Thus a satisfactory solution costing about $75,000 was found to a problem where plans called for an expenditure of about $200,000, which would have been entirely wasted.

These tests were completed before the laboratory was visited. A plunger type of wave machine was used for these tests, which was of the same design that was used on Ballona Creek and Maracaibo. It performed satisfactorily, but the design was cumbersome, noisy in operation and relatively expensive to construct. A new type of wave machine was being tested on the Port Washington Model. It consists of a steel cylinder partially immersed in the water, its axis being parallel to the surface, with its axis of rotation displaced from the geometric axis. The cylinder is rotated by a variable speed motor through a gear reduction and a chain drive. The frequency of the waves is determined by the speed of rotation, and the wave height is controlled by the amount of eccentricity existing between the axis of the cylinder and that of rotation. The machine performs very satisfactorily as judged by high speed motion pictures, the design is very simple and strong, and the cost of manufacture much lower than with the plunger type.

Bed-Load Tests

This Experiment Station has carried on a long series of tests on the transportation of bed-load materials in tilting flumes. The two flumes available for this work have been previously described. The first series of tests was made upon nine different varieties of sands, and a complete report was published in Paper No. 17 of the United States Waterways Experiment Station. The paper was entitled "Studies of River Bed Materials and their Movement, with Special Reference to the Lower Mississippi River." This work has been continued with the study of the bed-load movement of haydite, coal, gilsonite, pitch, and limed wood rosin. The reason for this great interest is that movable bed models have a great many limitations, and it is desirable to have a graduated series of materials at hand to meet the needs of such test work.

MODEL DISTORTION

The United States Waterways Experiment Station has specialized in river study with its model tests since its start in 1930. Most hydraulic laboratories have had little, if any, experience with this type of model work. The treatment of such models in design and operation is very involved, and ironclad rules cannot be laid down. In the last analysis, success in this type of test work depends upon the judgment of the experimenter developed in similar tests. However, some of the elementary conceptions which must be known in this work can be mentioned here.

Distortion can enter a model in many forms, some of which are familiar, so much so that their presence is ignored. In ordinary model work water and air are used as fluids where these are the identical fluids which occur in nature. The effect of this distortion can be determined and allowed for in the results of the test work. When using Froude's Law the effect of the changes in the fluid are usually not large, so that the change in the results, being slight, does not occasion any mental disturbance. But grave doubts arise as to the accuracy of the test results when the distortion exists in a more unusual form, especially where it is immediately and strikingly apparent to the casual observer.

The most usual form of distortion is geometric; that is, the horizontal scale is to one ratio, and the vertical scale ratio is to another and generally smaller ratio. Since hydraulic gradient is one of the more important quantities in model and field measurements, the larger ver-

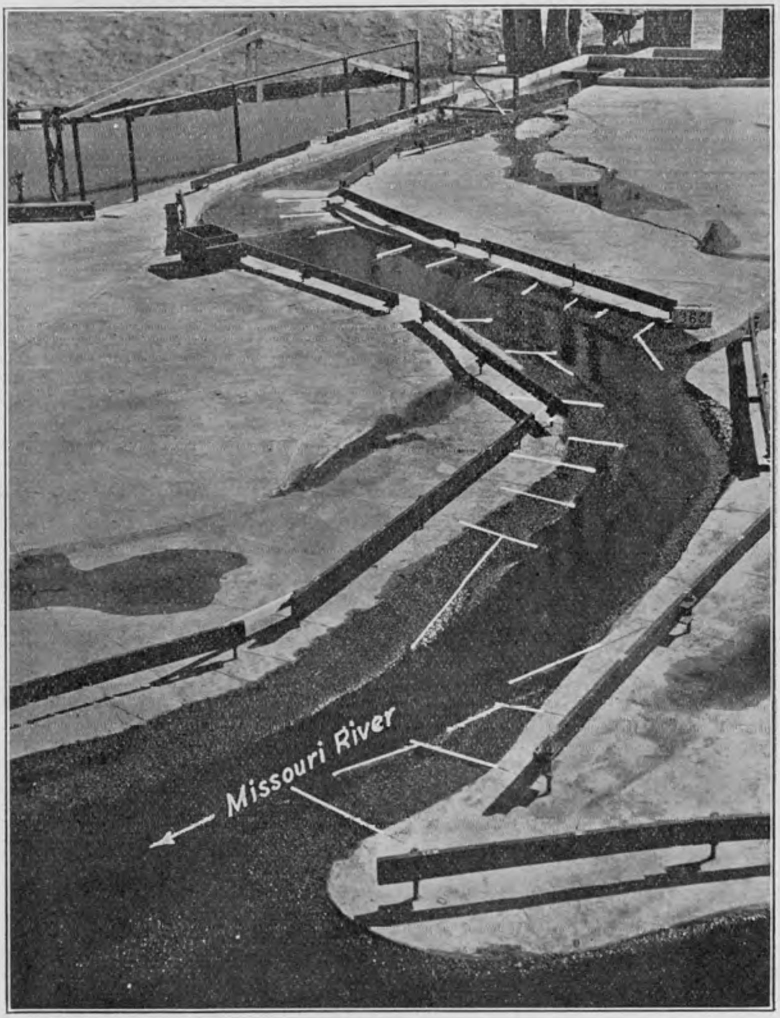

FIG. 60. — UNITED STATES WATERWAYS EXPERIMENT STATION — CHAIN OF ROCKS MODEL, WITH THE MISSOURI RIVER MOULDED IN COAL. MODEL RATIOS 1:600 HORIZONTAL AND 1:100 VERTICAL.

tical scale ratio allows greater accuracy of measurement in the same size of model. The effect of this distortion may be briefly seen by examination of the formula for discharge in an open channel.

$$Q = A\,V$$

where

Q = discharge in cubic feet per second.
A = area of the cross section of the stream in square feet.
V = velocity (mean) of the stream in feet per second.

The velocity of the stream is given approximately by a number of imperfect formulas of which the Chezy and the Manning formulas are probably the best known. Using the former it is seen that —

$$V = C(rs)^{1/2}$$

where C is the Kutter coefficient and depends upon roughness essentially; r = hydraulic radius of the channel in feet; and s = slope of the channel, a pure number or feet per foot.

Combining the two equations there is found —

$$Q = A\,C(rs)^{1/2}$$

A geometric distortion means that the horizontal scale ratio has one value, say 1:1000, and the vertical dimensions are reduced by a different ratio, say 1:100, for instance. It is seen in the formula that the area of cross section is immediately affected, since one dimension is a horizontal length and the other is a vertical distance. Presumably, however, the resulting area ratio would compensate for this distortion. The next quantity in the formula is the value of C which is dependent upon the roughness of the surface. Obviously, something has happened to the roughness, and this change cannot be easily evaluated mathematically, since at the present time roughness cannot even be defined. The next term in the formula is the hydraulic radius. Here again the effect of distortion may be serious. The hydraulic radius is a shape factor, and distortion may entirely change the carrying efficiency of a stream cross section. The experience at Vicksburg indicates that if the relative shape of the stream cross section is little changed by the distortion, then the results of the change will probably not be serious.

That is to say, if a very wide and shallow stream is being duplicated in a distorted model, then the model stream should still be wide and shallow after distortion. But if the wide and shallow stream becomes distorted into some shape resembling a semi-circular or some similarly efficient cross section, then the effects of the distortion will undoubtedly be more serious.

Coming to the last term of the formula, there is the slope to be considered. The slope is directly affected by a change in ratio between the horizontal and the vertical scales. However, this was the great advantage of the distorted model, since the accuracy of measurement and the transportive power of the stream in moving bed materials were thus to be increased.

The allowable distortion which may be used in a model depends upon the use to which the model is to be put. If the model is to be used to determine the hydraulic gradient that will occur in a stream with varying conditions of flow, then a relatively large ratio of distortion is permissible. Looking at the formula, the hydraulic gradient depends directly upon the slope. Since the roughness and the hydraulic radius are not specified in the problem, they may be modified in the model form to provide the proper hydraulic gradient with the known flows. With this type of fixed bed model rather large ratios of distortion may be used. At Vicksburg, the Helena–Donaldsonville model had a ratio of distortion of 20. Other experimenters have used even larger ratios of distortion in this type of work, particularly the English investigators, who have exceeded ratios of 40.

On the other hand, there are cases where the velocity distribution of the stream is important. Here the quantity V is represented in the formula as the product of the roughness the square root of the slope and the hydraulic radius. Obviously, since nearly all the terms in the formula have been defined, there is little left with which to make adjustment. Since so many terms help to determine the value of V, it is not to be wondered that this quantity is found to be much more sensitive to the effects of distortion in model work. The results of tests at the Experiment Station indicate that a ratio of distortion of between 2 and 3 may be employed without seriously affecting the distribution of velocity in a model under normal conditions. This figure has been checked by Professor Rehbock in his laboratory.

In the event that some quantity such as the kinetic energy was being measured in the model, a great deal of difficulty might reasonably be expected. This quantity is the product of the square of the velocity and the quantity together with a constant. Since both of these quantities include the effects of distortion in all their various parts, the sum total of these deviations could amount to a very sizable figure.

In the study of channel maintenance where movable beds must be employed in the model, there is further complication with distortion. The tractive force depends upon the depth of the water and the slope of its surface according to DuBoys' relation, which is customarily used at the present time even though it is not exact. The depth of the water is determined directly by the vertical scale, but the slope has been increased by the ratio of distortion in the model scales. On the other hand, since the velocities in the model have been greatly decreased by the model ratios for this quantity, or since the depth has been greatly decreased in the formula, there is not sufficient tractive force to move the bed material found in nature. Further, the bed material may not be directly reduced by the model ratio of dimensions, because the laws of bed movement of material show that movement does not vary directly or even simply with grain size. For this reason some other material must be selected that will show the proper general movement with the range of velocities found in that particular size of model. This constitutes another form of distortion, and it might be noted that this detail is one of the hard problems to solve in distorted model testing.

The above brief decription is not complete, but serves to enumerate the more common problems in distortion of models. It is seen that the present state of the art does not permit a mathematical solution of most of the problems concerning this type of model. The practical solution of the problem involves the adjustment of the model with certain conditions of flow, hydraulic gradient, velocity distribution, and any other factors which may have been carefully measured in the field. When the model has been brought into such a condition that it operates correctly with one set of test conditions, the performance is checked with another set of conditions as measured in the field, such as a different flood. This check on the adjustment of the model is called the verification of the model.

In conclusion, it is seen that in the testing of distorted models it is impossible to predict or allow for all the effects of the scale distortion. The model is made to act correctly with one set of test conditions and checked in its performance with another set of test conditions. The final accuracy of the predicted results can in no case be any more accurate than the original adjustment or calibration of the model.

Model Design

When looking at a branch of model test work which is entirely strange, possibly the first question which comes to mind is, "Why was this model built with these particular scales?" As might be imagined after contemplating the effects of distortion, the question of scale selection in model design is not a simple one. It is very complex, requiring care and considerable judgment based on experience to insure a satisfactory answer. At Vicksburg a problem is given to a project engineer who is to have charge of it. He works out the critical cross sections of the model, where the velocities might be too low for bed movement or for turbulent flow, or where there might occur shooting flow at high stages, or, finally, where the transverse side slopes might become too steep to stand. These sections are computed for various scales for consideration. After this preliminary work has been done there is usually a meeting of the laboratory director, his assistant, two or three senior engineers, and several project engineers who might have just completed similar projects. There the model scale is thrashed out in discussion. Even with all the above talent concerned with the problem, unforeseen difficulties frequently arise.

The selection of model scales is based upon the following fundamental facts. The horizontal scale which determines the size of the model also determines the cost. The cost varies with the area of the model, and the accuracy of measurement is increased with the size of the model, but not as rapidly as the square of the linear dimensions. Therefore, knowing the desired accuracy and approximately the amount of money that is available, the horizontal scale may be fairly readily arrived at. Before leaving this consideration, it should be borne in mind that the model cannot be more accurate than the field data that are available or obtainable. In the latter case it is probable that the total cost of the model work may be greatly increased if it is necessary to obtain a great deal of additional information in the field. It was observed that at least one half of the troubles experienced by the operating engineers at Vicksburg was due to insufficient or unreliable field information.

In selecting the vertical scale of a model there are a number of factors to be satisfied. In the first place, there is an allowable limit to the distortion of scale, depending upon the type of test work proposed. Where there is bed movement, such as in the tests for stable navigable channels, where velocities are important, the limit of distortion is 2 for small rivers, increasing to about 4 or 5 for very wide and shallow rivers such as the Mississippi. Where the hydraulic gradient is the essential factor, then the scale distortion may be increased to 10, or even 20.

Then the model slopes with the resulting velocities must be computed for various reaches of the model river. In order to avoid viscous flow the product of the velocity and the hydraulic radius at any cross section shall be equal to or greater than .02 in English units. This figure has been determined by experiments at Vicksburg, using dye to show the existence of turbulent or viscous flow. This low value of the Reynolds' criterion is noteworthy in view of the fact that in the testing of spillways, Venturi meters, and similar models, depending upon Froude's Law, the corresponding limit is .075 at 40° F.

In the next place, the velocities must be checked at the reaches having steeper slopes, to be sure that the mean velocity does not exceed the square root of the product "*gd*". In other words, there must not exist "shooting flow" at any point in the model for any flow stage, otherwise the model laws no longer apply.

In a similar fashion, the various reaches of the model must provide sufficient tractive force to move the bed material at all flow stages in the event that a movable bed is employed. In this case the product of depth and slope must exceed the critical value for the particular bed material which is being used.

Finally, in a movable bed model, the transverse slopes of the channel cross sections must not exceed the angle of repose of the bed material standing in water. This angle has been chosen as 20° for the work at Vicksburg. With some forms of material, this angle may be greatly exceeded, especially for short reaches in a bend, but the value given is safe for design purposes.

In some cases it is desirable to have somewhat greater slopes in the model than the normal scale values provide, in order to obtain better movement of the bed material. This has been done successfully a number of times by "tilting" the model; that is, adding a small supplementary slope through the course of the stream. Such a supplementary slope cannot be used in a model in which a cut-off study is to be made. Obviously, when the cut-off is completed, there will result a short channel with a slope all out of proportion to the true situation, with resulting velocities in excess of the critical velocity.

In conclusion, the above discussion presents the elementary considerations involved in the design of distorted models. For any one inexperienced with the use of such models, it is strongly recommended that any proposed distorted models be checked by some engineer well grounded in their design and use.

Model Construction

The following brief description of model construction methods applies only to those large distorted river models which are constructed out of doors. In the construction of small models, for flume testing and allied work, the methods used at Vicksburg do not differ very much from those methods found elsewhere. But in the large models at Vicksburg they have had a great deal of experience, and their construction procedure includes all the essentials with the unessentials omitted.

Before starting the actual construction of a model the project engineer has a set of sketches made which show the cross sections of the river channel to model scales, the extent of the model on each side of the channel, the location of gaging points, and the location of hook gage pits. All grade lines are worked out and included also. From these drawings the templates for the channel cross sectional outlines are marked out in thin sheet iron. Two kinds of templates are regularly used in this work, and they may be called male and female templates. The latter type is mounted on the base of the model with the upper edge delineating the elevation of the channel cross section at that point. The male type is hung from a pair of parallel straight edges mounted either side of the channel, and the bottom edge of the template determines the elevation of the channel cross section. Ordinarily the female type is used in the construction of the fixed bed portion of the model, while the male type is used as a guide in the molding of the movable bed of the model. However, in some cases (Swift Sure Towhead model, for instance) both the fixed bed and the movable bed were laid out with the aid of male templates.

After the templates are laid out in the engineering department the sheets of iron are taken to the shops, where the templates are cut out and the back lengthwise edge of the iron strip is attached to a piece of timber, about 1 inch by 4 inches in cross section, which provides support and stiffness to the whole.

In the field the plot of ground which is to be used for the construction of the model is staked out and leveled. First, a system of co-ordinates is laid out for a model of any size. Each co-ordinate point consists of a bolt set in a small block of concrete. All of these points are located outside the boundaries of the model itself, so that the reference points will not be disturbed during the construction work. Several of the co-ordinate points are also set carefully to grade, to be used as bench marks for the leveling work in connection with this particular model.

The ground which will constitute the foundation of the model is not given any special treatment in those portions which are excavated to grade. Where fills are made, support is provided for the model by concrete columns which extend to the undisturbed ground surface. These columns are constructed inexpensively by excavating holes in the fill with post hole diggers and filling these holes with concrete at the same time the model surface is being paved. In this connection it should be borne in mind that in Vicksburg there are only occasional frosts, and that the ground rarely, if ever, becomes frozen. It is obvious that some of these construction methods could not be employed in more severe climates.

With the ground prepared for the construction of the model, the course of the channel and deep portions of the model are staked out and the ground excavated to the required depth in these portions. Then the female templates are set up on the model base in the proper relation to the co-ordinates and to the proper elevation. The templates are carefully backfilled to within 1½ inches from the top with a special filler of sand-clay composition which is wet down and tamped to compaction. Great care must be used in this process to insure the preservation of the correct grade and alignment of the templates, and an engineer is employed who continually checks this work as it proceeds. When the work of backfilling is completed, a finish coat of concrete is placed to bring the model to its finished dimensions. If it is known that the surface must be left rough for the desired model performance, it may be done at this time. Usually, however, the model finish is made smooth, and any roughness is added during the adjustment period when the need thereof has become apparent.

Where a fixed bed model is being constructed the final concrete coat is finished to the proper channel dimensions. In the construction of a movable bed model this is not the case. Here the region where the channel is to be located is made from 4 inches to 6 inches, or even more, on occasion, greater than the channel dimensions in all directions. When the model is being put into operation the movable bed material, properly washed and graded, is placed in the fixed channel and molded to the correct contours, using male templates which were described above.

With the fixed bed models it is usually necessary to modify the concrete finish at some points in order to secure the proper hydraulic gradient. If slight roughness is desired, the surface of the concrete channel is scratched with a trowel point or some similar tool. Greater roughness is secured by the application of a thin coat of stucco which is so manipulated that it projects here and there as unevenly as possible — for all the world like a meringue frosting on a pie. For a smoother finish the concrete surface may be stoned, but usually the original finish is troweled smooth so that there is little to gain in that way.

A special form of roughness is met in some test work where the effect of overbank roughness on the flood waters must be duplicated. In nature this roughness is caused by trees, underbrush and grass. The water actually flows through these obstructions, but at a very reduced velocity. This effect is very nicely duplicated at Vicksburg by the use of screen wire strips set on edge at right angles to the general flow of the water. Changes in resistance are accomplished by the use of various sizes of mesh, and by the number of strips located in a given area. The strips are usually made of galvanized iron wire cut to a width of about 4 inches. Each strip is bent at right angles about every 3 inches of its length, so that the strip stands vertically without any outside support when used on the model.

In connection with the movable bed type of model tests there is one condition, namely, that of a caving bank, which is practically impossible to duplicate automatically in a model arrangement. Of course, if the bank is stable there is no problem, since it may be made of a concrete mixture. There are two ways of treating the caving bank in a movable bed model. In the first place, that critical section may be cast of a very weak concrete consisting of one part cement and ten parts loess (a wind-blown deposit of materials that compares with clay in the fineness of particles). This bank material is then carved away with a chisel or knife at the proper time intervals during a model test. Great care must be taken to prevent the fragments of the bank material from mixing with the bed material and thus spoiling the test results. In the second treatment, the caving bank may be cast in thin concrete sections which may be removed in the proper sequence during a test. A modification of this method is to cast replacement blocks to accomplish the same result where the changes are so small that the former method would give very thin sheets of concrete of insufficient strength for handling.

There are a few details of the model arrangement for test that might be briefly mentioned to complete the description of the model test work. The water supply is usually taken from some convenient constant head tank of which there were five at the time of the inspection. A gate valve in the supply line is used to regulate the flow to a wooden head box. This box contains suitable racks and baffles to provide quiet approach conditions for a "V" notch weir located at the downstream end of the box. These weir boxes or flumes are constructed as separate units made to an identical design. A number of the weirs have been calibrated by a volumetric tank, and the mean coefficient curve is used for all weirs of the same type. Sometimes a number of these flumes are necessary for a single model test where several tributaries connect with a main stream in the test reach of the model.

The discharge from the measuring weir usually falls into a small pool in which there is a grill of bricks or a labyrinth form of channel in order to secure quiet flow conditions at the entrance to the model channel.

At the downstream end of the channel the water is maintained at the proper elevation by a sharp-crested weir in the form of a movable gate which is operated by two or more interconnected worms. In most models this gate is manually adjusted. In some cases, as in the 8-foot testing flume, for instance, the gate is operated by means of an electric motor. In the case of tidal models, the gate is automatically operated by means of a float gage operating in conjunction with a cam cut to represent the tidal cycle. Suitable contacts control the motor circuits through relays and interrupters so as to maintain the water elevation within a few thousandths of a foot of the proper elevation.

The hydraulic gradient throughout the model is determined customarily with hook or point gages set up in suitable hook gage pits. One or more pits are provided for a model, depending upon the number of measuring points to be included and the length of pressure line required. These pits are drained and provided with a roof, both details making for convenience in operation. Each pressure line from a point in the model communicates with a separate hook gage pot. The pots are supported on a rack, side by side, a single hook gage pit ordinarily providing room for fifty pressure measurements. Two methods of reading the water elevation are employed. In the first place, a single point gage is mounted so that it can slide upon a horizontal steel machined bar. After the level of the bar has been checked, the single point gage can be used to measure the water elevation in all the hook gage pots of that battery. In the second method, which is more popular, an aluminum crossbar is attached transversely at the end of a hook gage. Upon this crossbar are mounted separate hook gage points. These individual hook gage points are carefully set to the same elevation with the crossbar horizontal by means of a fine thread and check nuts. Thus the same hook gage can be used to read a dozen pots without moving the hook gage or waiting for any ripples caused by the motion of the gage to die down in the pots. The hook gages used for this type of work are usually those made by Leopold Volpel, which are operated by a rack and pinion. This type of gage has been found most satisfactory. However, when a composite hook gage such as has just been described is being used, it has been found desirable to substitute a large operating handwheel on the pinion drive in order to make the continuous operation of the gage less tiring.

Conclusion

An effort has been made in the foregoing pages to present a brief description of the United States Waterways Experiment Station. This laboratory represents an investment of over $2,000,000 and provides work for about 220 men. It has been obviously impossible to present a complete description of such an organization in the brief space taken in this paper. However, it is believed that a cross section of their activity has been made which presents a reliable indication of their equipment, methods of construction, and methods of model testing.

University of Washington

The work in hydraulics at the University of Washington in Seattle is under the supervision of Prof. Charles W. Harris, who is connected with the civil engineering department.

The hydraulics laboratory at this university has a separate building housing the laboratory, classrooms and offices. The building is 40 feet by 72 feet in plan, and three stories in height. The second floor is only a half-width mezzanine, leaving a very high ceiling over the first floor for the remaining half of the building.

The water used in the laboratory is conducted through a 30-inch conduit to a sump beneath the floor of the laboratory. This connection to Lake Union is provided for make-up water, and also used when large quantities are being discharged with the high head reservoir in use. The storage reservoir is located 100 feet above the laboratory on the campus of the university, and has an area of one acre. It is a concrete-lined circular basin, so that it can readily be used for volumetric measurements of large discharges. The connection between the reservoir and the laboratory is an 18-inch concrete pipe, except for the last portion near the laboratory, which is made of 12-inch steel pipe, and a 4-inch pipe leading from a 6-foot surge tank. Just after the 12-inch steel pipe reaches the laboratory there is installed a 12-inch by 9-inch Venturi meter, allowing the discharge from the high level reservoir to be determined. The maximum discharge that can be taken from this reservoir is about 20 c. f. s.

There are two motor-driven 8-inch pumps which provide the water supply for laboratory use. These pumps are directly connected to the high level reservoir, and, both working in parallel, can supply approximately 7.5 c. f. s. under the existing 100-foot head. One of the pumps is driven by a 150-horsepower motor, and can be used at all heads ranging from 10 feet up to 400 feet. The high limit of head is reached by pumping directly into the closed distribution system of the laboratory. A steady low head for more usual laboratory work is provided by the standpipe 6 feet in diameter and 32 feet high, located outside the laboratory at the entrance to the 12-inch penstock. This is used as a supply for some of the smaller student experiments.

Continuing on the first floor under the mezzanine there is a room partitioned off from the remainder of the space. In it are located two impulse wheels and the 3-inch and 6-inch centrifugal pumps. Both impulse wheels have a capacity of 10 kilowatts under 400-foot head. One of the wheels has a case with glass sides, and this unit is often tested by the students. The other has a cast iron case and is directly connected to a 10-kilowatt generator. While used as a demonstration unit ordinarily, it has proved useful on occasion as a reserve power supply for night work and for electric welding. The 8-inch low head centrifugal pump is used as the subject of a student test, in addition to its use as a laboratory supply. When being tested the pressures are measured with Bourdon tube and mercury gages, and the discharge is measured by a 2-foot weir. The horsepower input to the pump is determined with a calibrated electric motor and electrical instruments.

On the first floor of the laboratory, at the far end from the supply pipe and still under the mezzanine, there is located a vertical cylindrical steel tank 6 feet in diameter and 13 feet high. A 16-inch pipe connection is provided about 30 inches above the floor level where hydraulic machinery can be mounted for tests. A jet dynamometer is available to measure the dynamic action of the jet. The discharge can be diverted into a weighing tank, or else directly back to the sump through a 3-foot concrete channel in the floor. The weighing tank has a capacity of 2 tons and is suspended in a 5-foot round concrete well in the floor. On either side of the 3-foot channel there are installed 4-foot square channels. In one of these channels there is installed a short rectangular flume with a bell-mouth intake. The characteristics of the intake had been the subject of an investigation.

A section at this end of the building is used as a shop. A lathe and drill press are available for power tools. A bench vise and a large number of hand tools are also provided so that a great deal of the machine and erecting work incidental to hydraulic testing can be done on the premises.

On the mezzanine floor there is a steel weir flume. The head tank is 6 feet in diameter and 4½ feet high. The flume is of the same height, 5 feet wide and about 15 feet long, with a suppressed weir located at the downstream end. The discharge from this weir falls into the 6-foot by 13-foot tank on the first floor, which can thus be used as a large volumetric tank for the weir test.

A 2-inch railing is installed on the mezzanine floor, and it also serves as a friction loss test for the students. The water is introduced at one end into the middle "rail" and flows back through the top "rail." Then the water is discharged into one of the volumetric tanks located on the first floor.

The third floor of the building is taken up with offices and the demonstration room. Professor Harris firmly believes that instruction in hydraulics is best presented with a combination of demonstration lectures and laboratory work. For this reason he has fitted up a classroom with a number of simple fundamental experiments which are used as demonstrations during his lectures and recitations. Upon the lecture table two glass tanks 2 feet high and 15 inches in diameter are mounted on rails. Connections are fitted at the bottom of the tanks for orifices, short tubes and a glass tube in which the classical Reynolds experiment is duplicated. Along one side wall an 8-inch pipe is set up over a concrete trough. The pipe is fitted with orifice connections along the top, and a glass manometer is connected into the side. An adjustable crossbar carried on vertical guides is mounted over the pipe so that the height of a stream rising from an orifice can be transferred to the gage glass, allowing the efficiency to be estimated directly.

Along the back wall of the room a 1½-inch by ½-inch Venturi meter is mounted between two 7-inch standpipes about 4 feet high. These standpipes are fitted with manometers. Piezometers are also tapped into the 1½-inch pipe and Venturi meter at six different places, allowing the hydraulic gradient of the system to be determined. The discharge can be caught in a pail or a similar constant volume.

Along the other side wall two experiments are set up. The first consists of 2-inch and 1-inch brass pipes connected by a bushing so as to give a sharp-edged contraction or expansion, depending upon the direction of flow. The pipe is so connected that the water can be supplied or discharged at either end. A number of piezometers are tapped into the pipes at intervals and connected to a bank of open-end manometers on the wall so that the losses and hydraulic gradient can be determined. The other experiment consists of an 8-inch pipe equipped with orifice connections and a pressure manometer. The essential difference between this and the other similar experiment is that the orifices in this case discharge horizontally into a collecting tube so that the discharge can be more accurately measured.

University of Wisconsin

The hydraulic and sanitary laboratories at the college of engineering of the University of Wisconsin, located at Madison, are operated by the department of hydraulic and sanitary engineering, under the direction of Prof. Lewis H. Kessler, acting chairman.

The laboratories are housed in a single building of three stories which is 40 feet in width and 150 feet in length. The sanitary laboratory is located on the upper floor and uses a floor space of about 60 feet by 30 feet. It is equipped with apparatus for testing the purity of water, complete sewage analysis, various types of experimental filters and similar apparatus. Bacteriological analyses are made by the students at the state laboratory of hygiene in Service Memorial Institute. Finally, those students majoring in sanitary engineering are required to do a certain amount of work in sewage plants in actual operation.

The lectures in the course of hydraulics are given in a special lecture room in the hydraulics laboratory which is approximately 32 feet by 48 feet in plan. A projector and screen are available so that slides or moving pictures can readily be used when desired. The lecture table is equipped with demonstration apparatus so that many simple experiments can be performed by the lecturer and his assistants in the classroom. There are two tanks 30 inches square and 5 feet high on the table, one of which is mounted on wheels. The discharge from these tanks falls into a channel and is carried to a weighing tank on a set of Toledo indicating scales, so that the students can determine the discharge in class. These tanks are equipped with short tubes, sharp-edged orifices, model weirs, etc., so that the trajectory of jets, hydraulic gradient, entrance loss, the loss of sudden expansion, and the friction loss in uniform pipe can be demonstrated. It is planned to rebuild this demonstration apparatus in the near future to increase its usefulness so that other phenomena such as the flow over dams, in open channels, and in surge tanks, for example, can be demonstrated, as well as the items mentioned above. The majority of the student experiments in elementary hydraulics are performed on the upper floor.

This portion of the laboratory (about 50 feet by 50 feet in plan) is described in connection with the experiments performed. The apparatus is as follows:

An experiment is performed with differential gages, using fluids heavier and lighter than water. The differential gages — in the one case containing carbon tetrachloride or mercury, and in the other, kerosene — are checked against deflections of water.

There are two sets of equipment available for tests of orifices and short tubes. In the first, a $\frac{3}{4}$-inch orifice is mounted on the end of a 3-inch line, which is supplied by a $1\frac{1}{4}$-inch pipe at some distance from

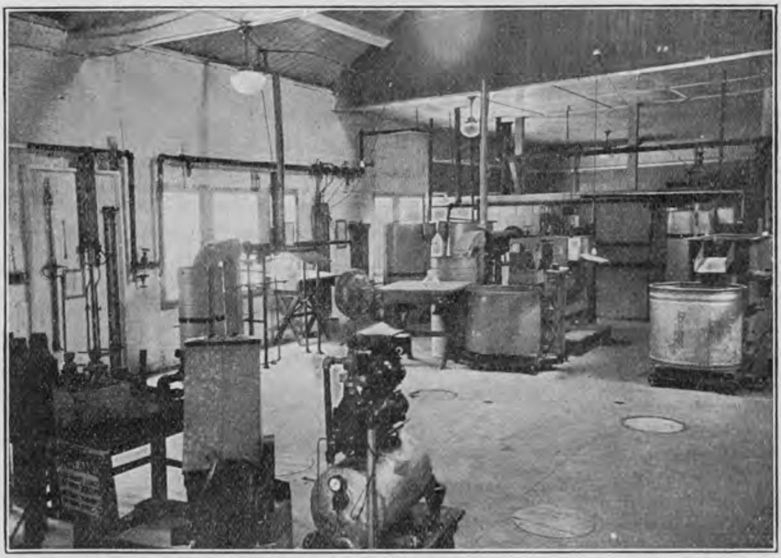

FIG. 61. — UNIVERSITY OF WISCONSIN — STUDENT EXPERIMENTAL LABORATORY ON THE UPPER FLOOR

the orifice. The head on the orifice is measured either by a water column or a mercury manometer. The discharge is determined by means of a volumetric tank 18 inches in diameter and 4 feet high. The other orifice test consists of a $\frac{3}{4}$-inch orifice mounted on the end of a 5-foot length of 8-inch pipe. The pressure is measured with water and mercury manometers as above, and similarly, a volumetric tank 2 feet in diameter and 4 feet high is used to determine the discharge.

There are two Venturi meters set up for test. In one of these experiments a 3-inch by 1-inch Venturi meter is calibrated by means of a volumetric tank 30 inches in diameter and 5 feet high. The deflection of the Venturi is read at the high discharges by a mercury manometer and at the low discharges by a three-legged water and air manometer which is connected to indicate the loss of head in addition to the normal deflection. The second Venturi meter test is similar to the first except that a 2-inch by ½-inch meter is calibrated by means of a volumetric tank 2 feet in diameter and 7 feet high.

There are two weir tests available. A rectangular contracted weir, 6 inches long and 4 inches deep, is mounted in the end of a steel tank 2 feet square in section and 6 feet long. A rock screen at the upstream end of the tank provides quiet flow conditions. The discharge is checked by a weighing tank having a capacity of about 1,200 pounds. The head on the weir is measured by means of a hook gage. The "V" notch weir test equipment is similar to the above except that a "V" notch weir is used which has an included angle of 57°.

A Pitot tube test is made determining the distribution of flow of water in a 3-inch pipe and calibrating the instrument. Water flows into an 8-inch pipe about 3 feet long, the purpose of which is to prevent any abnormal flow conditions which might exist in the upstream piping from being communicated to the test section in the pipe. The test is performed in a length of 3-inch pipe which is connected to the downstream end of the 8-inch pipe. The distance to the gaging section is approximately 8 feet. A Collins or Stevens type of tube is used and a single traverse on one diameter for two different discharges is made. The deflection caused by the Pitot tube is either read in a differential hook gage water manometer or a differential mercury manometer. The discharge is measured in a volumetric tank 30 inches in diameter and 5 feet high.

The friction loss in small pipes is determined experimentally, and the result compared with formulas given in handbooks. The work is conducted in a pipe rack located on the middle floor of the laboratory. There are five pipes in this rack, one being ⅜-inch galvanized iron, another 1-inch galvanized iron, and three ¾-inch pipes which are made of lead, copper and galvanized iron, respectively. The loss in head is measured with a differential air and water manometer, and the discharge is determined with a small weighing tank of about 500 pounds' capacity.

A small impulse water wheel is tested to determine the best speed for maximum efficiency at constant head and at one nozzle opening. This test is performed on a 12-inch Doble wheel mounted in a glass case. The student test is performed with full nozzle opening. The pressure at the nozzle is measured with a Bourdon tube gage, and the discharge measured with a small weighing tank of about 500 pounds' capacity. A Prony brake is used to determine the torque, and a hand counter measures the r. p. m.

The efficiency of a triplex pump is determined at various pressure heads and rates of discharge when operating at a fixed rate of speed. The pump is driven by an electric motor, the input being determined electrically. The suction and discharge pressures of the pump are measured with calibrated Bourdon tube pressure gages. The discharge is measured with a calibrated square-edged orifice. The r. p. m. is determined with a portable or hand counter and a pocket watch.

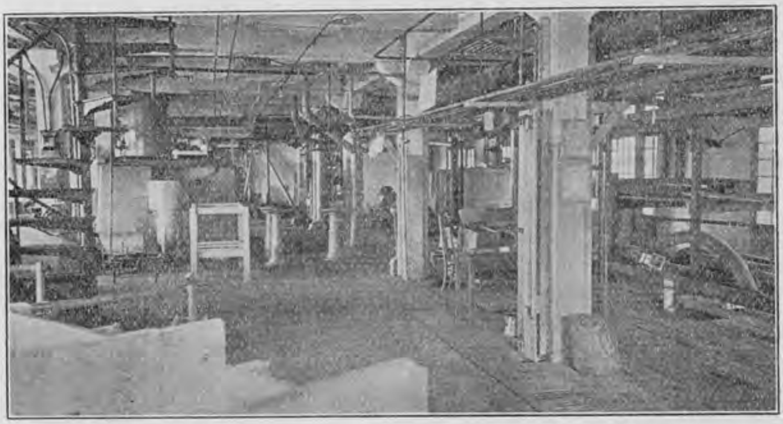

Fig. 62. — University of Wisconsin — General View of the Middle Floor of the Laboratory

In addition to the laboratory experiment noted above, and the demonstrations which are given in the lecture room, there are two pieces of apparatus which are available for use at any time by the students. One of these is a small tank about 4 feet long, 3 inches wide and 12 inches high, with one glass side. At the upstream end of this tank is located a small ogee spillway about 3 inches high. The elevation of the tail-water is controlled by a valve. By regulating the flow and the tail-water elevation, a hydraulic jump is formed and its operation can be studied by the student. Near by there is a model of an air lift pump built out of glass, the eduction pipe being 1 inch in diameter. This can also be operated by the students.

On the middle floor, the space beneath the sanitary laboratory is taken up with a small workshop and four steel cylindrical pressure tanks 8 feet in diameter and 45 feet long. The university water pumping plant is located in a building adjoining the hydraulic laboratory, and these tanks are used to equalize the pressure and as a reservoir for short periods. The high pressure water in this system can be used for some experiments in the laboratory where too great discharges are not required. The remainder of this middle floor, about 50 feet by 100 feet, is given over to hydraulic laboratory apparatus. The water supply can be taken from either of two pumps. The largest is a 30-inch steam engine-driven centrifugal pump which supplies 73 c. f. s. under a head of 12 feet. It is connected to a receiving basin from which is led off a 10-foot square channel, a 30-inch circular conduit, and a 4-foot square channel, all of which run the length of the building. The 10-foot square concrete flume has been reduced in section to about 4 feet square with a walk-way on either side, better adapting this piece of apparatus to model testing. At the end of these flumes is located a flume 10 feet wide, 5 feet deep and about 40 feet long, with a 5-foot contracted weir at the downstream end.

The other water supply comes from a centrifugal pump which is rated at 50 horsepower and 1,750 r. p. m. It delivers 1,800 gallons per minute (4 c. f. s.) at 110-foot head. This pump discharges into a reservoir on the bluff above the laboratory so that the pump does not have to be operated during experiments, thus obtaining very quiet flow conditions. In the supply piping to the laboratory there are installed 12-inch by 6-inch and 8-inch by 4-inch Venturi meters which can be used for checking the discharges when desired.

A 12-inch Trump reaction turbine and a 15¼-inch Girard impulse turbine are located above the approach flume of the 5-foot weir and discharge into it. The water supply for both turbines is taken from the reservoir on the hill above the laboratory. Both water wheels are equipped with Prony brakes for testing.

In the center of this middle floor is located a concrete flume 6 feet square in section and 20 feet long. At one end of the flume there is an opening for an 18-inch contracted weir. The discharge from this weir falls into three concrete volumetric tanks in the basement of the building.

In one corner of the laboratory on this floor there is a steel flume 4 feet wide, 5 feet deep and 12 feet long, in the end of which a "V" notch weir is mounted. The discharge from the weir passes either to a weighing tank 30 inches in diameter and 3 feet high, or to the sump. From the sump the fluid is pumped back into the flume. This weir is being calibrated with different fluids in an endeavor to arrive at a more fundamental formula for the flow of fluids over weirs. The weir has been calibrated with water, and at the time of the inspection the tests were being continued with oil.

Along the floor of the laboratory there is installed a 6-inch pipe about 70 feet long which has been used for some water hammer tests. The discharge is regulated with a gate valve and started and stopped with a lever type quick-acting valve. The pressure fluctuations are recorded by means of a Crosby steam engine indicator, operating with a large drum which is continuously rotated so that the complete pressure diagram is recorded at one revolution. The results of these water hammer tests were published in "Domestic Engineering," by Prof. Louis H. Kessler, in 1931.

A number of experimental filters are set up in one section of this room, being used in thesis work by the students. A Fairbanks-Morse motor-driven, duplex, double-acting, reciprocating pump is also located in this section of the laboratory.

Considerable work has been done at this laboratory on the hydraulics of plumbing and fixtures. At the time of the inspection, test work was in progress on the possibilities of back siphonage through the flushometer type of flush valves for toilets. Tests had just been completed on the pressure conditions existing in a vertical sewer or drain pipe under various conditions of flow. The nature of this work may best be learned from a study of some of the recent bulletins which have been published by the University of Wisconsin; for example, "The Interior Water Supply Piping for Residential Buildings," published in 1933 jointly by the State board of health and the department of hydraulics and sanitary engineering at the University of Wisconsin.

Alden Hydraulic Laboratory, Worcester Polytechnic Institute

The Alden Hydraulic Laboratory of the Worcester Polytechnic Institute is located in Holden about five miles from Worcester. It is operated by the mechanical engineering department, under the direction of Prof. C. M. Allen. The equipment has been arranged for student instruction, research and commercial testing.

The laboratory is located on a natural water privilege providing an adequate gravity supply for experimental purposes. The upper pond is the largest and is used for storage. At the maximum elevation it has an area of 200 acres and a storage of about 28,000,000 cubic feet.

Downstream a short distance from this pond is the second pond, which has an area of about 3 acres. This pond is usually operated at the same elevation as the first, and is separated from it by control gates and culverts through a state road and a railroad embankment. In this second pond there are located the current meter rating station, a spillway, and the intake structure for the 40 inch penstock which supplies the main laboratory building. The spillway discharges into the third pond, which has an area of about two acres. Its elevation is about 8 feet lower than the other two ponds. In this third pond are located a 16-foot Vaughn spillway and the intake structure for the low head laboratory building.

Between the low head and main laboratory buildings, and downstream from the main laboratory, there are a number of outdoor concrete channels available for various forms of test work. Below the main laboratory there is a tract of land having an area of about 200 acres lying on both sides of the stream, which is owned by the college, thus allowing ample room for future development.

The main laboratory building is of wooden mill type construction, about 50 feet by 180 feet in plan, with a basement and two floors above it. Water for power and testing purposes is brought to this building through a 40-inch pipe 350 feet long, having its intake at No. 2 pond. This pipe is connected to an 18-inch water wheel through a 36 inch by 16-inch Venturi meter and a 28-inch Dow butterfly valve. The water wheel was built by the S. Morgan Smith Company and designed to deliver 110 horsepower under 30-foot head at 420 r. p. m. The weight of the revolving parts is carried on a Kingsbury spherical seated thrust bearing which was the first of this design to be put in operation. The water wheel discharges into a tailrace flume 16 feet by 55 feet in plan, located in the lower basement. The flume has been narrowed in width to 8 feet for a distance of 45 feet. At the downstream end of this 8-foot flume there is located a brass-crested suppressed weir which is calibrated by means of a weighing tank.

This water wheel is the subject of student tests. For this purpose an Alden dynamometer can be mounted on the shaft. The torque is measured on platform scales, and the wheel speed determined with a hand-operated, mechanically driven revolution counter. Normally the wheel is belt-connected to a 55-kilowatt direct current generator which is used to supply power and heat to the laboratory.

A Johnson differential surge tank is connected to the penstock about 50 feet upstream from the water wheel. While primarily installed as a protection for the penstock, it has been used as the subject of research

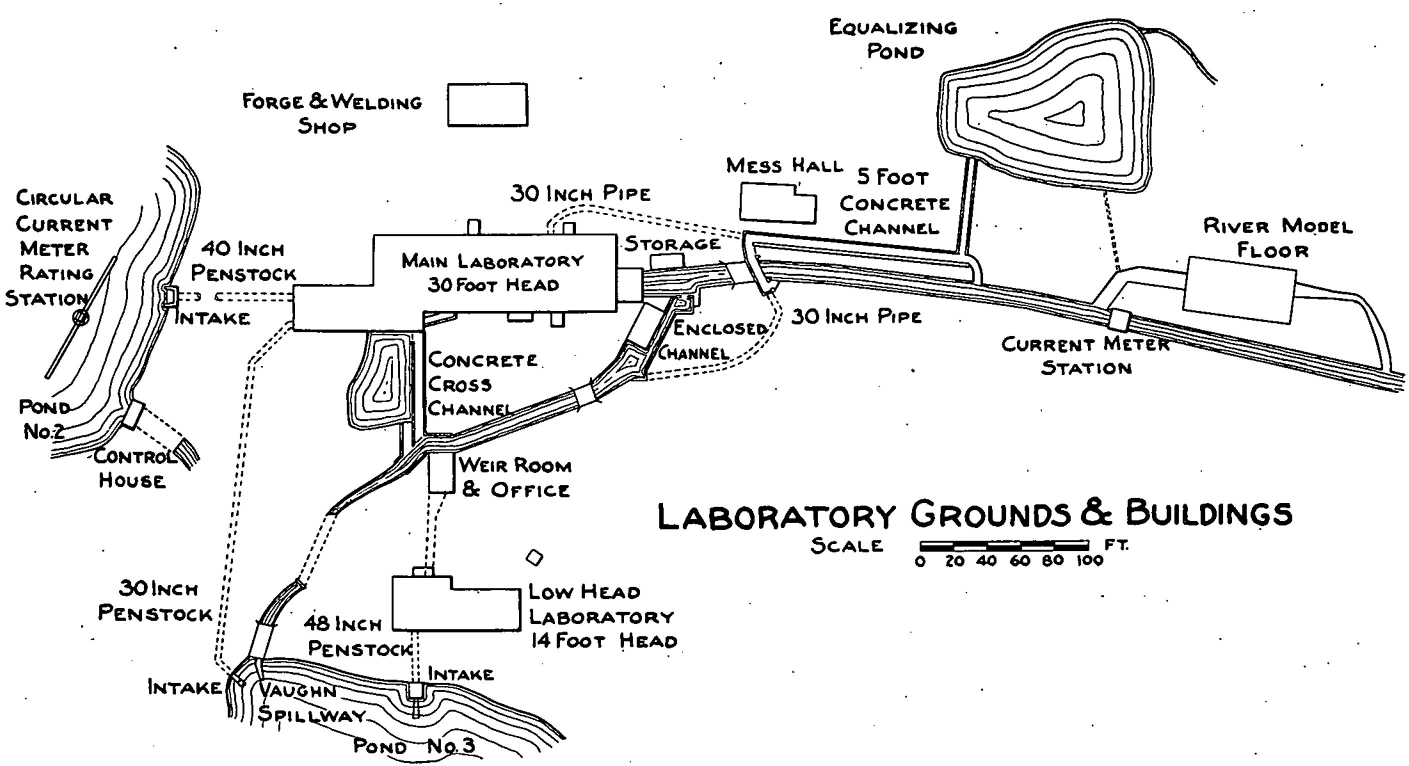

FIG. 63. — ALDEN HYDRAULIC LABORATORY OF THE WORCESTER POLYTECHNIC INSTITUTE, HOLDEN, MASS.

and for the measurement of discharge after the manner of a Gibson test.

Near the surge tank there is a 12-inch connection which supplies a 6-inch water wheel through 100 feet of pipe. This water wheel, which was built by the Newport News Shipbuilding and Dry Dock Company, is direct connected to a 10-horsepower vertical direct current generator, the stator of which is mounted on ball bearings so that it can be used as a dynamometer. The draft-tube of this unit discharges downstream from the 8-foot suppressed weir, so that discharge measurements of the main unit are not affected. The 10-horsepower unit is used throughout the year as a service unit for ordinary laboratory needs. A substation type of storage battery, located in the basement of the low head laboratory building, is floated on the line, taking care of any peak load demands.

Near the large water wheel unit there is installed a 50-kilowatt motor generator set which can be used to convert the entire output of the plant from direct current to 3-phase alternating current at either 110 or 220 volts. The flexibility of the power supply makes possible the ready testing of power transmission machinery, such as clutches, belt and gear drives, etc.

A 2,500-foot-pound Woodward water wheel governor is located beside the large water wheel and directly connected to it. The governor head is driven by a small electric motor connected to the main power bus. The operating servo motor is also connected by cables to the gate mechanism of the 10-horsepower wheel. The governor thus operates either water wheel connected to the power lines, or both of them together.

There are several lines taken from the 40-inch penstock for testing purposes. Just upstream from the 36-inch by 16-inch Venturi meter a 12-inch line is connected which supplies a 5-foot flume in passing, or can discharge into the large weighing tank. There is a 12-inch by 6-inch Venturi meter 20 feet from the inlet, which is used to measure discharges. A number of 1¼-inch connections are provided in the pipe for Pitot tube tests. On the main floor a 12-inch manifold is connected to the line through a tee. Four 6-inch openings are left blanked for future use. This connection was originally in the test of the 1:24 model of the intake structure of the Masson development.

At the intake of this 12-inch line there is also connected a 6-inch line which runs through the upper basement to the large weighing tank. There are three 6-inch by 3½-inch Venturi meters installed in this line for student instruction.

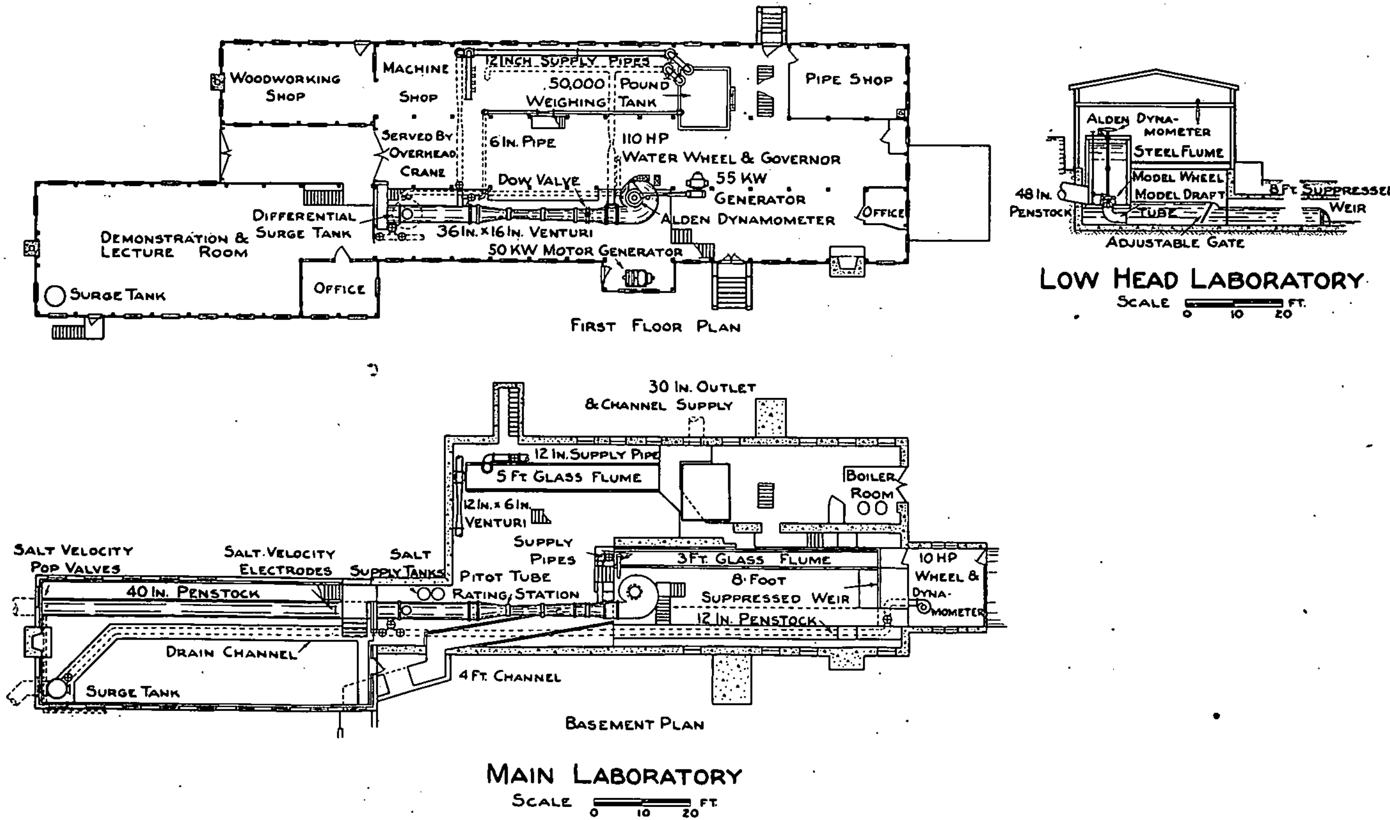

Fig. 64. — Alden Hydraulic Laboratory of the Worcester Polytechnic Institute, Holden, Mass.

Between the Dow valve and water wheel scroll case a 16-inch connection is made. About 6 feet from the inlet to this line there is located a 16-inch by 8-inch Venturi, the diffuser expanding to 12 inches in diameter, which is the pipe size of the remainder of this system. This line discharges into the large weighing tank, or supplies either the 5-foot or the 3-foot glass-sided flumes with water. Taps are also provided for Pitot tube work between the penstock and the weighing tank.

An 8-inch connection is made to the surge tank, and the line runs the length of the laboratory. At present it only supplies the 3-foot flume, but it has served as an additional supply for the 5-foot flume. One branch runs into the upper basement to serve an open space where models may be installed.

Near the center of the first floor of the main laboratory is located a weighing tank of 800 cubic feet capacity, mounted on a set of 50,000-pound Fairbanks scales. This constitutes the primary standard for discharge measurements in this laboratory, all other methods of water measurements being checked against it before use. The maximum discharge into this tank from a single pipe line is 10 c. f. s. In order to secure accurate measurement of this quantity, a contact is made at the mid-position of the switchway, and a calibrated pendulum clock provides a time scale, all data being recorded on a chronograph.

As noted above, two 12-inch lines and one 6-inch line normally discharge into the weighing tank. In addition, there is a sluice leading from the tank to the 8-foot weir flume in the basement, and a 30-inch tile pipe leading to a 5-foot concrete outdoor channel. Thus much of the equipment at the laboratory can be checked directly against the weighing tank.

In the upper basement beneath the first floor there is located a glass-sided test flume 5 feet wide, 6 feet and 3½ feet deep, and 40 feet long. It is supplied by two 12-inch lines, allowing a maximum discharge of about 25 c. f. s. Recently a long series of tests of a rock-filled dam was made in this flume for the Army Engineer Corps.

In the lower basement there is located a new 3-foot steel and glass test flume replacing an older wooden flume of the same width. The height of the new flume is 6 feet in the upper portion and 3 feet in the lower section. The overall length is 56 feet. A 12-inch and an 8-inch line normally supply this flume with a discharge of about 16 c. f. s. The sluice from the weighing tank allows a weir in this flume to be calibrated directly, and also provides an additional discharge of 6 c. f. s. when needed. This flume normally discharges downstream from the 8-foot suppressed weir.

In this lower basement there is also located a temporary wooden flume 18 inches wide, 28 inches deep, and 30 feet long. It was used for transportation and permeability tests. It is planned to replace this flume with one of permanent construction at an early date.

During 1936 a two-story addition 72 feet long was made to the main building on the south end. On the first floor the 40-inch penstock was exposed and thus made available for test purposes. There are four pairs of 3-inch openings in the penstock, which have been used for Pitot tube traverses and for salt velocity investigations.

In one corner of the room there is a steel standpipe 4 feet in diameter which is connected to No. 3 pond by means of a 30 inch tile pipe. Thus an entirely independent water supply is available for test purposes at this end of the laboratory. A 12-inch line connects this supply with the 6-inch water wheel line, so that the house turbine can be operated from either pond No. 2 or No. 3.

The first floor of this part of the building is of concrete with a free space 18 feet by 60 feet. Besides the two separate penstocks there is a small pool just outside the wall of the building with a head of 2 feet above the floor. Thus this section is admirably adapted for small river models and similar work.

On this floor there is also installed a hydraulic ram and a centrifugal pump for test. The 4-inch Rife hydraulic ram is operated with a 70-foot drive pipe from the 30-inch penstock. Water is discharged into a pressure tank with an air cushion to provide steady flow conditions. During a test the water pumped and the water wasted are measured with weighing tanks. Pressures are determined with a Bourdon tube gage.

The centrifugal pump is installed as a student test. A 3-inch Gould single stage pump is driven by a cradled 5-horsepower motor. The intake or suction pressure is measured with a mercury column, and the discharge pressure with a calibrated Bourdon tube gage. The discharge is measured with a calibrated Venturi meter. The torque of the dynamometer is determined with platform scales, and the motor speed with a hand-operated revolution counter.

Another student experiment, a test demonstrating hydraulic gradient, is mounted beside one wall of the building. A small head tank 30 inches in diameter and 3 feet high is supplied by a 2-inch line from the 40-inch penstock. This tank is equipped with an overflow to provide steady flow conditions. The test section consists of lengths of 4-inch, 2-inch and 2½-inch pipe which are equipped with piezometers for the determination of the hydraulic gradient. The discharge passes into a weir flume 18 inches wide, 12 inches deep and 12 feet long, with a calibrated "V" notch weir located at the downstream end.

The second floor of the addition is equipped as a lecture room, having a seating capacity of about 150. Moving picture and slide projectors are available for lecture or demonstrating purposes.

On the first floor of the main laboratory there are a number of power tools both for woodworking and metal working, including 12-inch and 16-inch circular saws, 12-inch band saw, 4-inch and 12-inch jointers, 9-inch lathe, $\frac{3}{4}$-inch drill press, hack saw, emery wheels, and a grindstone. There is also a 15-horsepower Sullivan air compressor, allowing

FIG. 65. — ALDEN HYDRAULIC LABORATORY, WORCESTER POLYTECHNIC INSTITUTE — MAIN LABORATORY BUILDING. SMALL GLASS-ROOFED FLUME IN THE FOREGROUND

the use of the pneumatic tools in construction work. The laboratory is so equipped that all model construction is done on the premises.

The low head laboratory is located about 300 feet from the main building and beside No. 3 pond which is used as a water supply. It is 35 feet by 75 feet in plan, and of two-story mill frame construction. The principal piece of equipment in this building is the water wheel test flume. Water for this flume is taken from pond No. 3 through the gate and rack house, and is brought into the building by a 4-foot diameter penstock. The flume itself is built of steel 8 feet by 10 feet in plan, and 15 feet high. There is a 4-foot diameter hole in the floor of the flume which is fitted with various rings adapted to different sizes and types of water wheels.

There is ample room in the pit below the flume to install any form of draft-tube, either of the concentric diverging type or of the more modern elbow types. A hand-operated gate is mounted in the tailrace so that any desired backwater can be maintained to seal the draft-tube. Below this gate the water passes into a rectangular concrete-lined tunnel 3 feet by 5 feet in section, and about 50 feet long, discharging into a weir flume located under the office building. The flume is 8 feet wide and about 30 feet long, with a brass crested, 8-foot suppressed weir at the downstream end. The discharge from the weir can be taken through a 5-foot concrete channel to the main laboratory, and there passed over that calibrated 8-foot suppressed weir; otherwise it runs down the natural brook bed.

The head on the water wheel under test is measured with a combination float gage and manometer. A scale is carried on the float in a stilling pot in the tailrace, and the water manometer is connected to the flume. Thus one reading provides the net pressure head on the water wheel being tested.

The output of the wheel is measured with a two disc, 14-inch Alden absorption dynamometer. Since the wheels are tested on a vertical shaft, the weight of the dynamometer is taken off the thrust bearing by means of a counterbalance. The torque is carried to a set of platform scales through a pull rod and ball-bearing bell crank. A connection is made to a balanced sleeve valve from the end of the beam of the platform scales. This sleeve valve is connected in parallel with the discharge valve of the dynamometer. In operation, the machine is roughly balanced by hand, and the automatic valve keeps the unit operating at a steady load throughout the run.

The speed of the wheel is measured by means of a revolution counter which is operated by a pendulum clock, thus eliminating personal errors from the timing of the test.

While the flume is designed to test 16-inch wheels under a 12-foot head, a 20-inch wheel delivering 36 horsepower and discharging 25 c. f. s. has been tested successfully.

Connected to one side of the test flume is a 9-inch Platt Iron Works water wheel which is belt-connected to a direct current generator. It is used as a reserve unit and can be blanked off at the flume wall when wheel tests are being made.

In this same building are located a 24-inch cylinder planer and a 36-inch band saw, which are used in model construction work.

There are a number of outside flumes located near the laboratory, affording an opportunity for various types of model testing. Just downstream from the main laboratory there is a glass roofed flume 11 feet wide and 24 feet long. A small pool, supplied by the brook, provides water under a head of about 4 feet. Water can be taken through stop logs at the upstream end of the flume, or from a 3½-foot concrete channel which forms one side of the flume. A 30-inch pipe takes the water from a spillway 8 feet in length, providing steady head conditions for test. The flow of water in the brook can be adjusted at the spillway of No. 3 pond or through the wheel testing flume, depending upon the quantity required.

FIG. 66. — ALDEN HYDRAULIC LABORATORY, WORCESTER POLYTECHNIC INSTITUTE — LOW HEAD LABORATORY

There is installed in this flume a model of a canal lock designed by United States Army Engineers. The model is constructed largely of wood and represents the lock, 4,700-ton ship, two systems of gates, and the approach channel, all to a 1:30 scale. The sector gates are built of brass and operated by an electric motor through gears and a cam and cable drive. The gate motion, water levels in the lock and upstream pool, transverse motions of the bow and stern of the ship, and the longitudinal motion of the ship are all recorded on a 15-inch strip chronograph chart. Thus after a test is started all data are recorded automatically. From this data the filling rates, the total filling time, the motion and the unbalanced forces of the sector gates are all determined.

The 3½-foot channel that is located beside the covered flume also supplies an overshot water wheel 6 feet in diameter, which is the subject of a student test. The discharge is measured upstream from the wheel by a suppressed weir located at the end of the 3½-foot channel. The output is measured with a Prony brake and a revolution counter. Since the speed of the wheel is very low, the revolution counter is geared up 10:1 to improve the accuracy of the short test runs.

Downstream from the covered flume, and on the opposite bank of the brook, there is located a concrete channel 5 feet wide, 5 feet deep and 120 feet long. Water may be brought to this channel either from the weighing tank or from the brook. In the former case, a 30-inch tile pipe connects the sump under the weighing tank with the head end of the flume. In the second case, another 30-inch pipe leads from the 8-foot spillway near the covered flume to a steel channel 3 feet square in section, which bridges the brook and connects with the head end of the flume.

There are two model tests at this point. In the channel itself a 1:30 model of the Holtwood spillway was tested. It is built entirely of sheet copper to avoid the effects of swelling. The purpose of this model was to determine the pressure distribution on the face of the dam under high discharges, and to determine the effect of a construction bridge on erosion at the toe of the dam. The pressure distribution was determined with the aid of numerous piezometers installed along the center line of the model. A bed of gravel 1 inch to 1¼ inches in diameter was used to determine the relative erosive forces.

A 1:50 model of the Holtwood deflection wall is installed upon the stone and gravel bed between the 5-foot concrete channel and the brook. The model was built to study the best shape for a wall dividing the spillway channel and the tailrace at Holtwood. The model included one end of the spillway, the diversion wall, the construction bridge, and the proper bottom conditions for a short distance above the dam. Both of these model studies have been completed.

At the downstream end of the concrete channel the discharge may pass either back to the brook, or else, by means of a short concrete cross channel, to a small equalizing pond. This pond, which has an area of about one third acre, serves as a supply for two outside model tests.

Between the pond and the brook there is located a 1:100 model of the Rock Island development. This model was constructed in 1929 and was protected for three winters while the test program was being carried to completion. Thereafter it had not been protected against frost. However, in 1935 it was put into operating condition for a short series of tests with very little expense.

This model was constructed on a level reinforced concrete base provided with a well-drained gravel foundation, so that future river models of about this size could be very economically installed. Small discharges, up to 5 c. f. s., can be taken from the equalizing pond. Larger flows are diverted from the main brook by means of a stop log dam. The discharge of the model is measured in a weir flume at the downstream end of the model. A 5-foot suppressed weir is used for the large flows, while a "V" notch weir is used for the smaller flows. Both of the weirs are calibrated before use.

The method of construction used on this model was interesting, inasmuch as the procedure differed somewhat from that found elsewhere. Wooden pins with their tops set to the proper elevation were used to determine the topography of the model instead of the more usual transverse templates. The system used was as follows. First, a paper topographical map was made of the entire model by projecting 3-inch squares of the available map onto 6-foot squares of paper and tracing the contours with crayon. These large squares of paper were laid on the flat concrete base in the proper positions, and ½-inch holes were drilled through the papers on the contour lines at suitable intervals. This was done with a portable electric drill set up in a bench mounting and operating against a stop. Hardwood dowels one half inch in diameter and cut to the proper length corresponding to that contour elevation were then driven into the holes. The model was backfilled with sand and given a coating of concrete in the usual fashion.

At the other side of the equalizing pond there is located a 1:24 model of the spillway and waste channel for the Bills Brook Dam of the metropolitan district of Hartford. The model is of composite construction, some parts being made of wood and some of concrete, as dictated by utility. The purpose of the model tests was to check computed values of spillway discharge and hydraulic gradient in the waste channel. Three different series of tests were made as the construction of the project progressed and as increased knowledge of the foundation conditions caused modifications of the original designs. Both this and the Rock Island test illustrate the desirability of leaving a model test set up as long as possible to study hydraulic problems arising during the construction period and the early operation of the plant.

Below the dam of the equalizing pond there is a large level space several acres in extent where extensive river models can be installed. The water supply can either be taken from the equalizing pond directly, or else the topography is suitable for the economical construction of a channel in the side hill along one edge of the model space. The available head from the equalizing pond varies between 5 and 10 feet.

Downstream from the river model there is located a stream gaging station on the main brook. A 90° "V" notch opening was left in a

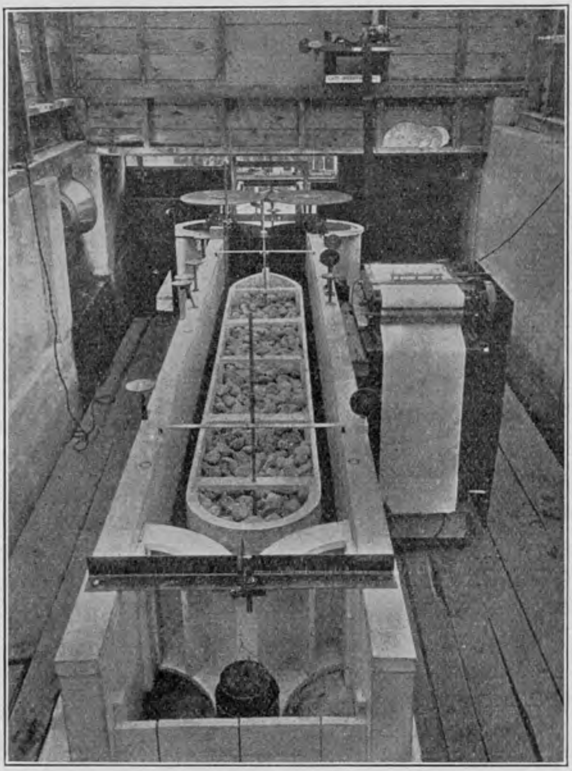

FIG. 67. — WORCESTER POLYTECHNIC INSTITUTE — GLASS-ROOFED ROOM FOR DAYLIGHT PHOTOGRAPHY OF MODELS. CANAL LOCK MODEL BEING TESTED

stone and concrete dam as a control. The water level recorder is located in a small house near the dam.

The circular current meter station is located in pond No. 2. It consists of a horizontal latticed steel boom 84 feet long, hung at the center from a ball-bearing support. The boom is rotated by a water wheel through gears and a rope transmission, providing mechanically quiet operation. Constant speed of the boom is obtained by the use of a governor head operating as a friction brake in the same manner as a phonograph governor. The governor drive is taken from a gear located at the base of the mast.

Since there is no axis of symmetry of the pond about the mast of the boom, and since there is ample room all around the boom for the disturbed water to move away from the zone of action, there is little tendency for the stirring action of the meter to cause circulation of the pond water on the gaging circumference. This point has been the subject of a number of investigations, and no evidence of circulation has been discovered.

The speed range of the boom is from about one third foot per second to 25 feet per second. This rating station has proved most satisfactory for the calibration of ship logs, Pitot tubes and current meters. As an indication of the versatility of this piece of equipment it has also been used for a series of full-sized airplane propeller tests in 1912, and for drag tests of model projectiles in 1917.

Among the miscellaneous equipment of the laboratory are six different types of current meters, a number of Pitot tubes and pitometers, ship logs, Venturi meters and two complete salt velocity recording outfits. The photographic apparatus includes a 3¼-inch by 4½-inch plate camera, a special Kodak moving picture camera, and banks of flood lights mounted in reflectors. A dark room equipped for developing and contact printing has also been installed in the main laboratory.

There are several buildings connected with the laboratory which are not used directly for testing work. At one side of the main building is located a pipe and welding shop. It is of stone construction 25 feet by 45 feet in plan. About one third of the floor space is used as a pipe shop in which are located the gas welding and cutting set, a forge, and the pipe taps and dies. The remainder of the space is used for the storage of pipe and fittings up to 4 inches in diameter.

There are two barns of wooden construction which are used principally for storage purposes. The small barn, 22 feet by 26 feet in plan, is located near the downstream end of the main laboratory. It has two floors and a basement. The latter is used as a garage for the truck and delivery wagon, as well as for field tools, such as shovels, picks, bars and so forth. The other two floors are used for the storage of spare pulleys, shafting, journals, belting, bolts and idle apparatus, such as recorders and Pitot tubes.

The larger barn is located several hundred feet from the main building. It is 42 feet by 65 feet in plan, with the equivalent of two

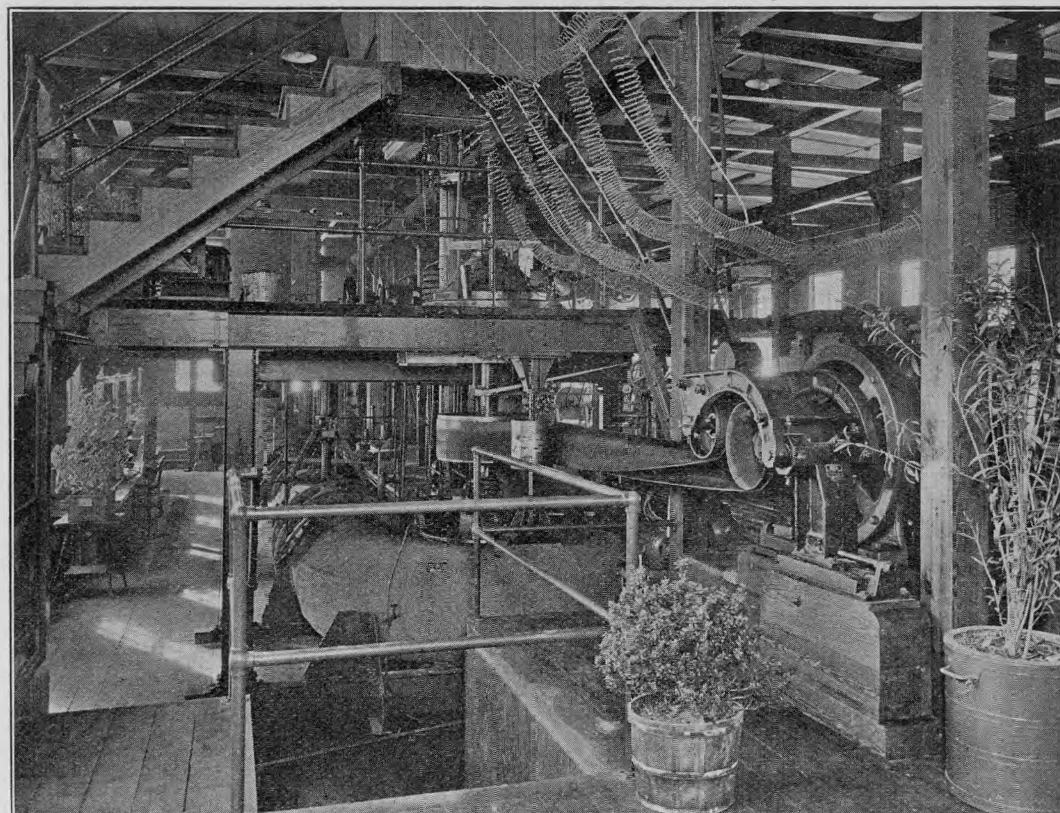

Fig. 68. — Worcester Polytechnic Institute — Interior View of Main Laboratory. 110 Horse Power Water Wheel and Generator in Foreground; Penstock with 36″ x 16″ Venturi Meter in Background

floors and a basement. The latter is used for the storage of heavy pieces, such as large valves, pipe fittings and heavy structural steel. The other two floors are used for electric motors, pumps, smaller piping and miscellaneous wood supplies.

Finally, there are a number of pieces of equipment available for ordinary construction work. A truck, grader, loader, concrete mixer, and a gasoline engine-driven diaphragm pump are among these items. A gravel bank on the property assists materially in economical concrete construction.

In conclusion, it is seen that this laboratory is well equipped for the performance of student and research work, as well as commercial testing over a wide range of hydraulic subjects.

Yale University

The hydraulic laboratory equipment at the engineering school of Yale University at New Haven, Connecticut, is found in both the civil and mechanical engineering departments. Both laboratories are designed for undergraduate instruction. Work in the civil department is directly supervised by Prof. Roscoe H. Suttie, and in the mechanical department by Prof. Fred W. Keator.

The laboratory equipment in the civil engineering department is installed in a room about 40 feet by 40 feet in plan. Two sources of water supply are used in the experimental work. A flow of 0.1 c. f. s. is available directly from the city main. This is connected to a constant level storage tank which provides a head of 60 feet at the laboratory floor. An electric motor-driven centrifugal pump recirculates a discharge of 1.2 c. f. s. through a 5-inch by $2\frac{1}{2}$-inch Venturi meter and over a 90° "V" notch weir located in a stilling tank.

The principal piece of equipment in the laboratory is a steel flume 1.8 feet high, 2 feet wide, about 18 feet long and elevated about 3 feet above the floor. Racks are provided near the upper end of the flume, and various types of weirs may be located at the discharge end. A deflecting chute is mounted at the end of the flume so that the discharge may be carried into a weighing tank of 600 pounds' capacity, or else allowed to flow directly into the sump. Small models are tested in this flume.

Above the weir flume two steel tanks, each about 4.5 feet high and 18 inches in diameter, are mounted on wheels running on a steel track. Each tank is fitted with several openings suitable for the ready installation of orifices, tubes and nozzles. This apparatus allows the coefficients of velocity, contraction and discharge, together with the jet trajectory, to be determined. In addition, the transfer of energy may be demonstrated between the tanks.

A small Pelton water wheel is available for test. The pressure at the nozzle is measured with a Bourdon tube gage, and the output is determined with a Prony brake and a hand counter.

A loop of 2-inch pipe having a test length of about 30 feet is arranged with a number of piezometers and connected to water manometers so that the hydraulic gradient and the pipe loss may be determined. The discharge is measured in the weighing tank. A 2-inch by 5/8-inch Venturi meter and a house type of water meter are also connected into this pipe system so that they may be calibrated directly by the weighing tank.

Current meters and pitometers are available for use by the students. The current meters are used in the Yale rowing tanks for a practice experiment, and also in actual stream gaging. A small model of the Yale rowing tanks has also been made for student study in the laboratory.

Several experiments concerning fluid flow are given to the students of mechanical engineering as a part of their elementary laboratory work. In one of these tests a 3-inch centrifugal blower supplies air to a pipe line in which there are located a well-rounded orifice plate, a sharp-edged thin plate orifice, a square-edged thick plate orifice, and, finally, a 3-inch by 1½-inch Venturi meter. All of these meters are permanently connected to suitable water manometers and draft gages, and the performance of the meters is compared by the students.

A 4-inch motor-driven centrifugal blower supplies air to a 12-inch galvanized iron pipe in which there is mounted a Pitot tube. The discharge in the pipe is measured by making a Pitot tube traverse. A sharp-edged orifice at the end of the pipe regulates the discharge, and also, by means of a suitable manometer, provides an indication of the discharge which checks the value obtained by the Pitot tube traverse.

A weir test is performed on an 8-inch "V" notch weir located in the end of a steel tank 24 inches square in cross section and 4 feet long. The discharge may be checked in a weighing tank. A second weir tank of welded steel construction has been recently added to the equipment. This tank is 3 feet by 4 feet in section and 6 feet long. It is equipped with a 14-inch 60° "V" notch weir.

A steam pump supplies water under pressure to a wabble plate water meter and a 1½-inch by ¾-inch Venturi meter, the discharge finally passing to a weighing tank for measurement. The Venturi meter deflection is read with a mercury manometer.

Three volumetric tanks 3 feet in diameter and 15 feet 9 inches high are being installed to make possible the more accurate determination of discharge. The service piping of a new condenser is being installed in such a manner that tests may be made on the circulating pump which has a capacity of 700 g. p. m. at 90-foot head.

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