SOME HYDRAULIC AND HYDROLOGIC ASPECTS OF THE NIAGARA POWER PROJECT

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GENERAL

THE installed Niagara River hydro-electric generating capacity in the United States and Canada exceeds 5 million HP and thus represents the largest local aggregation of electric generation in the world.

It is not size alone, however, that makes the developments at Niagara noteworthy. Unique hydraulic and hydrologic problems confronted the designers of the power projects at Niagara. These arose from the fact that the huge power developments were not permitted to disrupt the famed Niagara cataracts. These continue to demonstrate the awesome force and beauty of nature, as approximately one third of the annual natural river flow plunges 160 feet over the American and Canadian Niagara Falls.

Chas. T. Main, Inc., Boston, through its affiliated partnership Uhl, Hall & Rich, engineered and is supervising construction and offering technical advice on the operation of the most recent and largest Niagara project—that of The Power Authority of the State of New York (1, 2, 3). At this writing (November 1, 1961) eight of the ultimate thirteen units in the principal Power Authority station, the Robert Moses Niagara Power Plant are running—producing about 1,400,000 KW. The first of 12 reversible pump-turbines in the Lewiston Pump-Generating Plant has just gone into operation.

NIAGARA RIVER TREATY

Diversions from all the International Waters dividing the United States and Canada are controlled by Treaty (4, 5). Before 1950, Niagara diversions were controlled by the provisions of the original Boundary Waters Treaty of 1909, signed by Elihu Root, Secretary of State of the United States and James Bryce, the great authority

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on American political mores, who was Great Britain's Ambassador to the United States. This treaty provided, among other things, that Canada could divert at an average daily rate of 36,000 cfs from the Niagara River for power purposes, while the United States could divert 20,000 cfs. At the time of the treaty U.S. interests owned the Rankine and Toronto Power developments of approximately 22,000 cfs capacity on the Canadian side of the river and the City of Chicago was diverting more than 5,000 cfs from Lake Michigan through the Chicago Drainage Canal and into the Mississippi basin. During World War II, and later in the 1940's, notes were exchanged between the Governments of the United States and Canada permitting temporary increases in diversions aggregating about 25,000 cfs. These diversions lowered the level of the Chippewa-Grass Island Pool, the wide and deep reach of the river about four miles above the falls from which the high head power diversions are made. Since the river below the pool is relatively shallow on the American side, lowering the pool level caused a marked reduction in the flow down the American Rapids and over the American Falls. During the 1940's a submerged dumped stone weir was built out from the Canadian shore almost half way across the river at the head of the Canadian Cascades, the stretch of rapids above the Canadian Falls. The purpose of this weir was to raise the level of water in the Grass Island Pool in order both to improve hydraulic conditions at the power intakes in the pool, particularly during ice runs, and to increase the flow over the American Falls.

In 1950, as a culmination of over 30 years of discussion and study, The Niagara River Diversion Treaty was signed by representatives of the United States and Canada. This treaty recognized implicitly that the very geological processes that had created the falls refused to stand still and were gradually changing the character of the Canadian Horseshoe Falls to its detriment. What was happening was that erosion was proceeding upstream at a faster rate at the center of the Horseshoe than at its flanks, so that progressively less water was flowing over the flanks. The two governments reasoned that if judicious excavations were made in the river bed along the flanks of the Horseshoe, the scenic beauty of the falls would be enhanced to such an extent that power diversions could be increased beyond those previously authorized without detracting from the scenic beauty of the falls. The 1950 Treaty made provisions for the two countries to construct whatever remedial works would be necessary to enhance the beauty of the falls by providing them with an unbroken crestline. It also required minimums of 100,000 cfs flow over the falls during the daylight hours of the April-October tourist season and 50,000 cfs the rest of the time. The rest of the water was allocated for power—a sizeable amount since the monthly average flows of the river vary between limits of about 250,000 cfs and 170,000 cfs.

Pursuant to the Treaty elaborate surveys were made of the river bed in the Cascades reach of the river and were followed by model tests at the Vicksburg, Mississippi Laboratory of the U.S. Waterways Experiment Station and the Islington Laboratory of the Ontario Hydro-Electric Power Commission, and by model verifications from river measurements. From the model tests, the necessary excavation was determined, as was the need for a control dam just below the submerged weir. The control dam as built consists of 13 bascule gates 100 feet wide by 10½ feet high with 10 foot piers between gates (6). Without this gated dam, it would be impossible to quickly change the flow over the falls in accord with the terms of the Treaty. Also, the dam was designed to make it possible to maintain normal Chippewa-Grass Island Pool levels in the face of the increased pool diversions permitted by the 1950 Treaty. As discussed above in connection with the submerged weir, any lowering of pool levels would reduce the hydraulic efficiency of the existing power intakes and also make the passage of ice runs hazardous. Lowering the pool levels would also increase the required depth and thus the cost of the proposed new intakes. The gated structure permits surging the pool by alternately closing and opening the gates—the sort of operation that is often successful in dislodging ice and getting it to move.

After the 13 gate structure was completed, as a result of changed conditions including the collapse of the old American Schoellkopf plant, it was found that the desired degree of falls control would require lower than normal pool levels. That is, to restrict the falls flow to 50,000 cfs, it would be necessary to keep the pool at lower than expected elevations. Additional model studies were made in 1960-1961 at the Islington Laboratory, as a result of which 5 additional gated bays are now being added to the control structure and training walls are being built parallel to the Canadian shore, upstream and downstream of the dam to funnel ice through and beyond the three inshore gates of the existing structure.

LAKE ERIE OUTFLOW

The level of Lake Erie is subject to both an annual cycle and to longer but erratic cycles lasting for many years. Winds and pressure patterns are always acting on the lake to tilt its surface, sometimes toward and sometimes away from its outlet at Buffalo. The tilting effect of wind and pressure at times results in Niagara River flow variations in a single day of greater magnitude than are experienced on a monthly average basis over an entire year.

The Chippewa-Grass Island Pool Control Structure (Fig. 1) is a real asset to the power project. It makes it possible to absorb much of the variation in hourly Lake Erie outflow in the pool. Normal operating practice is to maintain the mean level of the pool at an

FIGURE 1.—CHIPPEWA-GRASS ISLAND POOL IN RIGHT FOREGROUND WITH CONTROL STRUCTURE AT ITS LOWER END. FALLS AT LEFT FOREGROUND WITH ONTARIO POWER PLANT JUST BELOW CANADIAN FALLS. POWER AUTHORITY CONDUITS PASS DIAGONALLY ACROSS CENTER. (Photo Oct. 21, 1959, courtesy Power Authority of the State of New York.)

elevation appropriate to the flow expected from Lake Erie. The operation of the structure can be illustrated by considering a case where Lake Erie is relatively flat at 9:00 A.M. during the tourist season, 200,000 cfs is coming down the river, the pool is at its normal level for 200,000 cfs, sufficient control gates (about three) are open to permit the passage of 100,000 cfs downstream over the falls and the Power Authority and Ontario Hydro are each withdrawing 50,000 cfs through their pool intakes. If Lake Erie were to now rise quickly at Buffalo, that fact would be telemetered to the water dispatch center located near the falls, apprizing the power entities of the changed situation on the lake. It would then be impractical and indeed impossible for the power entities to so change their power operations as to entirely accommodate such a change in Lake Erie outflow without the passage of any excess flow over the falls. As the increased flow from the lake reaches the pool, the power diversions can remain unchanged, the pool will begin to rise and the control structure gates can be closed sufficiently to prevent the flow over the falls from exceeding 100,000 cfs. The control structure although only "half-a-dam" is most certainly better than none. It controls rather effectively, not just the 4 mile long Chippewa-Grass Island Pool lying below Grand Island but the entire 18 miles of river up to the lower end of the Black Rock Rapids at the Lake Erie outlet. This "reservoir" has an area of approximately 8250 acres and thus a capacity of about 100,000 cfs hrs. per foot of storage. Normally, about a foot of live storage in this pool will be available to alleviate the effects of the vicissitudes of Lake Erie—about half a foot to absorb flows higher than expected and a similar amount to be drawn on for power when flows are lower than expected. Half a foot on the pool is equivalent to about 1/4 of the average volume of water that flows out of Lake Erie each hour.

Two methods of predicting Lake Erie outflows are being studied. For predicting outflows more than a day in advance statistical procedures will be necessary. There are records of many years duration of hourly levels of the lake at both Buffalo and the opposite end of the lake at Toledo. From these records groups of probability curves for each month can be constructed. The curves would assign frequencies to the full range of plus and minus deviations of the Buffalo gage level from the "flat" lake level (Buffalo-Toledo average). Separate curves would be developed for average Buffalo levels ranging perhaps from 3 hours to 24 hours (at 3 hour intervals) and from 2 to

30 days. The lake level at Buffalo, of course, is a good index of the Niagara River flow.

For short range predicting, Ontario Hydro is developing a mathematical model of Lake Erie incorporating the classical equations of hydrodynamics, the empirically determined natural period and damping characteristics of the lake and the effect of wind-induced tangential shear on the lake. It is expected that this model will be reproduced on either a digital or analog computer. Then with the "flat" lake level, the level at Buffalo, and the rate of level change at Buffalo at any instant together with the expected wind direction and intensity (at the lake surface), the expected course of Buffalo levels for the hours ahead could be readily computed.

ICE

Strong southerly winds blowing across Lake Erie towards the Niagara River outlet when a heavy ice cover on the lake is breaking up can hasten the breakup and cause large blocks of ice to wedge at the lake outlet, thus obstructing the lake outflow. Only rarely does this sort of thing occur to any great extent.

Normally ice from the lake breaks up during winter and spring thaws and floats down the river. The extent of these ice flows varies with the severity of the winter (which governs the ice cover formed on Lake Erie), with the nature of the thaw (whether it is sudden and extreme or gradual), and with wind conditions on the lake at the time of ice break-up. The acts of man can aggravate the ice problem to a considerable extent. In the spring of 1961, ice breakers moved in to open up Buffalo harbor and loosed "icebergs" down the river. These first hung up on the old submerged weir just upstream of the control structure and then threatened to obstruct the intakes to the Sir Adam Beck #2 Plant of Ontario Hydro. Since the new Power Authority plant had just begun operating in February 1961 and had but a few units on the line, the conditions at the Canadian intakes were not as critical as they would have been had the Authority plant been in full operation. There was a relatively large flow of water past the control structure, many of the control structure gates were open and conditions for the transport of ice to the falls were relatively favorable. It was disturbing that, under those conditions, ice represented such a hazard to the Canadian intakes. The model tests at Islington to determine the number of gates to be added to the control structure were also used to study the ice problem. Paraffin blocks, having about the same density as ice, were used to simulate the action of ice. These tests indicated that ice would indeed represent a serious problem and even with the two inshore gates open might stagnate at the Sir Adam Beck #2 intake. Many structures were tried in the model to correct the situation. The final solution was a wall paralleling the Canadian shore as an upstream and downstream extension to the pier between gates 3 and 4. This wall, with gates 1 and 2 and perhaps 3 open, created an ice gathering acceleration channel upstream and an ice escape channel downstream of the control structure. The acceleration channel principle has been successfully used for log sluicing by Ontario Hydro at a number of their northern dams. The Power Authority intake is parallel to the American shore and is of the "draft distributor" (1) type, similar to the Sir Adam Beck No. 2 intake. The ports are about 20 feet below the river surface and the entrance velocities are low. A dike upstream of the intake, that will accelerate surface ice past the intake, and an ice escape channel excavated in the river bed downstream from the intake are expected to produce a sufficient downstream surface current along the shore to carry the ice on the American side past the Authority intake. Whether a strong southwest wind blowing diagonally upstream toward the intakes will have any appreciable effect on ice movements along the American shore remains to be seen.

The treaty requires that 50,000 cfs pass over the falls in the winter, while the power entities have the capacity to divert about 160,000 cfs of ice free water from the Chippewa-Grass Island Pool to the lower Niagara River about 5 miles below the falls. The ice that is carried down to the pool from Lake Erie by the full river flow of about 200,000 cfs will be flushed over the falls by the normal flow of 50,000 cfs, augmented by judicious releases through the gated control structure. The location of the Ontario Power Plant, the Falls Observation Tower (Fig. 2) and other structures near the normal high level of the Maid-of-the Mist Pool appears to make it extremely desirable that ice jams be avoided in this pool (located at the foot of the falls) and that the ice be kept moving into the fast moving Whirlpool Rapids reach of the river. There have been instances in the past when large ice jams developed in the Maid-of-the-Mist Pool when the flow through that pool exceeded 100,000 cfs. It is anticipated that when ice flows are heavy, it will be necessary to release water in excess of the treaty minimum over the falls to keep the ice moving through the Maid-of-the Mist Pool. It will require a "learn by trial" process to determine what is the most economical way to keep the ice moving below the falls.

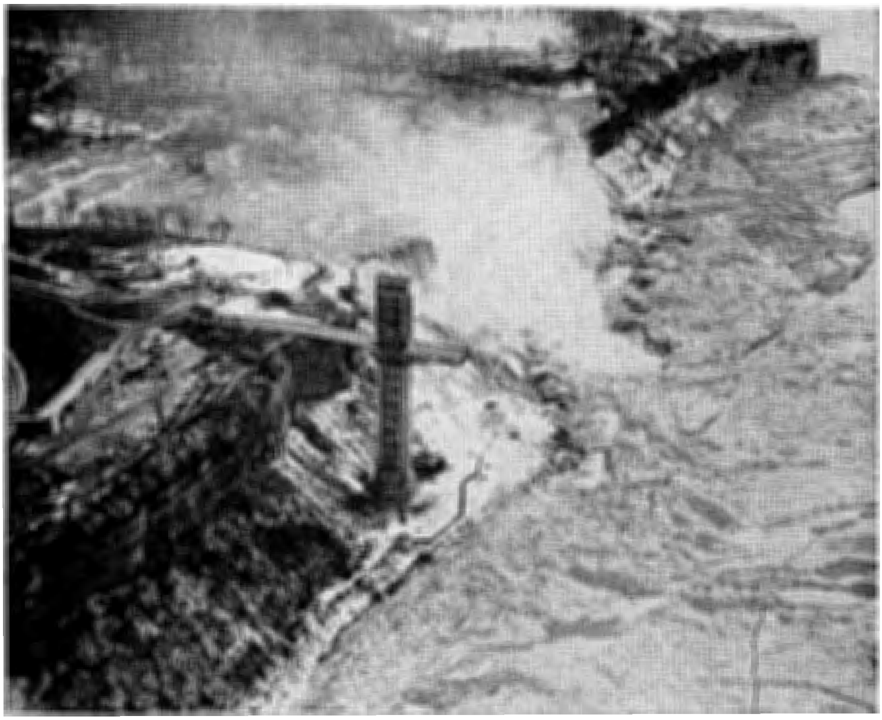

FIGURE 2.—ICE IN UPPER END OF MAID-OF-THE-MIST POOL. U.S. FALLS AND OBSERVATION TOWER. (Photo January 18, 1961, courtesy Power Authority of the State of New York.)

In occasional years there have been ice jams in the lower Niagara River backing up from an ice cover on Lake Ontario. In the spring of 1956 ice was piled almost 40 feet high at the site of the Robert Moses Niagara Power Plant, the Power Authority's main plant. The power house has, of course, been designed to operate safely if such a jam should reoccur. The major ice jams of this kind occur when north winds blowing across Lake Ontario and up the lower Niagara River coincide with the occurrence of an ice cover on the lake and heavy ice runs in the river.

Hydraulics of the Power Authority Development

To this point, the considerations common to all the power developments on the river have been discussed. Now the operation of the Power Authority project will be considered.

Water at specified but varying rates of flow will be dispatched to the Power Authority by a water dispatching authority—representing the United States and Canadian power entities. This rate will be changed as changes occur in some or all of the various factors entering into its determination, i.e., falls flow requirement, meteorological conditions on Lake Erie, the general level of the lake and ice conditions. The value of the power produced at the project would obviously be seriously impaired if power production were at the complete mercy of this water dispatch—thus, the need for the well-known pumped storage plant at Niagara (7). Not so well-known, perhaps, is the manner in which this plant will operate on an hour to hour basis.

Scheduling Project Power

The Power Authority has contracted for the sale of the power produced at the project at rates which guarantee the payment of the interest on and the amortization of the principal of the outstanding revenue bonds that provided the funds necessary to build the project. All the bonds were offered to and purchased by the public. The most economic use will be made of the water power available at the project. The power contracts provide that rural and domestic customers in the market area of the project who buy project power from the large utility purchasers of Niagara power shall be credited with any savings that accrue to the utility companies by virtue of the difference in cost between Authority power and the most economic alternate sources of thermal power for supplying the rural and domestic loads. Optimizing the hourly scheduling of steam generation in a utility system with no hydro resources is no simple problem. Adding hydro to the process complicates matters but does not render the problem insoluble. Operating the Niagara Project in such a way as to minimize, to the greatest practicable extent, the cost of thermal generation in the interconnected system, precludes changing the project load every time the water dispatch changes. An economic scheduling of hourly project loads must be accomplished when no one knows exactly what Lake Erie will do.

Thanks to the Lewiston Pump-Generating Plant this fact is not too disturbing. Consider, for example, a situation where river conditions dictate a 3,000 cfs cut in the Power Authority diversion rate in the face of a 23 megawatt load increase at a time when the Pump-Generating Plant is generating. The plant operators would first obtain the reservoir, forebay and Niagara River tailwater levels and then assume that the entire 23 MW increase were generated at the Robert Moses Plant. Under that assumption, however, an additional 1,000 cfs would be diverted from the Niagara River and the Authority would then be diverting 4,000 cfs more than its allocation. One Lewiston generating unit at best gate, with the observed Reservoir, forebay and tailwater levels, however, can furnish power at Lewiston and water for power at Moses equivalent in total to the power produced by about 4,000 cfs at Moses alone. Thus, the proper operation to keep the hydraulic system in balance is to put another Lewiston generator on the line at best gate. Electronic load-frequency control equipment sensing the Lewiston and Moses Plant generations and the desired project output will automatically impulse motors on the speed level devices of the Moses governors until the Moses units are at the proper load (desired project load less Lewiston generation).

SURGES IN FOREBAY CANAL

The 71 acre Forebay Canal (Fig. 3) acts as a simple surge tank for the two conduits that lead Niagara River water to the Moses and Lewiston Plants. Each of these conduits is 46 feet wide, 66 feet high and about 4 miles long. The combined conduit cross-sectional area is 5616 square feet. Equilibrium in this system is reached when the flow through the conduits equals the draft on the Forebay Canal. Whenever there is a change in the forebay draft, such as occurs when there is a load change on the Moses Plant, the immediate effect is to change the elevation of water in the forebay. The inertia represented by the water flowing in the conduits is large in amount and relatively slow to change. The large forebay, sized with this in mind, and the conduit friction (Manning's "n" of approximately 0.012) lead to rapid damping of surges. On sudden increases in draft even of large amounts, surges are damped in less than two hours. On decreases in draft, since conduit friction is relatively small at the end point, complete damping may take a few hours longer. The time of the first quarter cycle of these surges is about half an hour. That is, it takes about half an hour after a sudden load change for the forebay level to make its maximum change.

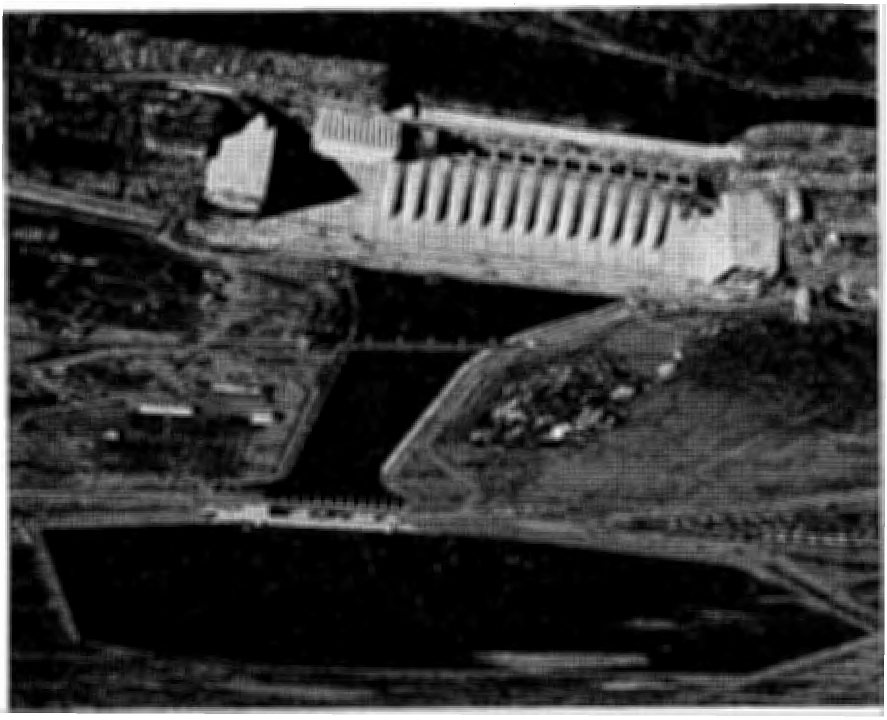

FIGURE 3.—IN CENTER IS 71 ACRE FOREBAY CANAL, BELOW IT IS MOSES PLANT, ABOVE IT LEWISTON PUMP-GENERATING PLANT WITH 1900 ACRE RESERVOIR. CONDUITS DISCHARGE INTO FOREBAY CANAL AT UPPER RIGHT. (Photo November 29, 1961, courtesy Power Authority of the State of New York.)

HEAD LOSS IN CONDUITS

Actual head losses in the conduits are about the same as those computed during the design of the project. As mentioned above the estimated roughness corresponds to a Manning's "n" of 0.012. Conventional bend loss formulas were assumed, and model losses were available for both the intake to and the exit from the conduits which were designed for best efficiency in the Islington Laboratory of the Ontario Hydro-Electric Power Commission. The maximum practical capacity of the conduits is as yet unknown. This limiting capacity, well above the design criterion, is expected to occur at some flow above 100,000 cfs, with conduit flow becoming unstable and the conduits alernately flowing full and part full causing the forebay to fluctuate severely. At 50,000 cfs, the head loss from river to forebay is about 4.5 ft.; at 100,000 cfs it is expected to be about 18 ft. Because of the large area of the forebay, if it were desired to divert an average of 50,000 cfs from the river for an hour following a diversion rate of 100,000 cfs, it would be necessary to change the forebay draft at the start of the hour from 100,000 cfs to about 40,000 cfs, and to maintain that 40,000 cfs for the hour.

Digital Computer Applications

As the multitude of studies related to operating the Niagara Project have been carried out, numerous applications have been found for digital computers. As one result of these studies a 16,000 word magnetic drum computer system will soon be installed at the Moses plant. It will dictate the operation of both the Lewiston and Moses plants in compliance with the two disparate requirements of water diversion and power production, and will also log hydraulic and electrical operating data and alert the plant operator to the need for rescheduling plant loads in the face of an impending empty or overflowing reservoir. The simple surge tank problem was programmed for direct solution using second derivatives and numerous surge studies have been made with a minimum of labor. Various tabulations that greatly facilitate operating studies have been made by computer. The statistical analyses of lake levels at Buffalo, mentioned previously, would be extremely time consuming and expensive were it not for the availability of digital computers.

Conclusion

The great developments alongside the scenic spectacle at Niagara are appropriate monuments to the art and science of hydraulic engineering. The design of these developments required and their operation involves recognition of a variety of natural and artificial variables. These range from meteorological influences on Lake Erie and the Niagara River to hydraulic transients in the conduit-forebay systems of the high head power developments, and from the treaty requirements for falls flow to the characteristics of the interconnected electric systems in the region.

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