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VOLUME 63 JANUARY 1977 NUMBER 4

VOL 57-63

1970-1977

1-4 for each vol

JOURNAL OF THE

BOSTON SOCIETY

OF

CIVIL ENGINEERS SECTION

AMERICAN SOCIETY

OF

CIVIL ENGINEERS

Volume 63 **January 1977** **Number 4**

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Second-Class postage paid at Boston, Massachusetts

Published four times a year, January, April, July, and October, by the Society
230 Boylston Street, Boston, Massachusetts 02116

Subscription price $10.00 a Year (4 Copies)
$2.50 a copy
All orders must be accompanied by check
Members' subscriptions are part of their dues.

JOURNAL OF THE
BOSTON SOCIETY OF CIVIL ENGINEERS SECTION
AMERICAN SOCIETY OF CIVIL ENGINEERS

Volume 63 **January 1977** **Number 4**

GEOLOGY OF THE DORCHESTER TUNNEL, GREATER BOSTON, MASSACHUSETTS

By
Steven M. Richardson[1]

Abstract

The Dorchester Tunnel extends 6.33 miles southeasterly from shaft 7B at the Chestnut Hill Reservoir in Brighton to a newly constructed shaft (7D) in Dorchester Lower Mills. The tunnel was constructed as a major water supply for the southern part of Greater Boston to complement the City Tunnel Extension to the north. It is entirely in bedrock, and is the first modern tunnel to be driven south of the axis of the Central Anticline in the Boston area, providing a previously unattainable geologic section through sediments in the southern half of the Boston Basin and into the volcanics of the Mattapan Formation. Approximately 3300 feet of the tunnel (less than 10%) was supported by structural steel ribs. Most of the excavation was performed by conventional blasting methods, but nearly 3800 feet of the tunnelling was performed by a full-face rotary drilling machine ("Mole"), used here for the first time in New England.

Introduction

Investigations of the bedrock geology in the Boston Basin have been carried on in a series of tunnels built under the supervision of the Engineering Division of the Metropolitan District Commission during the last thirty years (Rahm, 1962; Billings and Tierney, 1964; Billings and Rahm, 1966; Tierney, Billings, and Cassidy, 1968; Billings, 1975). Except for the Dorchester Bay Tunnel (Fig. 1; Clarke, 1888), these tunnels are in areas north of the axis of the Central Anticline.

The Dorchester Tunnel offered an opportunity to study in detail the stratigraphy and structure south of the Central Anticline. Various sedimentary and igneous rocks were crossed in the tunnel: conglomerate, sandstone, arkose, argillite, felsite, and melaphyre. Locally the rocks were extensively altered and fractured. These varying conditions were major factors influencing the method of excavation and the amount of support.

Of special interest in the construction of the Dorchester Tunnel has been

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the experimental use of a full-face rotary drilling machine, or "Mole", and of a rotary raise drilling machine. A short discussion of these excavation tools, as well as a consideration of some physical properties of the rock in the Dorchester Tunnel has been included here because of its significance for engineers. Shotcrete was used in an experimental way for structural support for 300 feet in the headings either side of shaft 7C, but was deemed inadequate for most of the tunnel.

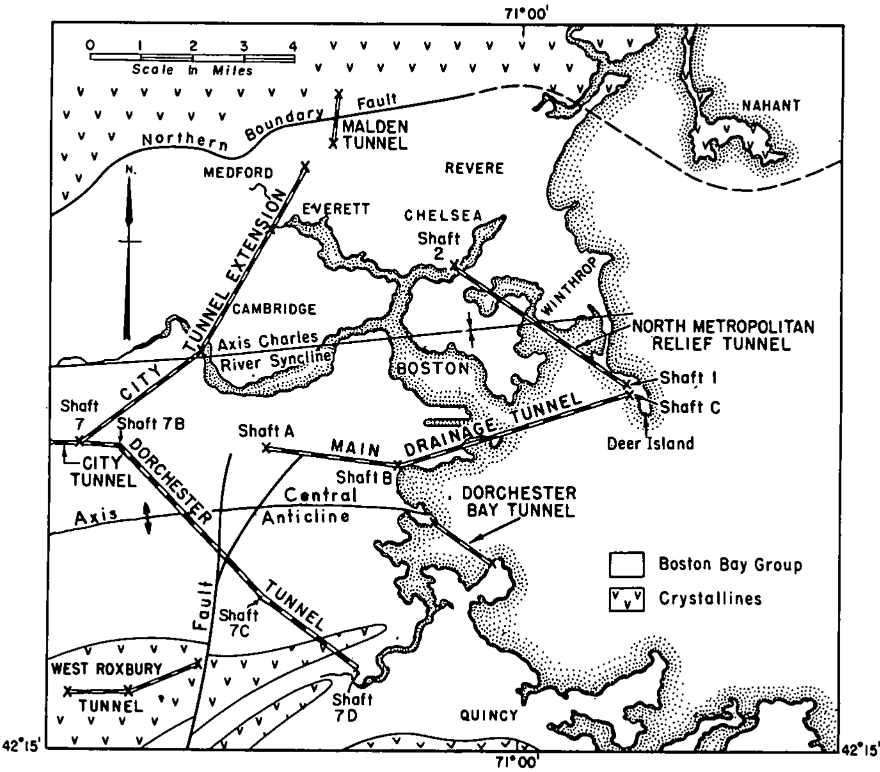

Figure 1: Index map, showing the location of bedrock tunnels in the eastern part of the Boston Basin.

Preliminary geologic maps and sections along the tunnel line were prepared in 1964 by Dr. Marland P. Billings of Harvard University, and were based on data from his own surface studies and from examination of 48 bedrock cores. Dr. Billings also mapped the headings extending 300 feet on either side of shaft 7C during construction and paid several visits to the excavation site during tunnel construction. I performed the remainder of the mapping between January 1970 and March 1973, and produced the final geological report on the Dorchester Tunnel for the MDC.

Location, Size, and Construction

The Dorchester Tunnel, built under the direction of the Construction Division (now the Construction Engineering Division) of the Metropolitan District Commission, Commonwealth of Massachusetts as contract C-338, is a water supply tunnel extending 33,437 feet (6.33 miles) from shaft 7B in Chestnut Hill to a newly constructed shaft (7D) in Dorchester Lower Mills (see figure 2). Shaft 7B, constructed as part of the City Tunnel excavation

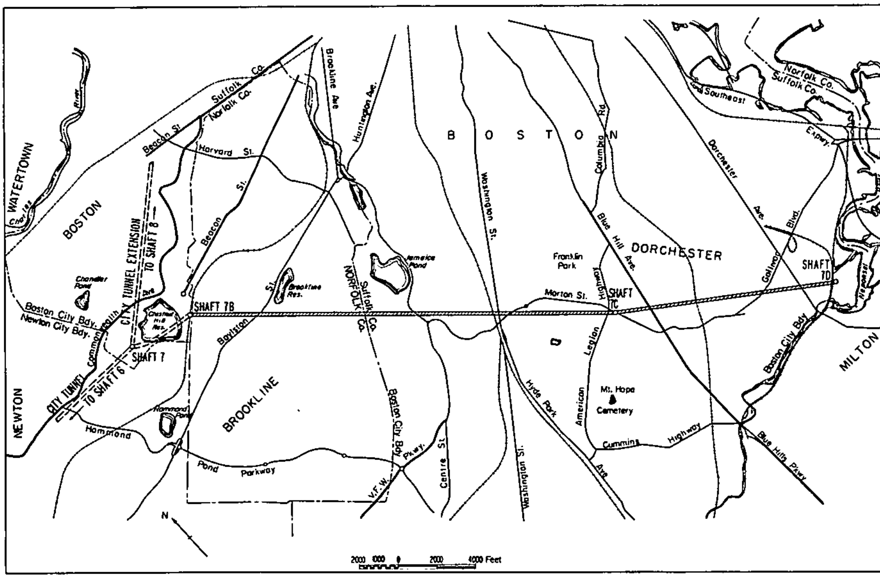

Figure 2: Detailed index map, showing the location of the Dorchester Tunnel.

completed in 1951, is located at the Chestnut Hill pumping station on the eastern end of the Chestnut Hill Reservoir in Brighton, a few hundred feet from the Brookline town line. Shaft 7D, built as part of the present contract, is located at the end of Bearse Avenue in Dorchester Lower Mills, a few hundred feet from the Neponset River. An intermediate shaft, 7C, is located on the grounds of the Mattapan State Hospital at the intersection of Morton Street and the American Legion Highway in Mattapan, and served as the working shaft during construction. From the plug at the end of City Tunnel construction, 150 feet S.82°E. of shaft 7B, the tunnel line extends 21,849 feet (4.14 miles) S.44°58'36"E. to shaft 7C, and thence 11,383 feet (2.16 miles) S.55°21'07"E. to shaft 7D. Excavation along this line was continued an additional 116 feet southeast of 7D to allow for future connections. During construction, all locations in the tunnel were referenced to the center line of shaft 5 (sta. 0+00) in Weston. Center lines of shafts 7B, C, and D are thus at stations 286+81, 506+92, and 621+64 respectively. All locations referred to in this paper are referenced to the same system. Colloquially, the headings northwest and southeast from shaft 7C were known respectively during construction as the Brookline and Dorchester (or Neponset) headings, and those designations are retained here.

The tunnel invert slopes downward from elevation -100.0 feet at shaft 7B to an elevation of -195.0 at station 440+94 and then on a slightly decreased slope to -210.0 at shaft 7D. The finished invert level at shaft 7C is -200.0. All elevations are taken relative to Boston City Base, which is 5.65 feet below the U.S. Geological Survey Base (mean sea level).

The tunnel was excavated to a nominal diameter of 12'2", though deviations toward a larger diameter were common in most sections of the tunnel. The tunnel was lined with concrete to a finish diameter of 10'0".

Geological Setting

The general geology of the Boston Basin has been described by LaForge (1932) and most recently by Billings (1976a). The bedrock consists of a thick sequence of intermontaine basin deposits, varying in lithologic character from a coarse pebble- or cobble-conglomerate to a fine-grained argillite, known collectively as the Boston Bay Group. The exposed thickness of these sediments in the tunnel is nearly 9000 feet. The group is subdivided into two formations: an upper, thinly laminated argillaceous unit called the Cambridge Formation (3500 feet thick here), and a lower unit, called the Roxbury Formation, composed of conglomerate, argillite, sandstone, and melaphyre (5500 feet thick here). The Roxbury Formation is further subdivided into three members which are, from top to bottom in the stratigraphic column, the Squantum, Dorchester, and Brookline Members. These members are best distinguished by particle size and sorting characteristics. The Brookline Member consists primarily of fairly well-sorted arkosic conglomerates in which the average clasts are well-rounded, locally spherical, but generally somewhat elongated in one direction. Clasts vary in diameter from 1 inch to 6 inches or more, with individual cobbles more than a foot across. The Brookline Member contains beds, some hundreds of feet thick, of sandstone and argillite. The Dorchester Member is characterized by conglomerates interbedded liberally with arkosic sandstones, grading locally into finely laminated argillites. The Squantum Member contains conglomerate and a rock that has been variously described as a tillite or a tilloid (Sayles, 1914, 1929; Dott, 1961; Lindsay *et al.,* 1970; Rehmer and Hepburn, 1974, 1975; Baker and Dott, 1975; Stuart, 1975). The tillite (tilloid) is characterized by its relatively high proportion of matrix to clasts, poor sorting within single beds, and angular clasts.

The basement rocks on which the Boston Bay Group have been laid down are different from place to place around the Basin, and may be either a plutonic rock or different volcanic rocks, ranging from very light-colored to reddish or brown felsites to dark green extrusives known locally as melaphyres. Any of these volcanics can and do appear as heterogeneous breccias or agglomerates, and the melaphyres are commonly amygdaloidal. In the southern portion of the Basin transsected by the Dorchester Tunnel, the volcanics are referred to collectively as the Mattapan volcanics, whereas those in the north are called the Lynn volcanics.

Dating of the Boston Bay Group is tentatively upper Paleozoic, no more refined dating being possible because of the rarity of fossils. Two poorly preserved cylindrical casts and molds of tree trunks or roots, described by Burr and Burke (1899), are presently in the collections at Harvard University, and may be either *Calixylon* or *Cordaites,* genera which span geological time from late Devonian to the Permian (Rahm, 1962).

Sedimentation of the Boston Bay Group was a continuous event, though the sources of sediments (as evidenced by the rock types of the clasts) were multiple and constantly changing, and the rates of sedimentation were locally quite variable. Billings and Tierney (1964) have shown that the various sediments of the Boston Bay Group are not purely sequential in a time-stratigraphic sense, but are facies of one another, representing different configurations of the sedimentary environment, varying distances from their source areas, and various degrees of reworking of primary sediments. The sedimentary environment presently envisioned is one of a large intermontaine basin, deeper in the north than in the south, and fed primarily by streams flowing from mountains in the south.

In all probability, the volcanic clasts that appear so commonly in the Roxbury Formation are derived from the Mattapan volcanics. Some vulcanism continued well after the Boston Bay Group began to accumulate, however; exposures of volcanic rocks high in the stratigraphic column have been noted in several localities (Billings and Tierney, 1964; Billings, personal communication). Although some of the melaphyres in the Roxbury Formation are intrusive, others are extrusive (flows, tuffs, and breccias) and may have been the source of some of the clasts in the Roxbury.

The Dorchester Tunnel crosses a series of major and lesser folds and faults which have distorted the stratigraphic record as just presented. The principal folds are: the Central Anticline (axis near sta. 350+00), the Roslindale Syncline (axis near sta. 547+00), the Mattapan Anticline (axis near sta. 576+00), and the Lower Falls Anticline (axis near sta. 614+00). The most important faults are the Mount Hope Fault, near sta. 547+00, and the transverse Stony Brook Fault Zone.

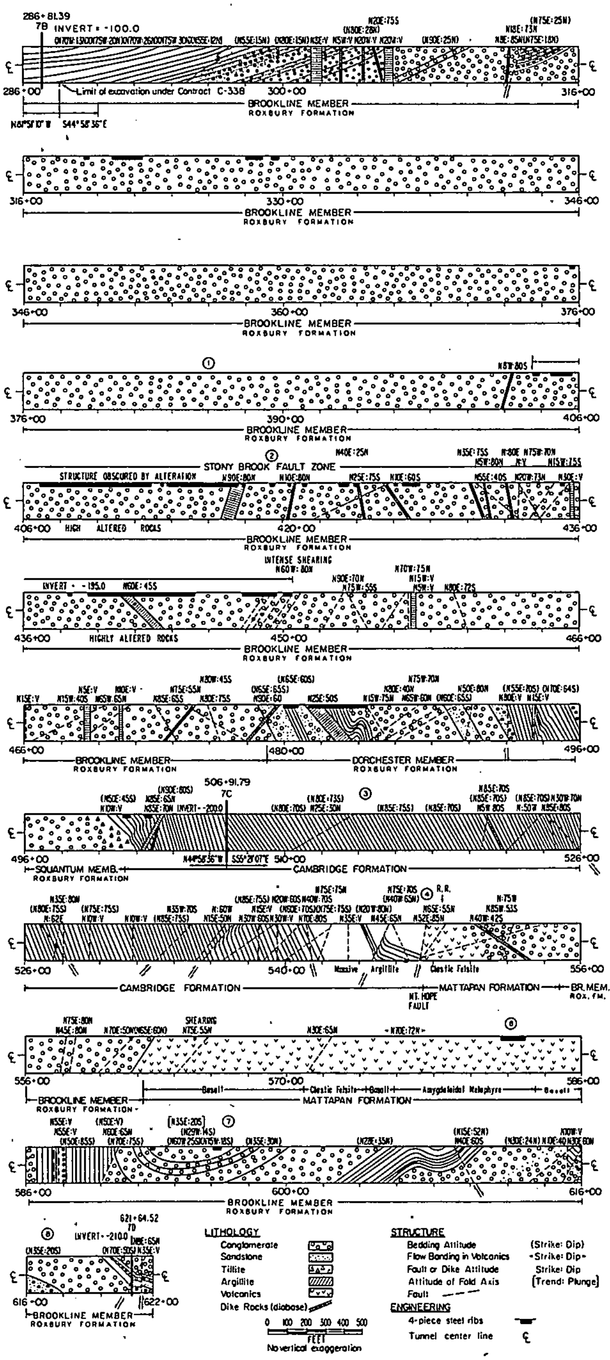

Figure 3: (Caption on facing page)

Stratigraphy and Lithology

The Dorchester Tunnel, which trends southeasterly across the axis of the Central Anticline in Brookline and then across a series of smaller folds and high-angle faults in Mattapan and Dorchester, provides extensive exposures of each of the rock units discussed in the previous section. Because earlier bedrock tunnels were constructed to the north of the Central Anticline, these exposures provide the first continuous view of the stratigraphic record in the southern half of the Boston Basin. From a study of the rocks in the Dorchester Tunnel, then, we may hope to improve our understanding of the sedimentary environment in this portion of the basin, and of the relationship between the Boston Bay Group and the underlying Mattapan volcanics.

In this section, I will present a generalized description of the rock units as they appear in the tunnel and will discuss their relationships to each other and to the stratigraphic sequence in the Boston area. A more detailed presentation of the rock units appears in an appendix. Discussion of the lithology and stratigraphy will proceed from the northwest (shaft 7B) to the southeast (shaft 7D), as shown in figure 3.

Sta. 288+43 to 479+04: Roxbury Formation; Brookline Member. This is part of the main body of the Brookline Member in the Boston Basin, occupying the core of the Central Anticline. Inasmuch as the Central Anticline plunges east, older units of the Brookline Member lie southwest of the tunnel. The minor quantities of argillite and sandstone in the northwest part of the tunnel are lake deposits. These were exposed in the City Tunnel Extension (Billings and Tierney, 1964), and persist to roughly sta. 296+00, where they gradually give way to coarser sandstones and conglomerates. Occasional sandstone beds are present to sta. 309+00, and then briefly again where minor faulting at sta. 312+50 drops them to the tunnel. From there to sta. 479+04 the only rocks exposed (other than occasional diabase dikes) are massive conglomerates in which bedding was never observed.

Sta. 479+04 to 495+75: Roxbury Formation; Dorchester Member. The relative abundance of sandstones and argillites in this section of the tunnel, taken together with their position above the Brookline Member, is sufficient to designate these rocks as Dorchester Member. Throughout the section,

Figure 3: (Facing page):Geological section along the line of the Dorchester Tunnel, facing northeast, based on observations made at the tunnel center line. No vertical exaggeration. Structure attitudes are indicated above the section at the points where they were measured on the center line. The sense of movement on faults, where known, is indicated by double arrows below the section. In most cases the offset on faults is small, and thus not shown at the scale of this drawing. Dikes narrower than 4 feet are not shown. Tunnel invert elevations are given in feet relative to the Boston City Base. Circled numbers refer to structural features discussed in the text.

feldspathic sandstones, argillites, and pebble conglomerates are intimately interbedded, and individual beds often display graded bedding, ripple marks, or other sedimentary indicators of tops. The appearance of well-defined beds is in distinct contrast to the rocks of the chaotic, poorly-bedded Brookline Member beneath. The contact between Brookline and Dorchester, therefore, has been arbitrarily placed where distinct bedding first appears, at sta. 479+04. The contact between the Dorchester Member and the Squantum Member is taken to be at the top of a white, kaolinitic layer of argillite at sta. 495+75. The thickness of the Dorchester Member in this tunnel is thus about 1250 feet, which is comparable to values in other tunnels.

Sta. 495+75 to 501+40: Roxbury Formation; Squantum Member. The base of the section, roughly to sta. 500+00, consists of unbedded sandy conglomerate; the upper portion consists of a light greenish tillite (tilloid(?); recall the discussion earlier). The lithologic character of the tillite is similar to that described by Rahm (1962) in the Main Drainage Tunnel, and by Sayles (1914) at the type locality for the Squantum Member. Stratigraphic position above the Dorchester Member in the present section makes the assignment of these rocks to the Squantum Member unambiguous. The conglomerates in the lower part of this section are included because the contact between them and the underlying argillite at sta. 495+75 is a fairly sharp bedding plane; the transition between the conglomerate and the tillite is gradual.

Sta. 501+40 to 547+52: Cambridge Formation. The rocks are argillite, of the type recognized elsewhere in the Boston Basin as Cambridge, and appear directly over the Squantum Member in the stratigraphic sequence observed in this tunnel. The contact between the Roxbury Formation and the Cambridge Formation is conformable and sharp.

Sta. 547+52 to 550+60: Mattapan Formation. The contact between the Cambridge Formation and the Mattapan Formation at sta. 547+52 is along a tight high-angle fault (the Mount Hope Fault), which will be described later in this paper. The rocks in this portion of the tunnel are pyroclastic felsites and minor basalts, and have evidently been thrown far up section. Their exposures in the tunnel correlate well with surface outcrops of the Mattapan Formation at its type locality.

The contact between the volcanics in this section and the conglomerates at sta. 550+60 (as well as similar contacts at sta. 562+30 and 586+18) was thought by LaForge (1932) to be an angular unconformity, implying that a hiatus existed between the end of Mattapan vulcanism and the beginning of Boston Bay Group sedimentation. I find no evidence for such an unconformable contact. Where Mattapan volcanics appear adjacent to conglomerates in this tunnel, the contact is invariably gradational. A large proportion of the clasts in the conglomerates of the Boston Basin are volcanic (Mattapan-type) rocks and, judging from their coarseness, have been derived from rather steep, nearby slopes. With the discovery of confused, transitional contacts rather than an unconformity between the volcanic rocks and conglomerates, therefore, it is reasonable to presume that vulcanism and sedimentation proceeded simultaneously for some time.

Sta. 550+60 to 562+30: Roxbury Formation; Brookline Member. There is some question about the placement of these rocks in stratigraphic sequence. By the argument just presented, it should be evident that some conglomerates may occur in the main body of the Mattapan Formation, far below the base of the Roxbury Formation. The rocks in this portion of the tunnel might be an exposure of such a unit and, if so, should be labelled as conglomerates in the Mattapan Formation. I have chosen not to do so for two major reasons.

First, although the proportion of volcanic clasts in these conglomerates is higher than in the "average" exposures of Roxbury conglomerate, the lithologic similarities, particularly with regard to granitic clasts and the arkosic matrix, are striking. This conglomerate, therefore, cannot be far below the Mattapan - Roxbury contact, if at all.

More important, however, these conglomerates lie on the northwest limb of the Mattapan Anticline, which has been well-documented on the surface, and they are probably stratigraphically equivalent to the conglomerates and sandstones in the vicinity of sta. 586+00, on the southeast limb. Thus, again, it is most likely that these conglomerates are not in an isolated bed within the Mattapan Formation, but are at the base of the Roxbury Formation.

This interpretation is admittedly open to argument but, in my opinion, is most consistent with the general geology. It also has the distinction of minimizing the uncomfortably large calculated separation on the Mount Hope Fault (see Structure).

Sta. 562+30 to 586+18: Mattapan Formation. This portion of the tunnel is in the type locality for the Mattapan Formation and contains extensive exposures of basaltic rocks, some of which are amygdaloidal.

Sta. 586+18 to 622+80: Roxbury Formation; Brookline Member. These conglomerates and argillites, similar to those described previously, lie between two anticlines of the Mattapan volcanics (fig. 1), one immediately to the northwest in the tunnel and a second to the southwest which, because of its northeasterly plunge, does not reach the tunnel. Since these conglomerates are only about 1200 feet thick and are at the base of the Roxbury Formation (Billings, personal communication), they belong to the Brookline Member.

Sedimentation

The evolutionary picture of the depositional history of the Boston Basin which can be deduced from the Dorchester Tunnel is essentially that described by Billings and Tierney (1964, p.149). Sedimentation apparently took place in a large intermontaine lake, shallower in the south than in the north, and with a gradually fluctuating water level. The shore line facies is the Dorchester Member, as evidenced by the many reversals of sedimentary lithology and by such features as ripple marks. Conglomerates were laid down by streams feeding the lake from the south. The apparent lack of bedding in most of the exposed Brookline Member conglomerates suggests that these sediments were multiply reworked after their initial deposition. The Cambridge argillite represents the deep water facies, and was primarily deposited in the lake in the northern half of the basin.

Structure

From northwest to southeast, the following major structural features are crossed by the Dorchester Tunnel:

1) Central Anticline, shaft 7B (286+81) to 501+40
2) Stony Brook Fault Zone, 403+50 to 450+50 and 480+00 to 484+55
3) Roslindale Syncline, 501+40 to 547+52
4) Mount Hope Fault, 547+52
5) Unnamed syncline, 547+52 to 562+30
6) Mattapan Anticline, 562+30 to 586+18
7) Unnamed syncline, 586+18 to 615+40
8) Lower Falls Anticline, 615+40 to 622+00

These features, as numbered, are shown on figure 3.

Folds

The north boundary of the Central Anticline lies several miles northwest of shaft 7B; the southeast boundary is arbitrarily placed at the base of the Cambridge argillite, at station 501+40. In the Dorchester Tunnel the attitude of the northern limb is shown very well near shaft 7B; the average dip is 20°N. The attitude of the southern limb is well shown between stations 479+04 and 501+40; the average strike is N.60E.; the average dip is 60°S. Assuming concentric folding, the axial plane of the Central Anticline thus dips 70°NW.

The section of the tunnel between stations 313+80 and 479+04 was disappointing in that bedding was never observed. The geology is well-exposed at the surface, however, and shows that the Central Anticline is a broad open fold that plunges 12°E. The tunnel should cross the axis near sta. 386+00.

The Roslindale Syncline extends between stations 501+40 and 547+52. Only the northwest limb is preserved. The southeast limb has been cut out by the Mount Hope Fault. For 4200 feet, as far as sta. 544+00, the attitude of the bedding is very constant; the strike ranges from N.60E. to N.90E., averaging N.77E.; the dip ranges from 70° to 80°SE., averaging 73°SE.

Between sta. 544+00 and the Mount Hope Fault (sta. 547+52) the average strike of the bedding is N.30W., the average dip 70°NE. The synclinal axis, near the Mount Hope Fault, plunges 65°NE.

An unnamed syncline lies between stations 547+52 and 562+30. The Mattapan volcanics (felsites on the northwest, basalts on the southeast) are on the limbs of the syncline; the Brookline Member occupies its core (recall earlier discussion of this area, however). The southeast limb dips 60°NW., but the dip of the northwest limb is unknown.

The Mattapan Anticline extends between stations 562+30 and 586+18. The core is occupied by basalts, felsites, and melaphyres of the Mattapan Formation. The northwestern contact with the Roxbury Formation dips 60°NW., whereas the southeastern contact is vertical. The axial plane dips 75°NW. The surface geology (Billings, personal communication) shows that this band of the Mattapan Formation pinches out to the northeast, indicating a northeasterly plunge.

An unnamed syncline extends between stations 586+18 and 615+50. The core is occupied by conglomerates and argillites of the Brookline Member. The axis is near sta. 594+00. The north limb, which dips 80°S., is cut by a fault at sta. 590+50. The dip of the south limb ranges from 24° to 54°NW., and averages 35°NW. This syncline plunges 20°SW; this is very exceptional for the Boston Basin, since most of the folds plunge NE. The presence of this southwesterly plunging syncline has been known from surface data for many years (Billings, personal communication).

The Lower Falls Anticline occupies the southeast end of the tunnel. Its northwest limb is the same as the southeast limb of the unnamed syncline to the northwest. The axis is near sta. 615+50. The axial plane dips 74°NW. Billings (1976a,b), on the basis of good surface exposures, says that this anticline plunges 18° in a direction N.67°E.

Faults

In all, 67 faults or probable faults with measurable or inferred displacements greater than one or two inches were recorded in the Dorchester Tunnel. Of these, the average fault was a single fracture or a very narrow fracture zone, measuring no more than two or three inches across. Most of these were occupied by gouge or loose breccia, which showed a tendency to wash out with normal ground water flow after several weeks of exposure in the open tunnel. These narrow, tight faults comprise all but about 5% of the faults (exclusive of the Stony Brook Fault Zone) observed in the tunnel. The remainder of the faults in the tunnel are zones of intense shearing, each no more than 15 feet wide, containing large amounts of breccia and usually discharging a moderate flow of ground water.

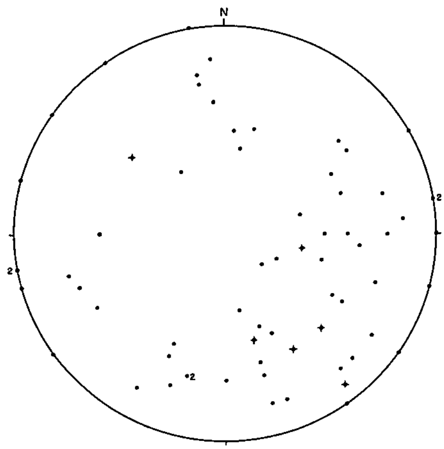

Figure 4: Poles of perpendiculars to 67 major faults or probable faults, projected on an equal area net from the lower hemisphere. Multiple observations with the same attitude are indicated by numerals. Crosses indicate faults with measured or inferred offsets greater than 20 feet.

The attitudes of these 67 faults are shown in figure 4, a point diagram of poles to the fault planes, projected onto the lower hemisphere of an equal area net. For a planar feature, such as a joint, a fault, or a dike contact, each point on the diagram represents the projection of a perpendicular to the planar feature to a horizontal plane. Simultaneous projection of planar features onto a single diagram allows us to assess their "average" attitude in the tunnel. Examination of the diagram in figure 4 shows that the attitudes of faults other than the Stony Brook Fault Zone vary quite a bit. If we consider only the 8 faults with large (greater than about 20 feet) of vertical separation, we observe that their average attitude is more rigidly defined, giving a strike of about N.30E. and a dip close to 60°NW. This fault attitude is the same as the general, or "regional", fault attitude as observed in other tunnels in the Boston Basin. (For comparison, see point diagrams reproduced in Rahm (1962, p. 356), Billings and Tierney (1964, p. 142), Billings and Rahm (1966, p. 130), and Tierney, Billings, and Cassidy (1968, p. 79).)

A few of the faults deserve individual discussion here because of their very large inferred stratigraphic separation. One such is the nearly vertical fault at sta. 547+52, called the Mount Hope Fault by Billings. The attitude of the fault is N.52E.:85N. The stratigraphic throw can be estimated by noting that the southeast side of the fault is in the upper Mattapan Formation, while the northwest side is in the middle to upper Cambridge Formation (see *Stratigraphy and Lithology)*. In order to bring the two stratigraphic units adjacent to one another, it would be necessary to have a vertical displacement at least equal to the entire thickness of the Roxbury Formation, plus a large portion of the Cambridge Formation. This total thickness can be estimated roughly by adding together the true thicknesses of each of the rock units to the northwest of sta. 547+52 (that is, up dip across the exposure of Boston Bay Group rocks in the tunnel). The figure thus derived is around 12,000 feet, but may be in error by as much as 10% either way. Billings (1976a,b) estimates a stratigraphic throw of approximately 10,000 feet.

Physically, the Mount Hope Fault is a tight, single fault, no more than two or three inches across. Brecciation in the wall rocks is negligible. There is only a minor amount of quartz mineralization in the fracture.

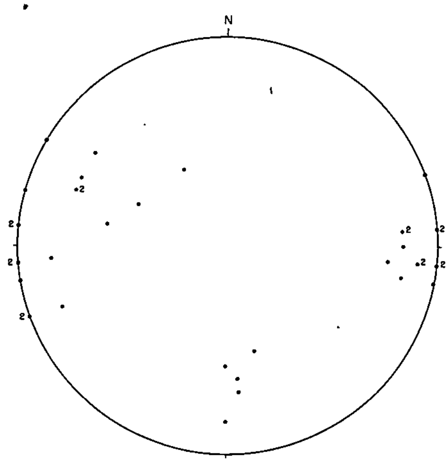

Figure 5: Poles of perpendiculars to 37 diabase dikes, projected on an equal area net from the lower hemisphere. Multiple observations are indicated by numerals.

Billings (1929) and LaForge (1932) assumed that the contact of the Mattapan volcanics and the Roxbury conglomerate in the vicinity of sta. 562+30 was a major fault, called the Sally Rock Fault by Billings. He assumed, by analogy with other observed faults in the basin, that it was vertical. Exposures in the tunnel, however, showed that the contact is sedimentary, striking N.65E. and dipping 60°NW. It is clear that there is no Sally Rock Fault. On the basis of my observations, Billings (1976a,b) no longer shows a Sally Rock Fault.

At sta. 565+00, however, there is a large fault zone, 20 feet wide, striking N.75E. and dipping 55°NW. There is no difference in lithology on the two sides of the fault, and there are no features on which to measure either sense or magnitude of movement.

The third major single fault worthy of extra mention here is the one that crosses the tunnel at sta. 590+50. It strikes N.60E., dips 60°NW. Argillites at the base of the Brookline Member are thrust over conglomerates higher in the stratigraphy. At present no data are available to calculate the stratigraphic throw.

Southwest of the southeast end of the tunnel, Billings (1929) shows a large fault, the Neponset Fault, on the northwest limb of the Lower Falls Anticline — the anticline near sta. 616+00. Billings (1976a, figures 1 and 3) shows this fault extending across the Dorchester Tunnel, but in the text mentions the possibility that the fault may die out before reaching the tunnel. A vertical fault with a strike N.10W. has been mapped in the tunnel at sta. 615+26, on the northwest limb of the Lower Falls Anticline, but this cannot be the Neponset Fault, which has a northeast strike. On the basis of this observation, Billings (1976b) has since terminated the Neponset Fault southwest of Dorchester Lower Mills.

In addition to the major single faults in the tunnel, there are several extensive sections of the tunnel dominated by shear zones on the order of hundreds of feet wide. The bulk of these shear zones lie between stations 403+50 and 450+50, and between stations 480+00 and 484+55, and are collectively referred to as the Stony Brook Fault Zone. On a large geologic scale, the Stony Brook Fault Zone may be observed (Billings, 1976a,b) to

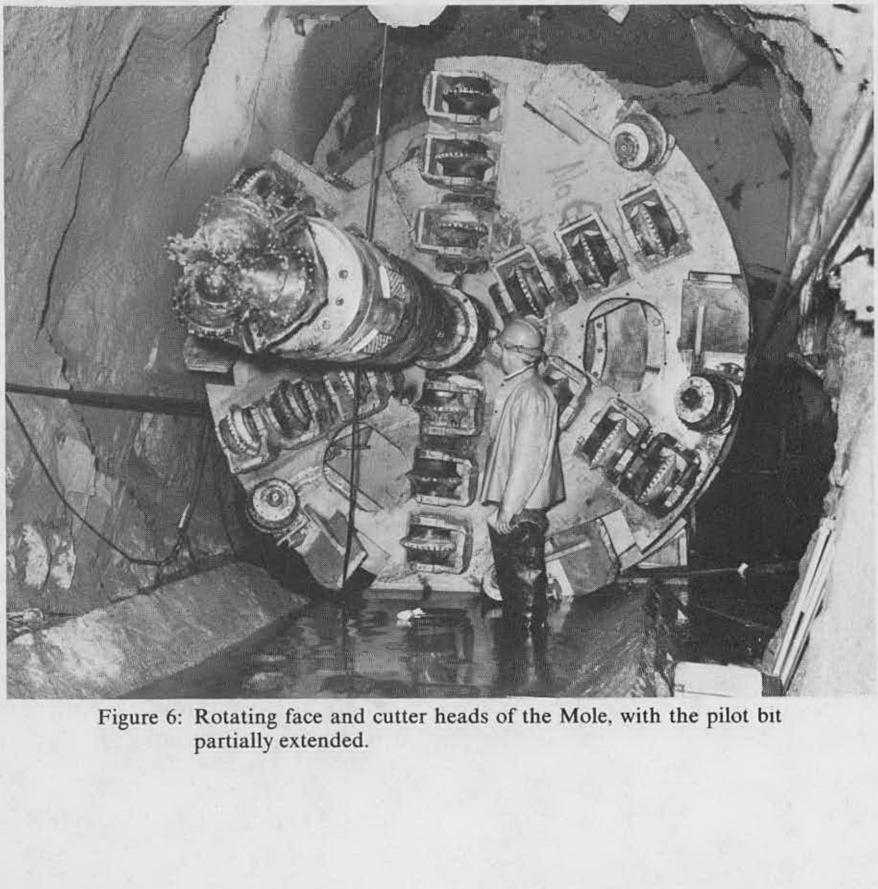

Figure 6: Rotating face and cutter heads of the Mole, with the pilot bit partially extended.

Figure 7: View southeasterly from shaft 7C into the Mole-driven section of the tunnel. The rock is Cambridge argillite.

strike N.10E. across the Boston Basin, cutting the nose of the Central Anticline and downdropping the western end of it approximately 2100 feet relative to the eastern end. The dip is nearly vertical. The fault zone dies out a few miles north of the Dorchester Tunnel, and hence has not been crossed in other tunnels in the Boston area.

The fault zone appears to have two distinct branches, one followed fairly closely on the surface by the main line of Conrail (Jamaica Plain) and Hyde Park Avenue (Hyde Park), and the other lying roughly along the Arborway in Jamaica Plain. It constitutes an easily erodable zone on the surface, where it occupies a broad, poorly defined topographic valley. Core borings along the tunnel line in this area indicate that the bedrock surface lies beneath 125 to 175 feet of glacial deposits, in contrast to areas away from the fault zone, where the surficial cover is from 0 to 25 feet thick.

In the tunnel, the Stony Brook Fault Zone appears in most places not as a series of distinct fractures on which attitudes and displacements can be measured, but as a series of areas characterized by advanced alteration, flowing ground water, and occasional diabasic intrusives. The total width of the fault zone is 4700 feet, of which 2725 feet or 58% of the zone is fractured badly enough to necessitate steel support.

Dikes

Attitudes of the dikes in the tunnel were measured wherever possible, and have resulted in the point diagram shown in figure 5. Three average dike attitudes emerge from this diagram. The first of these, about N.90E.:65°N., represents about 15% of all the dikes in the tunnel. The second, at N.10W.: Vertical, represents nearly 50% of the dikes. The remaining 35% lie in a poorly defined set about N.20E.:70°S. There are no cross-cutting relationships in the tunnel to indicate relative ages of the three sets of intrusions. The median width of 4 feet, calculated from measurements in this tunnel, is typical of dikes in the Boston Basin, as measured in other tunnels.

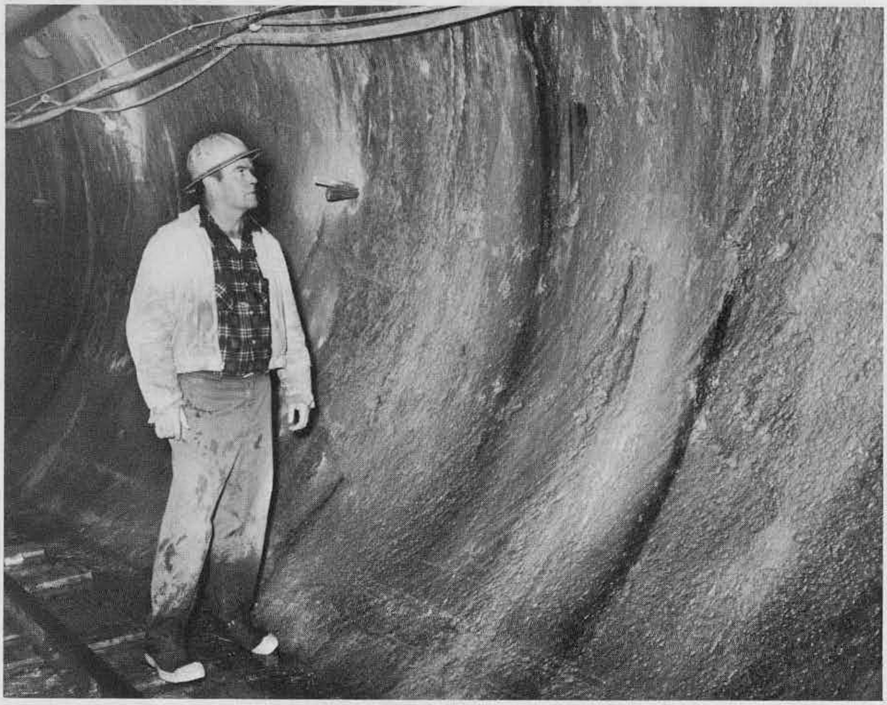

Figure 8: Southwest wall of the Mole-driven tunnel at sta. 510+50, showing bedding in the Cambridge argillite.

Engineering Aspects of the Geology

The Mole

Excavation in the southeast, or Dorchester heading, between stations 511+10 and 548+87, was performed by an Alkirk Hard-Rock Tunneller, model T-7, manufactured by the Lawrence Company, and referred to conversationally as the "Mole". Use of the Mole was experimental in this tunnel, since the contractor had no previous experience with the machine and there was no precedent for its use in the Boston area. Several problems were encountered with the machine during excavation, most of them mechanical or related to human inexperience rather than problems related to the rock.

The problem which ultimately made it necessary to remove the Mole from the tunnel, however, was purely related to the geology. Almost all of the excavation completed by the Mole was in Cambridge argillite, a relatively soft sedimentary unit with well-defined bedding planes. In such rocks the Mole was capable of over 300 feet of progress per week in a 12 foot diameter tunnel. Beyond sta. 547+52, however, excavation was in felsites in the Mattapan volcanics, which are characterized here by a lack of bedding or other planar features (other than widely spaced joints), and extremely high compressive strength. Total progress made in these rocks, with several changes in cutting heads, was only 135 feet in the several weeks before the decision was made to remove the Mole.

It is obvious from the experience gained in the Dorchester Tunnel that the Mole in its present state of development is unsuited for drilling in rocks as hard as the felsites in the Mattapan Formation. There are undoubtedly large portions of the Roxbury Formation which, because of the high proportion of large volcanic cobbles, cannot be drilled by the present Mole as well, though no experience was gained with Roxbury conglomerates in this tunnel.

The Raise Drill

Another innovation in tunnelling technique, a rotary raise drill, was used in construction of shaft 7D. The shaft was sunk by conventional drilling techniques to an elevation of -42.6 feet, from which point a 10 inch pilot hole was bored along the shaft center line from the surface to the tunnel. Figure 9 shows the raise drill itself, which was attached to a rotating shaft through the pilot hole and pulled to the surface. Rock debris was removed to the surface by standard mucking procedures at the invert during the raising operation. In this manner the shaft was bored to a diameter of 6 feet at a rate of 20-40 feet per day.

Steel Support

Support for loose or weakened rock in the tunnel was provided almost exclusively by four-piece steel ribs, each weighing 746 lbs., four feet apart. These were supplemented by steel spacers and wood blocking. In the Brookline heading, 696 ribs were used; the Neponset heading required only 50. A total of 3343 feet, or 9.88% of the tunnel was supported in this fashion. Few rock bolts were used or necessary.

Figure 9: Raise drill being lifted into position at shaft 7D.

Eighty percent of the total support (2725 feet) was needed in the Stony Brook Fault Zone. By way of comparison, the preliminary estimates of steel support necessary for the tunnel were for 7700 feet, of which over 4650 feet was anticipated in the Stony Brook Fault Zone and over 1000 feet in the Dorchester Member of the Roxbury Formation, which needed full support in the Main Drainage Tunnel (Rahm, 1962).

The 618 feet of steel support placed in sections of the tunnel outside of the Stony Brook Fault Zone were primarily necessitated by local jointing. Of the steel support required in the Neponset heading, virtually all falls into this category and, further, the jointing can probably be said to be genetically related to the folding observed or inferred in the heading. The only steel section for which this is not true is the short piece between 561+60 and 561+70, which was required because of faulting. In the Brookline heading, steel support sections not related to the Stony Brook Fault Zone were again related to locally intersecting joint sets, except in the two short sections between 502+45 and 502+85 and between 501+25 and 501+65. These last sections were required partly because of cleavage associated with minor drag folds, and partly because of the soft, kaolinitic character of the basal layers of the Cambridge Formation.

Shotcrete

Early in the construction the contractor was interested in the possibility that shotcrete might be utilized for support in some places instead of structural steel. The headings extending for 300 feet northwest and southeast of shaft 7C were lined with shotcrete. The rock in the immediate vicinity of 7C, however, is argillite, which tends to fracture smoothly and to expose a minimal surface area. For this reason, and because argillite is a rather impermeable rock, the shotcrete failed to make a satisfactory bond with the tunnel walls and was judged to be structurally inadequate. The experiment was not continued into other rock units, but it is reasonable to predict that shotcrete would have been more successful on the extensive exposures of conglomerate.

Acknowledgements

Mapping of the geological features in the Dorchester Tunnel was performed during construction between the spring of 1970 and the late summer of 1972, with the periodic advice and encouragement of Dr. Marland P. Billings of Harvard University. Dr. Billings, whose contributions to New England and Boston Basin geology are well known in the geological profession, first interested me in the mapping venture and has been of immeasurable assistance in the interpretation of the observations. I appreciate the generous and continuous support given to this study by the Metropolitan District Commission, and in particular by Mr. Francis T. Bergin, Chief Engineer for the Construction Division (now the Construction Engineering Division). The assistance of many MDC engineers, notably Mr. Tadeus Medowski and Mr. John Buckley, has been invaluable. The photographs appearing in these pages were taken by Mr. Thomas Reilly, photographer for the MDC. Mr. John H. Peck made several suggestions for substantial improvements on an earlier draft of this manuscript.

Appendix

Lithology by Stations

Descriptions of the general lithology of the Boston Basin have been presented adequately in several previous papers, particularly those dealing with the geology of other MDC tunnels. Except for descriptions of the Mattapan volcanics, exposed to date only in this tunnel and in surface outcrops, the reader is directed to previous literature for physical and chemical descriptions of the rock units referred to in this paper. This appendix is a brief log of the rocks encountered in the Dorchester Tunnel, and an indication of their extents of exposure. The true thickness of a rock unit is always less than its exposed or apparent thickness, unless the measured section is perpendicular to bedding planes. Where possible, true thicknesses for each rock unit described here have been calculated trigonometrically.

Sta. 288+31 to 288+75: The rock in the extreme northwest end of the tunnel is finely-laminated argillite, four feet thick. Above this, in the City Tunnel Extension, 602 feet of strata, mostly argillite but including a little conglomerate, was exposed (Tierney *et al.*, 1968).

Sta. 288+75 to 313+80: This portion of the tunnel consists of interbedded sandy argillites and conglomerates, varying in their relative abundance throughout the section. In the northwest section, to around sta. 297+30, argillite predominates to the virtual exclusion of conglomerate. From 297+30 on, however, the percentage of conglomerate in the section increases, with beds of argillite or sandstone becoming less frequent and narrower in outcrop to sta. 313+80, from which point no further argillite appears. Thickness of rocks in this section is about 900 feet.

Sta. 313+80 to 403+50: The entire section consists of unaltered, unbedded conglomerate. Based on surface exposure, the axis of the Central Anticline should be at about sta. 386+00. Because the tunnel is diagonal to the structure, though, the reversal of apparent dips should be near sta. 337+00.

Sta. 403+50 to 450+50: Rocks in this portion of the tunnel are conglomerates, but are generally very highly altered by water passing through extensive fracture zones (the Stony Brook Fault Zone). Virtually all of the rock supported by structural steel in this portion of the tunnel is altered in some degree. The pattern of alteration is a relatively simple one. Conglomerates farthest from the water-filled fractures are well-indurated; pebbles in them are usually unaltered and rigidly cemented to the surrounding matrix. Closer to fracture zones the pebbles are unaltered, but show an increased tendency to break free of matrix, leaving a smooth hole. Whether this is due to partial dissolution of the pebbles or of the matrix is uncertain. Further into the zone of alteration, pebbles (specifically the granitic ones) are kaolinized — that is, the feldspars are altered to clay, appear white or pale yellow, and are punky to the touch. More intense alteration is signalled by a general darkening of the clays, from a pale yellow to a deep yellow-brown, as the iron-bearing minerals in the conglomerate are oxidized. Kaolinization intensifies as the fracture zone is approached, proceeding through matrix as well as pebbles. In the areas of most intense alteration, no trace of the original pebbles is left, and water flowing through fractures easily washes alteration products from between the few remaining blocks of matrix, making them much less structurally competent. Depending on the intensity of the fracturing and the amount of water flowing through the rocks, it was possible in some cases to predict the advent of "bad ground" as early as forty or fifty feet before it was encountered, by observing this alteration pattern.

Sta. 450+50 to 479+04: Unaltered conglomerate, similar to that on the northwest side of the Stony Brook Fault Zone, and again displaying no bedding, comprises the entire section. As in the preceding sections, no direct measurement of thickness is possible.

The thickness of the strata between stations 313+80 and 479+04 cannot be determined from any data in the tunnel, due to the lack of bedding. Fortunately, however, geological data from the surface may be utilized, although a detailed analysis would be too long to present here. The thickness of the conglomerates between stations 337+00 (the probable location of the axis of the Central Anticline) and 479+04 is 3600 feet; this is the upper part of the Brookline Member. Estimating on the basis of surface outcrops to the southwest of the tunnel line, approximately

1700 feet of rock lies between the base of this upper part and the base of the Boston Bay Group. Thus, in this area, the Brookline Member is 5300 feet thick.

Sta. 479+04 to 480+40: The rock varies in character from a coarse, pinkish feldspathic sandstone to a sandy pebble conglomerate, the two types being intermixed as lenses or as discrete beds from 1 to 3 feet thick. Sandstones are locally laminated on a scale of an inch or less. The thickness of these rocks is 110 feet.

Sta. 480+40 to 480+90: The section is dominated by a purplish-gray slaty argillite, sandy in spots, and with ¼ to ½ inch laminations. Its thickness is about 40 feet.

Sta. 480+90 to 481+90: The rock is the same in character as that between 479+04 and 480+40, with the feldspathic sandstone predominating. Graded sequences approximately 10 feet thick indicate tops to the southeast. The thickness of the rock in this section is 85 feet.

Sta. 481+90 to 482+80: The section is dominated by dark, unweathered diabase, containing irregular areas of dark gray sandstone or coarse argillite. The diabase may either be interpreted as a single intrusive containing large blocks of unoriented wallrock, or as a swarm of contemporaneous dikes following irregular fractures in the country rock. The thickness of these rocks is 65 feet.

Sta. 482+80 to 484+55: The rocks in this section consist of finely laminated pinkish purple argillites, some spotted with white flecks of kaolinite lying concordantly with the bedding. Thickness is not directly measurable, due to folding, but is probably no more than 65 feet.

Sta. 484+55 to 489+20: The rocks are unaltered arkosic conglomerate, unbedded. Calcite veins are fairly common. Thickness of the rocks is about 375 feet.

Sta. 489+20 to 490+20: The section contains interbedded pebble- or cobble-conglomerates and coarse sandstone. The purplish gray sandstone is predominant, occurring in beds up to a foot thick. Thickness of the section is about 86 feet.

Sta. 490+20 to 491+60: The rock in this section is all unbedded conglomerate. Its thickness is about 70 feet.

Sta. 491+60 to 492+30: Rocks in the section are interbedded coarse sandstone and pebble conglomerate, with the sandstone predominating. Some conglomerate bodies are isolated lenses, about two feet across. Thickness of the rocks is approximately 50 feet.

Sta. 492+30 to 495+75: The section is comprised of argillitic rocks, largely dark reddish brown to purple and finely laminated. The southeasternmost ten feet of exposure, however, is cream-colored, contains quite a bit of kaolinite, and has no visible laminations. Oscillation ripple marks appear in the section at 493+60. The thickness of the rocks in this section is 310 feet.

Sta. 495+75 to 501+40: Sandy, arkosic conglomerate extends southeastward to approximately sta. 500+00, where there is a gradual change over a distance of about fifteen feet to a light greenish tillite characterized by an increased proportion of matrix to clasts and an increased angularity of clasts. This unit is 520 feet thick, including 120 feet of tillite.

Sta. 501+40 to 547+52: The entire section consists of light to medium gray argillite, laminated on the average in ¼ inch thick layers. Slaty cleavage is rare, though there is some hint of an unmeasurable cleavage in some areas. (Since this portion of the tunnel was excavated by the Mole, it was always extremely difficult to measure fracture attitudes. See figure 8.) Portions of the section, especially those in which the rocks have been fractured heavily, contain swarms of calcite veins, vuggy in places and containing overgrowths of pyrite. Near the southeastern end of the section, from sta. 541+75 on, the argillite is massive, showing no signs of bedding for distances of two or three hundred feet at a time. The thickness of rocks in this section is difficult to assess directly, since the section is heavily faulted and the magnitudes of the throws on the faults are not known. A reasonable estimate, however, is about 4000 feet.

Sta. 547+52 to 550+50: The rocks in this section are pyroclastic felsites, varying in color from cream or buff colored to bright red to yellowish-green to a dark gray green. Common to all of the rocks are the abundance of irregular, sub-angular clasts and a large amount of siliceous, irregularly-shaped bodies, generally lighter in color than the surrounding rock. If the contact with the conglomerate to the south is vertical, this felsite is 300 feet thick.

Sta. 550+60 to 554+80: The section consists of dark gray-green conglomerate, dominated by reddish andesite pebbles and occasional large granitic cobbles, rather than by the more heterogeneous mixture of quartzite, volcanic, and granitic pebbles found in most conglomerates of the Boston Bay Group. Dark gray-green clastic volcanics also occur. There is no distinct bedding, and clear distinctions between the conglomerate and the clastic volcanics are nearly impossible at times, since one is apparently the matrix of the other locally. These rocks have been interpreted earlier in this paper to lie on the north limb of a syncline; if they are vertical and the synclinal axis is at sta. 556+00, they are 540 feet thick.

Sta. 554+80 to 562+30: Rocks in this portion of the tunnel are conglomerates similar to those common in sections in the northwestern end of the tunnel. Granitic and volcanic pebbles predominate in a matrix which is arkosic and sandy. No bedding is observable. The contact with the underlying Mattapan Formation to the south dips 60°N, and these rocks occupy the southern limb of the syncline. The thickness in this section is thus about 540 feet.

Sta. 562+30 to 571+00: Dark green basaltic rocks comprise the entire section. There is no evidence at any point in the section for flow banding, chill features, color or compositional changes to indicate the mode of emplacement or the number of events represented in the exposure. Locally, calcite veins fill fractures in the rock.

Sta. 571+00 to 574+35: Rocks in the section are felsites, varying in color from northwest to southeast from cream-colored to reddish brown to grayish white to deep red-brown. The general lithologic character is similar to rocks between sta. 547+35 and 550+60.,

Sta. 574+35 to 575+85: Rock in this section is a dark green basalt with occasional clasts of a lighter volcanic in it. No bedding or flow banding was seen.

Sta. 575+85 to 583+50: Rocks in this section are purplish-red to green amygdaloidal melaphyre, with amygdules measuring from ¼ to ¾ inch across. Most amygdules are filled entirely with quartz, some of which is stained red with iron oxides, though some of the larger amygdules also contain calcite and some authigenic plagioclase. Abundance varies considerably, with some portions of the rock being nearly barren and others so amygdaloidal that adjacent amygdules join to form a continuous sheet. Observing the concentrations of amygdules, it is possible to discern individual rock units dipping generally northwest and having approximate thicknesses of 10 feet or less. Such units are hardly measurable and, though they might possibly be individual flows, they are not well enough defined to identify easily. Surface outcrops of similar rocks in the Boston Basin occur along the shore in parts of Hull, and are virtually identical in terms of texture and general petrology.

Sta. 583+50 to 586+18: Rocks in this section are basaltic, showing no flow banding or other indications of mode of emplacement, and containing no amygdules. The thickness of the rocks from sta. 562+30 to here is uncertain because of folding, but may be as much as 2000 feet.

Sta. 586+18 to 590+50: The entire section with the exception of about 30 feet of dark grayish-green conglomerate centered around sta. 587+95 consists of finely laminated dark to medium gray argillite. Thickness of the rocks is about 430 feet.

Sta. 590+50 to 603+90: Rocks in the section are predominantly conglomerates of the type appearing in abundance elsewhere in this tunnel, but locally containing beds of coarse arkosic sandstone from one to three feet thick. Thickness of the rocks in this section, taking into account uncertainties due to folding, is about 500 feet.

Sta. 603+90 to 609+60: Rocks in the section are all dark gray argillite. Thickness is about 175 feet, corrected for folding.

Sta. 609+60 to 615+20: With the exception of some interbedded sandstones near sta. 613+00, the section consists of conglomerate. The thickness is about 180 feet.

Sta. 615+20 to 615+50: This section contains finely laminated light gray argillite. It is about 20 feet thick, and bounded on both sides by faults.

Sta. 615+50 to 621+00: With the exception of roughly 40 feet of mixed coarse sandstone and conglomerate and the northwest end of the section, the section consists of conglomerate. Thickness is about 300 feet.

Sta. 621+00 to 622+80: Rocks in this section consist of conglomerate, sandstone, and argillite, interbedded and faulted so that exposures in the tunnel and in shaft 7D show each rock type for only thirty feet or so at a time.

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FOURTH INSTALLMENT (CONCLUSION)

HYDRAULICS IN THE UNITED STATES 1776 - 1976

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CHAPTER VIII

POSTWAR DEVELOPMENTS

At the risk of oversimplification, it might be remarked that the writing of history becomes both easier and more difficult with the remoteness of the events under consideration. The necessary perspective for the proper interpretation of a given situation is surely not acquired in a matter of days, months, or even years. As time passes, on the other hand, memories become dimmer and the number of participants in a given event who are still alive steadily diminishes. The recording of situations as they develop is surely helpful in their later assessment, and it is to this end that the present story continues well into the lifetimes of its initial readers. However, the number of occurrences that have some bearing on the study seems to be increasing—like everything else—at an exponential rate, and the selection of those to record requires in itself some semblance of perspective. The dilemma will now have to be overcome in some degree by discussing generalities rather than details, and the result may thereby become steadily more subjective, whereas objectivity is essential to true history. In any event, some twenty years of the two centuries that the book is intended to cover still remain to be discussed, and these will be divided by chapters into two roughly equal periods—the first including the tremendous upsurge in scientific research accompanying the initial orbit of Sputnik I, and the second, the inevitable reaction thereto.

Following the war years, cavitation research at Caltech gradually shifted from Bureau of Ordnance sponsorship to that of the ONR. In 1952 Robert Knapp was honored by an invitation from the British Institution of Mechanical Engineers to deliver the James Clayton Lecture of that year, for which he chose the title "Cavitation Mechanics and its Relation to the Design of Hydraulic Equipment." From 1952 to 1955 he was an ASME National Lecturer on the subject, and in 1955 he received the ASME's Melville Medal. One of his noteworthy accomplishments in these years was to record, in a soft aluminum portion of the boundary, impressions of individual bubble collapses accompanying incipient cavitation. In the meantime, an important postwar development had been the analysis of cavitation-bubble mechanics at the hands of Milton Spinoza Plesset (1908-. . . .), a Pennsylvanian educated in physics at Pittsburgh and Yale who had joined the Caltech teaching staff shortly after the war. With the instrumental aid of Albert Tromly Ellis (1917-. . . .), a Californian educated at Caltech, the magnetostrictive device used by Spannhake and many others to compare the resistance of various materials to cavitation pitting was supplemented by the resonance method of studying both bubble stability and material damage. This period also saw the addition to the hydrodynamics staff of Allan James Acosta (1924-. . . .) of California and Theodore Yao-Tsu Wu (1924-. . . .) of China, both of whom had just received Caltech doctorates; Acosta was to specialize in cavitation and rotating machinery, and Wu in free-surface flow and the swimming of organisms. They were followed by Robert Ching-Yee Koh (1938-. . . .), also of China, whose interests ranged from thermally stratified flow to sedimentation. Unfortunately, Vanoni's ability to serve as a cushion between Knapp and his staff, previously mentioned in passing, reached its limit in 1956, and the staff issued the ultimatum that Knapp would have to step down or they would leave. Plesset then took over as acting director. There is probably some good in every tragedy, and Knapp, in relinquishing control of the research establishment that he had built, was able to return to productive work on his own. One of his projects, in addition to his final report to the ONR on cavitation damage, was the preparation of a general treatise on cavitation itself. The Navy eventually protested Knapp's displacement, and his post as director was happily restored to him in 1957, not long before his untimely death later that year.

Cavitation was by no means the only research under way in Knapp's laboratories even during the war. Vanoni's sediment investigations had continued, though at a greatly reduced rate, with the collaboration of Albert Einstein and En-Yun Hsu. In 1945, moreover, with the support of the Navy's Bureau of Yards and Docks, a wave laboratory had been developed at Azusa, where model studies of specific harbors and general wave investigations were continued well after the war's end; Knapp's pneumatic wave generator motivated by vacuum-cleaner blowers was a typical by-product. The year 1950 saw the arrival from Massachusetts and Harvard of Norman Herrick Brooks (1928-. . . .) as a doctoral student in civil engineering and physics. He soon teamed up with Vanoni in various phases of open-channel research. A third member of the team, John Fisher Kennedy (1933-. . . .), arrived from New Mexico by way of Notre Dame five years later. In addition to producing a steady stream of papers on sediment transport and related phenomena, the team began the preparation of plans for a new building to take the place of the temporary SCS structure from 1937. This was completed in 1959 and named the W. M. Keck Laboratory of Hydraulics and Water Resources. Whereas Kennedy's interests centered on the mechanics of dune and ripple formation, those of Brooks gradually shifted to other environmental problems, particularly the diffusion of wastewater discharged into the ocean. Kennedy received a faculty appointment with Ippen at MIT in 1961. Another of Brooks' doctoral students, Hugo Breed Fischer (1937-. . . .) of New Jersey, followed more directly in his mentor's environmental tracks but joined the Berkeley staff in 1966, acquiring the Straub Award, the Croes

Medal, and the Hilgard Prize en route. At much the same time Frederic Raichlen (1932-. . . .) moved from MIT to Caltech, where he carried on productive work in turbulence, ocean waves, breakwaters, and tsunami mechanics. Through much of this period Vanoni strove valiantly to persuade an ASCE Task Committee to complete a general handbook on sediment transport, but progress was slow.

In the foregoing chapter brief mention was made of the chain of developments that began with Arthur Ippen's appointment in 1945 to a position in the MIT Department of Civil Engineering. His first years there were devoted in considerable measure to the planning of a new laboratory to replace the temporary wooden structure that had been used since 1930; James Daily and Donald Harleman played essential roles in this work. Completed in 1951, the new Hydrodynamics Laboratory was a two-story building providing 30,000 square feet of floor space (not to mention a small towing tank for the Department of Naval Architecture). Early research in the new facility included studies by Ippen and Harleman on the hydraulic analogy to supersonic flow and by Daily on transient flow and cavitation. In 1953 Allan Gifford's place was taken by Gordon Ryerson Williams (1906-. . . .) of Massachusetts, who had had experience with both public and private engineering organizations after graduation from MIT. In addition to these tenured members of the staff, an important part was played by the growing stream of graduate assistants, a number of whom remained on the staff after receiving their doctorates. Chief among these in the period 1951-65 were the following:

Peter Sturges Eagleson (1928-. . . .) of Pennsylvania, who transferred in 1952 from the graduate staff at Lehigh; he worked on the motion of particles on beaches due to shoaling waves, and remained at MIT. Robert George Dean (1930-. . . .) of Wyoming studied wave forces on submerged structures, continued his coastal-engineering research with an oil firm, and later headed the Coastal Engineering Department at Florida. Gershon Kulin (1926-. . . .), of Massachusetts, Worcester, and Carnegie Tech, worked under Ippen on the attenuation of solitary waves and went thereafter to the Bureau of Standards. Ronald Elliott Nece (1927-. . . .) of Washington investigated flows induced by enclosed, rotating disks under the guidance of Daily and then returned to his alma mater. Gerrit Hendrik Toebes (1927-. . . .) of the Netherlands, who studied the hydroelastic behavior of plates, went on to Purdue and there developed an additional interest in water-resource systems. George Bugliarello (1927-. . . .), of Italy and Minnesota, began with Daily what was to become a continuing investigation into the transport of dilute fiber suspensions for the paper industry. Yun-Sheng Yu (1926-. . . .), who came to MIT from China via Iowa, later joined the staff at Kansas. Frederic Raichlen of Maryland and Johns Hopkins worked on harbor oscillations; after a postdoctoral appointment, he moved to Caltech, as already noted. Frank Edward Perkins (1935-. . . .) of Massachusetts wrote a thesis on a finite-difference approach to transient-flow problems; this was among the first in the field of hydraulics to result from the rapidly developing interest in computer applications; he also remained at MIT.

The arrival in the early Sixties of John Kennedy and Ronald McLaughlin (1929-. . . .) of Canada, both from Caltech, Lynn Walter Gelhar (1936-. . . .) from Wisconsin, and Emmanuel Partheniades (1926-. . . .) from Greece via Berkeley, all as full-time staff members, rounded out a powerful research group. Projects during the first fifteen years of laboratory operation covered a very wide variety of subjects and nearly as many sponsors, both governmental and private; some two hundred contract reports and technical papers were produced in this period. In many of these the digital computer came to play an important role, great emphasis being laid on its use as a matter of departmental policy. Research projects included many aspects of material transport, such as beach erosion, particle cohesion, and paper manufacture; fluid dispersion, both underground and in the ocean; the mechanics of wave motion, whether stable or breaking; hydraulic transients in power installations; stratification of flows by heat, salinity, and suspended sediment; recirculation of cooling water; urban drainage and water-supply networks; hydrology, and other aspects of water-resource planning.

When Maurice Albertson was invited to Colorado State College in 1947 by Dean Nephi Christensen, who had already begun the upgrading of the hydraulics curriculum, he brought with him not only the interest in atmospheric research that he had acquired at Iowa but also the tremendous promotional drive that had characterized his student days. Christensen then left for Cornell University, and Albertson took over what can only be called a bootstrap operation, for the college was sadly lacking in both a postgraduate program and modern research equipment. Jack Edward Cermak (1922-. . . .), a native of Colorado who began graduate work the year that Albertson arrived, became the latter's assistant, and together they designed the first Fort Collins wind tunnel. It was completed with ONR support in 1949, and additional backing was obtained for the further study of evaporation. That same year Dean Freeman Peterson (1913-. . . .) of Utah was appointed head of civil engineering; with his strong promotional aid, and the equally strong support of the ONR and the NSF, the organization began to assume a remarkable rate of growth. James Richards Barton (1917-. . . .) of Utah, one of McNown's graduate students at Iowa, joined the staff in 1952, the year that also brought Adrian Ramond Chamberlain (1929-. . . .), a Michigander who became Albertson's first doctoral candidate and later chief of research. On his retirement from the Bureau of Reclamation in 1953, Emory Lane received a temporary appointment at Fort Collins, which he held till illness forced cessation of his activities in 1957; by then he was well along the road toward formulation of a general philosophy of sediment transport.

In 1955 the Army Air Force granted funds for a larger atmospheric wind tunnel, and this became operational in 1960. Erich Jurgen Plate (1929-. . . .) of Germany, previously a graduate student at CSU, was recalled to the staff in 1959; at first involved in wind-tunnel design under Cermak, he later participated in atmospheric modeling and diffusion studies. The USGS stationed Daryl Baldwin Simons (1918-. . . .) of Utah at Fort Collins in 1957 to collaborate in the growing research program on open-channel flow and sediment transport, to which the Nebraskan Everett Vern Richardson (1924-. . . .) had been transferred from Iowa by the Survey in 1956. The year 1957 also saw the arrival of the hydrologist Vujica Yevjevich (1913-. . . .), a native of Yugoslavia who had previously headed a research institute in his own country. The Texan Lionel Baldwin (1932-. . . .) came to the campus in 1961, after experience with NACA-NASA; a chemical engineer, his specialty was fluid turbulence. William Whitaker Sayre (1927-. . . .) of New York and Princeton, initially a graduate student, became a member of the USGS staff in 1962, moving to Iowa in 1968 after receiving the doctorate; his particular interest was the mechanics of diffusion. Hsieh Wen Shen (1931-. . . .), a native of China who, after study at Michigan, had taken the doctorate in sediment transport under Einstein at Berkeley (and was to become a Freeman Scholar the following year), arrived at Fort Collins in 1964.

With such a staff—not to mention the considerable support of various agencies—recirculating and tilting flumes, wave basins, and additional wind tunnels came into being, and graduate enrollment steadily rose. The pressure of growth inevitably prompted the construction of a new research center in the foothills of the Rockies five miles west of the original Fort Collins campus. By 1965 the new hydraulics laboratory contained some 50,000 square feet of floor space, plus forty acres of surrounding land for outdoor experiments, and much more equipment. Some of the new wind tunnels were provided with means of controlling the distribution of velocity and temperature, and one of the new flumes was claimed to be the largest tilting and recirculating facility in the country. Aside from the laboratory's very effective programs on wind dynamics, open-channel flow, hydrology, and fluid mechanics in general, the hydraulics staff actively promoted summer institutes on various aspects of fluid motion with the support of the NSF. Not only was Albertson himself behind the original developments, but he continued to take some part in subsequent activities and shared in the authorship of at least one prizewinning paper. But he had many other irons in the fire, particularly of an international nature; one wonders what the outcome would have been had all his energy been channeled in the one direction!

The various fields of postwar research covered by the St. Anthony Falls Hydraulic Laboratory and listed in the foregoing chapter should still be augmented by several items. After both Lorenz Straub and Alvin Anderson had returned to the University, funds were obtained from the ONR for the construction of a 50x1½x1-foot flume which could be tilted through an extreme angle of almost 90°, for the amplification of DeLapp's initial work on air entrainment in high-velocity flow. This was used by Anderson for his doctoral dissertation, the superposed phases of the stream—water droplets in air and air bubbles in water—being analyzed individually. The resulting Straub-Anderson paper was awarded the ASCE's Norman Medal. In this period, Chieh-Shyang Song (1931-. . . .), of Formosa by way of Iowa, was added to the staff after completing his doctoral studies; his field of competence, like that of Edward Silberman, was fluid-mechanics analysis. John Ripken continued his work with laboratory apparatus and instrumentation, particularly that involving water-tunnel design and cavitation, and Anderson maintained his original interest in sediment transport.

Except for the Hydrodynamics Laboratory at Caltech, probably the most mechanical-engineering-minded over the longest period was the Alden Hydraulic Laboratory at Holden, Massachusetts. Under Leslie Hooper's direction during the War, it had conducted many a water-entry (and -exit) test on model projectiles for the Navy's Bureau of Ordnance, using Edgerton high-speed lights for photography. The flow pattern at entry was also studied by repeated photos showing the displacement of a field of slowly rising bubbles. All this was in addition to the more routine hydraulic tests that dated even from "Prof" Allen's time. In the period following the War, various aspects of the power problem came to be modeled, including both the dispersal of waste heat in water (beginning in 1952) and the diffusion of smoke from power-plant stacks. Lawrence Carlton Neale (1918-. . . .) of Massachusetts, who had been on the Worcester staff since 1940, became the BSCE Freeman Scholar for 1954-55, and after his return was appointed Assistant Director of the laboratory. On Hooper's retirement in 1968, Neale assumed responsibility in his place (ultimately resigning the post in 1975). With the passage of time, it might be noted, the Alden Laboratory has generalized its approach fully as much as other leading institutions, the distinction between the civil- and mechanical-engineering points of view having in large measure disappeared.

Also in this period, during the presidency of Freeman Scholar Blake Van Leer, the teaching of hydraulics at the Georgia Institute of

Technology began to be upgraded. This occurred at the hands of Carl Edward Kindsvater (1913-. . . .), who was born and educated in Kansas, did postgraduate work at Iowa, and then went to Georgia Tech in 1945 after employment with the TVA and the Corps of Engineers. By 1949 he had developed a good instructional and research laboratory there at Atlanta. He then returned to Iowa for advanced study, leaving things in the charge of a former student, Harold Robert Henry (1928-. . . .), a Georgian who had also studied at Iowa with Rouse and at Columbia with Bakhmeteff and Craya; Henry later served on the faculties of Michigan State and Alabama. On his return to Georgia, Kindsvater was able to attract three able men to the Georgia Tech staff. The first was Marion Robert Carstens (1919-. . . .) of Washington, who had first gone back to Washington State to teach after taking his graduate degrees at Iowa; his research interests at Georgia Tech were in the fields of sediment transport and open-channel hydraulics. The second was Paul Gustav Wilhelm Mayer (1923-. . . .) of Germany, who had studied at Cincinnati and Cornell and served on the latter faculty; his fields were interfacial mass transfer and turbulent free-surface flow. The third was Charles Samuel Martin (1936-. . . .), a Virginian who had taken graduate work at Georgia Tech before joining the staff; his research efforts lay primarily in the realm of hydraulic transients and two-phase (air-water) flow. It is noteworthy that all three spent time abroad in either teaching or postdoctoral study: Carstens at the Asian Institute of Technology in Bangkok, Mayer at the University of Wales in Swansea, and Martin at the University of Karlsruhe.

Ever since its formation, members of the U. S. Geological Survey had sought to improve their methods of measurement and analysis of data, but usually on an individual basis rather than as a concerted agency effort. For example, Hollister Johnson (1890-1955) of New York developed techniques of estimating flood flows by indirect methods. Charles Vernon Theis (1900-. . . .) of Kentucky contributed to the hydrodynamic theory of aquifer systems and its laboratory and field application. Walter Basil Langbein (1907-. . . .), originally of New Jersey, was primarily a hydrologist, but his interests ranged into many phases of river hydraulics, such as water storage, resistance, and theory of meanders. Three others (not to mention their forerunner, G. K. Gilbert) contributed notably to the mechanics of sedimentation and sediment transport: William Walden Rubey (1898-1974) of Missouri, Bruce Ronald Colby (1908-. . . .) of Minnesota, and Thomas Maddock Jr (1907-. . . .) of Arizona. Three others followed in the footsteps of Theis in the study of groundwater hydraulics: Hilton Hammond Cooper Jr (1913-. . . .) of Georgia, who developed the equations of flow of a compressible fluid in a deformable porous medium; Charles Edward Jacob (1914-1970) of Arizona (a graduate student of Bakhmeteff's), whose analyses extended to leaky aquifers and both laminar- and turbulent-flow regimes; and Robert William Stallman (1924-. . . .) of Indiana, who was recognized for his critical evaluation of multiphase flow in porous media.

The one who probably had the greatest influence on establishing research as a USGS policy was Luna Bergere Leopold (1915-. . . .) of New Mexico, who had studied at Wisconsin, UCLA, and Harvard and had served as hydrologist with the SCS, the US Engineer Office, and the Bureau of Reclamation before going to the Survey in 1950. Not only did Leopold write perceptively in many fields, including the hydraulic subjects of river morphology, erosion, and sedimentation, but on becoming chief hydrologist in 1956 he was influential in making at least his own branch of the Survey research-minded. First of all, selected staff members were sent to university laboratories for collaborative work, including advanced study. The USGS offices at Iowa, Minnesota, and Colorado State have already been mentioned. The Georgia Institute of Technology should also be included in this group because of the laboratory and consulting services of Carl Kindsvater. While stationed by the Survey at Atlanta, Rolland William Carter (1916-. . . .) of Texas worked closely with Kindsvater, and for their papers on open-channel constrictions and thin-plate weirs they received not one but two Norman Medals. Carter was followed there by Hubert Jerome Tracy (1918-. . . .) of Arkansas, who conducted experiments on open-channel resistance. Herman John Koloseus (1919-. . . .) of Colorado went to Iowa for doctoral research under Survey sponsorship; he was later joined by Jacob Davidian (1926-. . . .), and together they conducted investigations on boundary resistance in high-velocity flow. In 1965, the initial form of the AGU's current bimonthly *Water Resources Research* was founded, with Walter Langbein as editor.

Model testing at the Waterways Experiment Station continued to expand in the postwar years, but several developments of this period are especially noteworthy. One was the Station's success in persuading Garbis Keulegan to become a special consultant to the WES on his retirement in 1960 from the Bureau of Standards. (Rumor has it that he insisted on three specific clauses in his contract: he would consider only those problems that interested him; he would work on them when he felt so inclined; and there would be a green tree outside his window!) Not only was a top-rate analyst thus regularly at hand for the solution of complex problems, but the effect of his presence on the other members of the staff was catalytic. It is to be remarked in particular that the use of mathematical modeling began soon after he reached Vicksburg. A second development was that of the huge outdoor model of the Mississippi Basin begun in 1942 at nearby Clinton. Eventually including the Ohio, Missouri, and Arkansas tributaries as well as the delta region, the entire model occupied some 200 acres and cost $12,000,000. Its construction and operation took place till 1952 under the direction of Haywood Dewey, who later had charge of a tidal model of the bay region at San Francisco; then from 1959 to 1971 he managed a very extensive project of the California Department of Water Resources for the transport of water from the northern to the southern part of the state. The third notable development was the formation and activation of the Hydraulic Analysis Branch in 1951 under the direction of Frank Campbell, who had been transferred for the purpose from the Corps' Omaha District. This division of the WES was responsible for the digest of countless technical papers, reports, and graduate theses, and the reduction of the results to some 400 pages of design information for ready use by hydraulic engineers; 16 issues of *Hydraulic Design Criteria* have appeared to date. With Campbell's retirement in 1967, his place was taken by Ellis Bertram Pickett (1927-. . . .) of Iowa by way of the Little Rock District. Fred Brown succeeded Joseph Tiffany as Technical Director of the Station in 1969.

Perhaps the most effective of the committees activated by the Corps has been that on tidal hydraulics. By the end of the first postwar decade its activities had come to include the sponsorship of investigations and scientific research, the furnishing of advice to the field offices of the Corps, special missions, and the publication and distribution of papers and reports. Fields of investigation included the influence of adjacent beaches on tidal inlets, salinity intrusion, office analysis of existing data, effects of tides and currents, shoaling processes, mathematical modeling, and general inlet studies. In the first quarter century of its existence, roughly 70 reports were prepared in response to requests for consultation. These were of various forms, ranging from those of the committee itself to those on sponsored studies. Aside from a steadily updated bibliography on tidal hydraulics, probably the most noteworthy was the 1965 revision of the 1950 Report No. 1, *Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena*. This was edited by Clarence Felton Wicker (1907-. . . .), a Pennsylvanian who served many years with the Philadelphia District Office, chaired the committee for a dozen years, and then was appointed consultant. Also worthy of mention is the Corps' Committee on Channel Stabilization and its 1969 Technical Report No. 7, under Bradford Fenwick's editorship, reviewing the current state of knowledge on the subject.

In the latter part of 1946 the Hydraulics Laboratory of the Bureau of Reclamation was moved under James Ball's supervision from the New Customhouse to its present home at the Denver Federal Center. Jacob Warnock died three years after the move, and his place as head was taken by Harold Melville Martin (1908-. . . .) of Indiana and Purdue.

During the postwar years the laboratory attained an area of 53,000 square feet, with special equipment for high-head tests of gates and valves, an 80x8x4-foot glass-walled flume, sloping flumes for both open-channel and groundwater studies, and facilities using air as the testing fluid. The most recent addition has been a minicomputer for data acquisition and control. A major facility for hydraulic machinery is located at the power plant in Estes Park, Colorado, where a head of 550 feet is available, permitting full-scale tests of gates and valves. The laboratory probably became best known for its cavitation studies and development of new designs for high-head controls, under Ball, and the investigation of a wide range of energy dissipators under Joseph Newell Bradley (1903-. . . .) of Illinois and, in turn, Alvin Peterka, who had transferred from the TVA in 1946. The latter work resulted in the 1958 publication, *Hydraulic Design of Stilling Basins and Energy Dissipators,* now in its third printing. Another contribution to the understanding of hydraulic laboratory practice was the publication in 1953 of Engineering Monograph 18 on that subject. (Note might be taken at this point that Martin retired as head in 1969 and was replaced by William Emory Wagner (1915-. . . .), a Coloradoan by birth and education, who was succeeded in 1974 by Danny Lee King (1938-. . . .) of Idaho and Colorado. Ball, who retired from the Bureau in 1962, managed a private laboratory at Vancouver for several years and then returned to CSU as research associate.)

There occurred in this period an unfortunate episode that would best be forgotten were it not for conflicting stories about it that still persist. In 1959 an Engineering Societies Monograph was published under the title *Hydraulic Energy Dissipators.* The New Jersey-born author, Edward Arthur Elevatorski (both 1930 and 1933 are given as his year of birth), listed himself on the title page as "Head, Hydraulics Laboratory, and Assistant Professor of Civil Engineering, University of Arizona." The book itself contained some 214 pages, was profusely illustrated with photographs supplied by the Bureau of Reclamation and the Corps of Engineers, and received favorable comment by Steponas Kolupaila in *Applied Mechanics Reviews* the following year. Not long after its appearance, however, the Bureau laboratory staff and the Executive Committee of the ASCE Hydraulics Division were up in arms. It appears that Elevatorski, then employed by one of the Bureau's field offices, had obtained Bureau material prior to the appearance of Peterka's Monograph No. 25, and not only replotted and misinterpreted many of the data, but published the result without Bureau knowledge or permission. A significant gaffe is seen in the statement "The earliest use of a hydraulic jump was as a head increaser, which was first described by Da Vinci in Bologna, Italy, during 1828." (Leonardo lived from 1452 to 1519; passages on hydraulics from certain of his notebooks were compiled three centuries later!) The Hydraulics Division thought that it should have had a chance to review the manuscript before submittal to the Monograph Committee, although the latter had had the work examined by three referees of its own choosing, as was its usual custom. To make matters worse, it was discovered at roughly the same time that Elevatorski had falsified records in order to claim degrees from both Michigan and Colorado, neither of which he possessed, and further evidence of plagiarism soon turned up. He was thereupon expelled from the ASCE, his state engineering registration was canceled, and he disappeared from the University of Arizona. Quite aside from the fact that some 2800 copies of the book were eventually distributed, the tragedy of the situation lay in the fact that Elevatorski possessed sufficient initiative and ability (albeit incompletely trained) to have become a credit to the profession.

In 1948 George Hickox resigned from the directorship of the TVA laboratory, and his place was taken by Rex Alfred Elder (1917-. . . .) of Pennsylvania, Carnegie Tech, and Oregon State. During the latter's 25-year tenure, studies were completed on 10 dams, a major pump-storage project, 6 ship locks, and the movement of gravity currents in deep, thermally stratified reservoirs. In the same period the experimental, shop, and office space underwent a four-fold increase, though the original water system continued to prove adequate. Both electronic-instrument and air-test facilities had in the meantime become necessities. Beginning in 1952, the TVA embarked on a program of steam generation by fossil fuel, which led to studies on dispersion of stack emissions, skimmer-wall control of thermal discharges into and out of neighboring water bodies, improvement of fluid flows in the boiler systems, and many related problems. Especially noteworthy accomplishments were the measurement of very low-velocity currents in reservoirs using the Atomic Energy Commission's deepwater isotopic current analyzer, and the model testing of hydraulically induced structural vibrations. In the mid-1960's the TVA started the design of nuclear reactors, which led to intensive analyses of environmental impact well ahead of the national programs of the following decade. When Elder retired in 1973, he was succeeded by Edward Ely Driver (1935-. . . .), a native of Tennessee with degrees from Vanderbilt and Stanford.

With the war years well past, a number of staff changes took place in the Iowa Institute of Hydraulic Research. John McNown, who had markedly stimulated graduate-student research in such varied fields as particle hydrodynamics, manifold hydraulics, and conformal transformation, left in 1954 for a professorship at Michigan and eventually for the deanship at Kansas. His position was taken by Louis Landweber (1912-. . . .), a New Yorker educated in mathematics and physics at City College, George Washington, and Maryland, who had been on the research staff of the Taylor Model Basin for twenty-two years; at Iowa he continued his productivity in the fields of boundary-layer theory, potential flow, and ship drag, turning out papers and reports at a steady rate in addition to his teaching. With the support of the ONR and the design experience of Milton Martin (1912-. . . .), also a New Yorker from the TMB staff, the 10x10x300-foot river channel of the Institute laboratory was enclosed and equipped with precision towing equipment for experimental purposes; later, after completing the doctorate, Martin went to Hydronautics by way of the Davidson Laboratory of Stevens. An Argentinean whom Rouse had met at Grenoble, Enzo Oscar Macagno (1914-. . . .) joined the Iowa staff in 1956 and thereafter engaged in a broad spectrum of flow investigations—particularly that of density stratification; his wife Matilde, a mathematician, was of great assistance to Landweber on a part-time basis. Emmett Morton Laursen (1919-. . . .), a North Dakotan who had come to Iowa via Minnesota as a graduate assistant in 1945, remained for some twelve years as an adept designer of equipment as well as model investigator, particularly in the sediment field. When he left for Michigan State in 1958, he was replaced by Lucien Munson Brush (1929-. . . .) of Pennsylvania, who had studied at Princeton and Harvard and come to Iowa via the USGS; on Brush's return to Princeton in 1963, his work was taken over by Emmett Michael O'Loughlin (1937-. . . .), a graduate assistant who remained on the staff till his return to Australia in 1967. In 1960 Eduard Naudascher (1929-. . . .) of Karlsruhe, Germany, moved to Iowa after a year at Minnesota to hold a senior teaching and research position (flow-induced vibration, fluid turbulence, and the decay of wakes) for some seven years, thereafter accepting a chair in hydrodynamics back at Karlsruhe. A contemporary of O'Loughlin was René Chevray (1937-. . . .), a native of France, who conducted studies on various aspects of fluid turbulence, did postdoctoral research at Johns Hopkins, and then continued his productivity on the faculty at the State University of New York on Long Island. It is noteworthy that much of the equipment in the Laboratory Annex constructed by the Institute in 1948 was sponsored by the ONR, including both the tilting flume for sediment studies under Laursen, Brush, and O'Loughlin, and the air tunnel for hot-wire measurements of wake turbulence under Naudascher.

The ASCE Fluid Mechanics Committee's listing of available films grew rapidly in the years following the War, in no small measure through those contributed by the St. Anthony Falls Laboratory. Then in the very late Fifties both an MIT-based group called the National Committee for Fluid Mechanics Films and the Iowa Institute of Hydraulic Research submitted proposals to the NSF for the preparation of two extensive educational series. The group at MIT was headed by Ascher Herman Shapiro (1916-. . . .), a thermodynamicist of considerable repute, and that at Iowa by Rouse. The proposals were quite different, in that the National Committee envisioned a continuing series of films in which authorities from various institutions would discuss and demonstrate their specialities, whereas the Iowa series was to be limited to six half-hour films illustrating phenomena treated in the usual undergraduate course—namely, introductory material, fundamental principles, gravitational effects, laminar and turbulent flow, lift and drag, and compressibility. The NSF decided to fund both projects. The NCFMF series were written and narrated by the individual specialists and produced by the nonprofit firm Educational Services Inc. The first few were in black-and-white, rather slow-paced, and prepared under the direction of Shapiro himself. Eventually over 25 other specialists were involved (the most memorable being Sir Geoffrey Taylor), color rather than black-and-white film was adopted, and the results were finally turned over to the Encyclopedia Britannica Educational Corporation for marketing; a special outgrowth of the project was the preparation from the longer films of a series of short loops on particular topics which could be shown to or by students on small projectors. Rouse wrote and narrated each film of the Iowa series, color was used throughout, the IHR shop fabricated all of the sets, and the production was in the hands of the Audio-Visual Department of the University. Lucien Brush assisted with the first three films, and a department photographer handled the camera; O'Loughlin not only assisted with the last three but did the camera work as well. At the time of writing, some 425 copies of one film or another have been purchased from the Iowa Extension Division by 150 institutions in 35 different countries.

A major innovation of the postwar years has been use of the electronic computer in fluids research. Stemming from the purely mechanical integraph and differential analyzer devised at MIT by Vannevar Bush, it is only logical that their vacuum-tube and solid-state versions should also have come into early and widespread use at MIT, as has already been noted. The former MIT doctoral student, George Bugliarello (the g is silent), made extensive use of the computer for fluids investigations at the Carnegie Institute of Technology, on the one hand developing a computer language for hydraulic engineering and, on the other, solving the Navier-Stokes equations for problems of fluid flow. Similar studies were conducted at Iowa by Enzo Macagno (pronounced Macahnyo), among others, with the aid of a Chinese doctoral student Tin-Kan Hung (1936-. . . .), who thereafter joined Bugliarello at Carnegie and continued his analytical productivity. The computer also proved invaluable to Louis Landweber in the solution of both boundary-layer and potential-flow problems. With Rouse's motive force, Landweber's know-how, and the University's IBM computer series, three Iowa doctoral candidates were able to obtain two-dimensional free-surface solutions that had been sought by Rouse for a third of a century: the weir nappe, by Theodor Serafimovich Strelkoff (1932-. . . .) of California, who returned to teach at Davis; flow over spillways of arbitrary profile form, by John Joseph Cassidy (1930-. . . .) of Wyoming, who thereafter joined the staff at Missouri; and the jet from a circular orifice, by Bruce Woodson Hunt (1941-. . . .), who then accepted a position at Washington; all three have continued to be productive in related investigations. Special note should be taken of a series of computer-derived motion pictures of unsteady-flow patterns produced at the Los Alamos Scientific Laboratory of the University of California under contract with the Atomic Energy Commission; though the investigators were not hydraulicians, their films included many transient free-surface phenomena of hydraulic import (gate-flow establishment, wave instability, etc) as well as such internal patterns as pendulating viscous wakes.

When the International Association for Hydraulic Structures Research was founded in Europe in 1935, eight of the 66 charter members were American, four of them (Eaton, Straub, Kramer, and O'Brien) having been Freeman Scholars. Necessarily at a standstill during the War, activities of the Association were revived thereafter through the efforts of Fellenius of Sweden, Thijsse of Holland, Danel of France, and Straub. The latter became the first postwar president of the organization, and in 1949 its name was shortened to International Association for Hydraulic Research. Two other Americans have also served as president: Arthur Ippen (1959-63) and James Daily (1967-71); and two of the international congresses have been held in the United States: at the University of Minnesota in 1953, and at Colorado State University in 1967. Ippen's most noteworthy accomplishments as president were the establishment of the quarterly *Journal of Hydraulic Research,* currently in its fifteenth year, and the formation of regional divisions—particularly in Latin America. About 20% of the IAHR members now come from the United States, and they have contributed to the *Journal* and played a prominent role in the congresses held biennially in various parts of the world.

Participation by American hydraulicians in international exchanges on a group basis began after the 1961 IAHR Congress at Dubrovnik, Yugoslavia, when five laboratory directors from the States visited Moscow, Sochi, and Leningrad in the Soviet Union. The trip was organized by Rouse and included Ippen, Straub, Harold Martin, and Joseph Tiffany. A return visit by five Soviet hydraulicians (after a typical last-moment cancellation) took place the following year; they went from one to another of the five American laboratories of the original American travelers, being accompanied to four of them by Theodor Strelkoff, who had been born of Russian parents and spoke their language fluently. In 1964 a Coastal Engineering Seminar was held in Japan as part of the US-Japan Cooperative Science Program supported by the NSF. Organized by Joe Johnson, the group included D. L. Inman, A. T. Ippen, D. R. F. Harleman, R. L. Miller, R. L. Wiegel, and B. W. Wilson. One year later ten American specialists in the various aspects of flow measurement visited Japan with similar support; this trip was organized by Rouse and included G. Bugliarello, J. E. Cermak, P. G. Hubbard, S. J. Kline, J. L. Lumley, F. C. Michelsen, F. E. Perkins, J. F. Ripken, and G. B. Schubauer. A return visit by the Japanese was made in 1967, John Kennedy acting as American organizer; MIT, St. Anthony Falls, Iowa, Fort Collins, Stanford, and Berkeley served as host institutions, and the discussion topic was the use of models in hydraulic research.

Though any Iowa meeting after the Fourth Hydraulics Conference of 1949 could only come as an anticlimax, the fifth in the series was held in 1952, with sediment transport as the general theme; it was attended by 213 participants. This was followed three years later by the Sixth Hydraulics Conference, on the topic of flow measurement, with 219 in attendance. The seventh and last in the series took place in 1958, on the theme of prototype verification of theoretical and experimental prediction, with an attendance of 173; in each instance, a *Proceedings* volume was published. In the meantime, largely on the initiative of Albert Fry, the Hydraulics Division of the ASCE had begun its own series of annual specialty conferences, the first of which was held in 1950 at Jackson, Mississippi, and the second in 1953 at Minneapolis in conjunction with the initial American congress of the IAHR. With but one exception the series has continued annually to date, the programs being arranged by the Division, and the local arrangements made by the university (or federal agency) and the ASCE section. The conferences have been held at each of the following cities: Austin, 1954; Berkeley, 1955; Madison, 1956; Cambridge, 1957; Atlanta, 1958; Fort Collins, 1959; Seattle, 1960; Urbana, 1961; Sacramento, 1962; University Park, 1963; Vicksburg, 1964; Tucson, 1965; Madison, 1966; no conference was held in 1967, in view of the IAHR congress at Fort Collins; Cambridge, 1968; Logan, 1969; Minneapolis, 1970; Iowa City, 1971; Ithaca, 1972; Bozeman, 1973; Knoxville, 1974; Seattle, 1975; and Lafayette, 1976. Because of the steady increase in number of papers, in 1956 the ASCE instituted in place of its *Transactions* a series of separate *Journals*, that of the Hydraulics Division initially appearing bimonthly and including some 25 papers and 40 discussions per year. In 1959, however, the increase in number of papers made changing to a monthly basis necessary, and at present more than 100 papers and 150 discussions are published annually. A few hydraulics papers of a more analytical nature are published in the *Journal* of the Engineering Mechanics Division. Mention has already been made of the *Journal of Hydraulic Research* of the IAHR. Note should also be taken of the British *Journal of Fluid Mechanics,* a prestigious magazine which has attracted many of the best analytical papers that American hydraulicians have produced.

During the next-to-last decade of the second century of the country's existence, the appearance of textbooks continued apace—largely for undergraduates and essentially all with the fluid-mechanics slant. Only six books of an advanced nature will be mentioned here. The first, in 1959, was *Open-Channel Hydraulics* by Ven Te Chow (1919-. . . .), a former Chinese professor who had been on the faculty at Illinois since 1951; he was also a prolific writer and stimulating editor in the fields of hydrology and water resources. *Advanced Mechanics of Fluids,* which appeared the same year, was written by nine staff members of the Iowa Institute under the editorship of Hunter Rouse, to form a sequel to his *Elementary Mechanics of Fluids;* its eight chapters dealt with principles of research, fundamental concepts, irrotational flow, conformal representation, turbulence, boundary layers, and free-turbulence shear flow. The third of the books represented perhaps the most stupendous editorial venture undertaken by an American hydraulician: Victor Streeter's *Handbook of Fluid Dynamics,* published in 1961, 1200 pages in length, and containing 27 sections by 31 authors; not only did it review the usual fundamental principles, but these were extended to include compressible, multicomponent, and nonNewtonian fluids; the principles were then applied to such varied matters as porous media, two-phase flow, sediment transport, open channels, turbomachinery, cavitation, transients, jet propulsion, lubrication, stratified flow, and magnetohydrodynamics. Scarcely less formidable was the work of Steponas Kolupaila (1892-1964), a native of Latvia who had studied in Russia, taught in Lithuania, and joined the staff at Notre Dame in 1949 after losing everything during the War; his 1961 *Bibliography of Hydrometry* represented at least the third version of a lifelong collection of card references; 7370 titles in 30 languages (many abstracted), with a name index of 4500 entries, all pertaining directly or indirectly to flow measurement. Another advanced textbook was James Robertson's *Hydrodynamics in Theory and Application;* released in 1965, it bore the marks of his years of teaching at Penn State and Illinois, including his research activity with Penn State's Garfield Thomas Water Tunnel. The last book of the six also revealed the continuing interest of the author over an extended period: Chia-Shun Yih's *Dynamics of Nonhomogeneous Fluids,* which covered his investigations at the

University of Michigan in the field that he had first selected as a graduate student at Iowa.

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CHAPTER IX

EVENTS OF THE TWENTIETH DECADE

In the middle Sixties a very complex series of reactionary trends began to reach a head, the many ramifications of which may not be clear for some time to come. Hydraulics was not spared from the resulting unrest. Perhaps the most obvious indicator of the situation was the students' reaction, which displayed various forms on various campuses, ranging from minor disturbances to outright rebellion. One of their phobias was the Vietnam War, but many also took a very dim view of anything technical, pleading for more use of the heart and less of the mind. Engineering enrollments dropped accordingly. Curricula became more general in their approach, and undergraduate laboratories received less and less attention. The growing distaste for technology stemmed in good measure from America's irresponsible use of natural resources and pollution of the environment, much of which was unjustly laid at the feet of the engineer. Federal support of science became rapidly less enthusiastic, and the strong post-Sputnik research largesse dwindled appreciably. Questionable as the logic of these developments actually was, a certain amount of good resulted. Academic belts were tightened, efficiencies increased, and governmental steps were taken to alleviate various aspects of the situation. Agencies were established to reduce pollution and otherwise protect the environment; funds for applied research and development were made available as those for pure research were curtailed; and still other agencies came into being for the protection of the nation's expendable resources.

Interest in water resources, of course, was by no means new. As early as 1951 the Engineers Joint Council had produced the report "Principles of a Sound National Water Policy," and six years later a "Restatement" of that report was issued. In 1959 the ASCE's Hydraulics, Sanitary Engineering, Irrigation and Drainage, Power, and Waterways and Harbors Divisions set up a Coordinating Committee on Water Resources, as a device for advancing their mutual concerns. At much the same time certain of the engineering colleges around the country began emphasizing the systems approach to water management in their civil-engineering curricula. Chief among these were Georgia Tech, where a Water Resources Center was formed by Carl Kindsvater in 1963; MIT, under Arthur Ippen; the University of Illinois, under Ven Te Chow (1919-. . . .), a native of China; the University of Texas, under Walter Moore; Stanford University, under Ray Keyes Linsley (1917-. . . .) of Connecticut and Joseph Bernard Franzini (1920-. . . .) of California; and Colorado State, under Maurice Albertson, as well as two specialists who were recently added to the staff for that particular purpose: Victor Alvin Koelzer (1914-. . . .) of Kansas and Iowa, and

Warren Acker Hall (1919-. . . .) of South Dakota and California, both of whom were broadly experienced in the field, including service with the government (Hall, in fact, became the first to hold Colorado State's newly endowed Elwood Mead Professorship). The ASCE's 1959 move was further formalized in 1972 by the establishment of a Technical Council on Water Resources Planning and Management, and by its change in status from a Technical Council to a Division in 1975.

Passage by Congress of the Water Resources Research Act of 1964 authorized the Department of the Interior (a) to create research institutes administered by the Land-Grant Colleges in each of the States, (b) to allocate funds for their support, and (c) to make additional funds available for research by other parties. The Water Resources Planning Act of 1965 established the U.S. Water Resources Council and a series of River Basin Commissions; the Council was to consist of the Secretaries of the Departments of the Interior, Agriculture, the Army, Health, Education and Welfare, and Transportation, and the Chairman of the Federal Power Commission, all as members; the Secretaries of Commerce and of Housing and Urban Development, and the Administrator of the Environmental Protection Agency, as associate members; and some fifteen observers, including the Chairmen of the River Basin Commissions and Committees. The Council's goals as set forth by the Planning Act were as follows:

to maintain a continuing study and prepare periodic national assessments of water supplies and needs;

to maintain a continuing program for preparation of regional or river basin plans;

to appraise the adequacy of existing and proposed programs and policies to meet the nation's water requirements;

to recommend improvements in programs and policies to the President;

to establish principles, standards, and procedures for Federal participation in comprehensive planning and for Federal projects;

to establish and assist River Basin Commissions, interagency committees, and coordinating groups to foster joint State-Federal cooperation and coordination in water resources planning and programs;

to assist the States to participate in water and related land resources planning.

At the time of writing, active research programs were under way in most parts of the nation. It is of interest to note in this regard that the People's Republic of China sent a water-resources delegation to the

United States in 1972, and that two years later an American delegation—which is believed to have been the first group of engineers from this country to have entered the PRC—returned the visit. Led by Maurice Albertson, those making the trip were George Bugliarello, V. T. Chow, J. W. Daily, Charles Greer, J. E. Nickum, D. F. Peterson, Hunter Rouse, W. W. Sayre, R. T. Shen, and C. H. Zee.

The matter of pollution was also as old as civilization itself, but for at least the first century or more of American development the population concentration was not great enough to cause either discomfort or worry about the future, and, by the time these factors became appreciable, industrial pressures and public apathy were strong enough to maintain the status quo. Air pollution, first in Los Angeles and then in most other large cities, brought the gravity of the problem into focus, and with the aid of militant students and other environmentally minded citizens attention was also brought to bear on the pollution of our streams, lakes, and estuaries—not to mention such matters as oil spills and the growing concentration of injurious chemicals in marine life. The immediate results were severalfold. Federal agencies were formed and laws were passed or strengthened against both air and water pollution, with some good and some negligible effect, the latter being due to lethargy, industrial resistance, and—as will soon be discussed—conflicting public interests. Funds were directed toward hydraulic research on antipollution measures. And the environment assumed a prominent place in both literature and life—for instance, sanitary engineering changed its name (if not its scope) to environmental engineering—and the preservation of nature for posterity became an important part of the American ethic. At Georgia Tech Carl Kindsvater promoted the formation of an Environmental Resources Center in 1970. Under the National Environmental Policy Act of 1969 the Environmental Protection Agency was established in 1970, whereupon it assumed responsibility for administering such earlier laws as the Clean Air Act, the Water Pollution Control Act, and the Noise Pollution and Abatement Act. The somewhat arbitrary rulings of the EPA soon aroused mixed reactions, depending upon whether one was an industrialist or an ecologist.

Also of long duration and equally long disregard has been the growing rate of energy expenditure, in particular by the United States. Just as the environmental situation began to show some signs of alleviation, the need for more power and for its more efficient production gave rise to an opposing trend that offset much of the initial gain. To a considerable degree, both aspects of the matter involved problems of fluid motion, some of which may not even yet be evident. One that soon became obvious, however, was the disposal of the waste heat produced during the still-inefficient generation of power by either fossil-fuel or nuclear plants. Following WPI's lead, the recirculation of cooling water had been studied at MIT for the TVA in 1953, and within a decade various other institutions—Iowa, TVA, Minnesota, and Caltech—were all involved in model studies of both atmospheric and river cooling. That the problem was world-wide rather than merely local was demonstrated by the fact that the most recent exchange visit of American hydraulicians to Japan took place in 1974 on the topic of waste-heat disposal; the visit was organized by Donald Harleman, and the other participants were N. H. Brooks, L. P. Jensen, J. F. Kennedy, L. C. Neale, and F. L. Parker.

While research at MIT during the past decade has dealt with many of the same topics as in the preceding fifteen years, the four senior members of the staff (Williams having left for private practice in 1960, Daily for Michigan in 1964, Kennedy for Iowa and Partheniades for SUNY at Buffalo, Florida, and eventually Greece, in 1966, and McLaughlin for private practice in 1967) each tended to develop his own special field in addition to the general program: Arthur Ippen's particular interest had long been the estuary phase of coastal engineering, and he served many years on the Beach Erosion Board (later the Coastal Engineering Research Board) and the Committee on Tidal Hydraulics of the Corps of Engineers; both curricular and investigational emphases on the subject were developed under his direction. Donald Harleman's field of specialization was that of flows affected by density variation due to either thermal effects or salinity gradients; he consulted extensively both in the States and abroad and was host to week-long conferences at MIT in 1971 and 1972 and at MIT and Delft in 1975 on the thermal aspect of the subject. Peter Eagleson focused his attention on dynamic hydrology and in 1970 published a book under that title. And Frank Perkins steadily intensified his earlier work on numerical analysis. The Hydrodynamics Laboratory of 1951, once so commodious, seemed in the meantime to have shrunk in proportion to the numbers of students and projects taken on. By 1967, when plans to double the size of the laboratory were approved, the full-time faculty had grown to eight, there were 28 teaching and research assistants, and a total of 275 graduate degrees had been awarded. In 1970 the two-story addition to the building was dedicated under the name Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics; a two-day symposium on "The Water Environment and Human Needs" was held as part of the dedication ceremony, with former graduate students and staff members as contributors. That same year Eagleson became head of the Civil Engineering Department (a post which he held till 1975, when Perkins replaced him as acting head). A year later the Hydraulics Division was renamed the Water Resources Division, still under Ippen's jurisdiction. In 1972 Harleman was chosen to head the Division, Ippen continuing as director of the Parsons Laboratory. On the latter's retirement in 1973, Harleman assumed the directorship as well. Ippen, unfortunately, had less than a year left to live, but no one would dispute the fact that neither his professional nor his personal life could have been more complete.

Following Lorenz Straub's equally untimely death in 1963, the Straub family had established an annual award for the best doctoral dissertation submitted on his advisee's behalf by an American or foreign university professor. Recipients of the Lorenz G. Straub Award to date have been as follows: H. B. Fischer, Caltech, 1966; W. W. Sayre, CSU, 1967; R. E. Arndt, MIT, 1968; W. C. Huber, MIT, 1969; T. Gangadharaiah, Indian Institute of Science, Bangalore, 1970; G. D. Ashton, Iowa, 1971; A. Lejeune, Liège, 1972; F. Durst, London, 1973; R. B. Singerman, Iowa, 1974; and N. K. Kotsovinos, Caltech, 1975. Edward Silberman took Straub's place as director, and was replaced by Alvin Anderson in 1974, only a year before the latter's unfortunate death. At what was by then Colorado State University, Daryl Simons had left the USGS in 1963 to become Associate Dean for Research; Lionel Baldwin was appointed Dean of Engineering in 1965; and in 1969 Ray Chamberlain assumed the post of President. Under Jack Cermak's direction, another environmental wind tunnel was completed that year, and two more the year following. Erich Plate, who had been closely associated with the wind-tunnel investigations, left in 1970 to accept one of the chairs in hydraulic engineering at Karlsruhe. In the same period a large outdoor rainfall-runoff facility with an area of 25,000 square feet was constructed under Vujica Yevjevich's direction; fed by 400 irrigation sprinklers of variable capacity, rainfall and runoff measurements versus space and time are now reduced to their significant form by computer. At California, with Einstein's retirement in 1971 (and death in 1973), activity in the sediment field was greatly reduced, but that in coastal engineering remains unabated. Hugo Fischer continues his research on the hydraulics of pollutant dispersion. The Californian Robert Louis Wiegel (1922-. . . .), with the university since 1946, has become increasingly effective in the solution of ocean problems. And Joe Johnson, although he nominally retired in 1975, had just arranged the sixteenth in a presumably unending series of international coastal-engineering conferences.

During the last decade a number of changes in laboratory personnel and facilities have also taken place at Iowa (not to mention adoption of the name The University of Iowa to avoid further confusion with the new title of its sister institution at Ames). In the summer of 1965, Philip Hubbard canceled a year of teaching in Chile under the aegis of the Organization of American States to become Dean of Academic Affairs, and John Richard Glover (1937-. . . .) of Ohio, a doctoral student in electronic instrumentation who was to pinch-hit for the year, continued instead as Hubbard's successor. Later that year Hunter Rouse was persuaded to help remedy a difficult administrative situation by assuming the deanship of the Iowa College of Engineering, and he secured John Kennedy of MIT to replace him in 1966 as director of the IIHR. Kennedy and Glover together obtained for the Institute an IBM 1801 data-acquisition system, which permitted on-line recording and analysis of experimental measurements from all parts of the laboratory; Glover was greatly assisted in this endeavor by Frederick Albert Locher (1940-. . . .) of Colorado, Michigan Tech, and Iowa. Kennedy also installed a sizable low-temperature facility (i.e. a refrigerated room enclosing a refrigerated flume carrying refrigerated water) in which the formation and decay of ice in open-channel flow could be studied experimentally. As federal interest in the problems of waste-heat diffusion from power plants became ever greater, tests on cooling towers, ponds, and submerged manifolds came to occupy many members of the research staff, in particular William Sayre from CSU, Virendra Chaturbhai Patel (1938-. . . .) of India, and César Farell (1935-. . . .) of Uruguay. A new building with a thermal flume 8x10 feet in cross section was constructed in 1975 for large-scale experimentation. Details of these and other investigations, as well as thesis contributions of the 500-odd past graduate students, are presented in *The First Half Century of Hydraulic Research at the University of Iowa.*

Of the more than 200 American engineering colleges currently listed in the journals of the American Society for Engineering Education, it is probably safe to assume that all have hydraulic-laboratory facilities of a sort, whether for student experimentation or purely demonstration. Some of these have been treated in detail in the foregoing pages, but most are so small that they do not really warrant attention herein except as a group. Perhaps a dozen others, however, deserve mention for one reason or another—whether because of a lone researcher who has made himself heard, or because of a noteworthy sequence of people, or even because of some distinction in the past or promise for the future. These will now be dealt with in brief, starting at the east coast. There Harvard University possesses the fortunate combination of three individuals in complementary fluids fields: Harold Thomas Jr (1913-. . . .) of Indiana, who studied at Carnegie and followed in the footsteps of his hydraulically minded father; Howard Wilson Emmons (1912-. . . .) of New Jersey, a specialist in the aerodynamics of combustion and propulsion systems; and Garrett Birkhoff (1911-. . . .), also of New Jersey, an outstanding mathematical hydrodynamicist. At what was then the Case School of Applied Science, George Eric Barnes (1898-. . . .) of Washington DC, who had studied at MIT and subsequently developed an extensive consulting practice, carried out many model investigations in connection with his work before and after the War. During the same period Ohio State University had active hydraulics people in both civil and mechanical engineering: Ralph Waterbury Powell (1889-. . . .) of Michigan, who wrote extensively on open-channel flow and later joined Chesley Posey at his Rocky Mountain Laboratory; and Samuel Reid Beitler (1899-. . . .), an Ohioan who was an expert on fluid meters.

At the University of Michigan, Ernest Frederick Brater (1912-. . . .), a Michigander from the start, became known both as a hydrologist and as director of the Lake Hydraulic Laboratory, where he investigated the protection of shores and offshore structures. On Raymond Binder's assumption of fluid-mechanics instruction at Purdue, he developed a very effective demonstration laboratory; in the Fifties the civil engineering program was taken over by Jacques William Delleur (1924-. . . .) of France, with degrees from Rensselaer and Columbia and subsequently a Freeman Scholar, and Gerrit Toebes from MIT; their fields of interest are, respectively, open channels, boundary layers, and turbulence, and hydroelasticity and water resources. Before becoming dean at Illinois, the Iowan Melvin Lorenius Enger (1881-1956) developed a sizable teaching laboratory in the Department of Theoretical and Applied Mechanics; there he was succeeded by Wallace Monroe Lansford (1900-. . . .), a native of the state, and he in turn by James Robertson, already mentioned in previous chapters; the civil-engineering phase of hydraulics was greatly strengthened by the advent of Ven Te Chow, who remained on the staff after obtaining the doctorate in 1950, became best known for his great activity in the field of hydrology, but also developed a fairly large hydrosystems laboratory; in recent years he has been assisted by Ben-Chie Yen (1935-. . . .), also a native of China, who did his graduate work at Iowa and has written widely on matters of open-channel flow. Following the laying of groundwork in sanitary and hydraulic engineering by Daniel Mead and Francis Dawson, the Wisconsin laboratory was taken over by Freeman Scholar James Gelston Woodburn (1894-. . . .) of Indiana, Purdue, and Michigan; he was succeeded by Arno Thomas Lenz (1906-. . . .) of Wisconsin; a somewhat younger and still active colleague is James Richard Villemonte (1912-. . . .), also of Wisconsin, and a still younger one is Peter Leonard Monkmeyer (1930-. . . .) of Germany.

The laboratory at the University of Missouri was manned in turn by William McCoy Sangster (1925-. . . .) of Minnesota and Iowa, who eventually left for Georgia Tech, where he almost simultaneously became Dean of Engineering and President of the ASCE; and by John Joseph Cassidy (1930-. . . .) of Wyoming, Montana, and Iowa, who recently accepted the post of chief hydrologist with Bechtel Corporation in San Francisco. Vaughn Ernest Hansen (1921-. . . .) returned to Utah State after doctoral study at Iowa and there developed a very large water-resources laboratory, which he left in 1966 to devote full time to his consulting practice in ground-water hydrology; he was succeeded by Jay Merrill Bagley (1925-. . . .) of Utah and Stanford, who in turn resigned in 1975. The Albrook Hydraulic Laboratory at Washington State University was developed after the War by Edwy Roy Tinney (1925-1974), a native of Canada with a Minnesota doctorate, and a very great deal of hydraulic-model work was undertaken there under his energetic direction; on Tinney's return to his homeland in 1969, he was succeeded by John Frederick Orsborn (1929-. . . .) of Colorado, Minnesota, and Wisconsin, and in 1974 the directorship was assumed in turn by John Arthur Roberson (1925-. . . .) of Washington, who had written his Iowa dissertation on synthesis of the coefficient of surface drag. At the University of Washington a small laboratory was established well before the War by Charles William Harris (1880-1973) of Washington, who had done graduate work at Cornell early in the century; he was a boat-builder from his student days on, his masterpiece being the *Vivace*, a 55-foot seaworthy ship; the laboratory that bears his name has been manned by Ronald Nece since his return from MIT and by Eugene Porter Richey (1917-. . . .) of Washington, Alaska, Caltech and Stanford, with postdoctoral experience at Delft and Sheffield; after a few productive years on the Washington staff following his doctoral studies at Iowa, Bruce Hunt accepted an appointment at the University of Canterbury, Christchurch, New Zealand, where Richey is now also in residence. The westernmost of American laboratories is the Look Laboratory of Oceanography at Honolulu, directed by John Thomas O'Brien (1911-. . . .) of Minnesota; since 1968 this has been operated as part of the Department of Ocean Engineering of the University of Hawaii, which is in the charge of Charles Leroy Bretschneider (1920-. . . .) of South Dakota, California, and Texas A & M.

As was remarked in an earlier chapter, the original Hydraulic Division of the ASME consisted primarily of those members dealing with flow measurement, losses in ducts, water hammer, and the design of hydraulic turbines and pumps—traditional hydraulics, so to speak. With the advent of fluid mechanics a younger generation, interested in a broader range of applications and attuned to the uses of long-range research as well as ad hoc techniques, began to appear on the scene. To some degree their research papers were sponsored by the Hydraulic Division, but also by the Division of Applied Mechanics, which had an established tradition of research orientation as well as its own well-respected *Journal*. The group of "Hydraulic Old-Timers" continued to hold together, but at the same time those concerned with the flow of steam and gas, phase mixtures, and nonNewtonian fluids gathered both numbers and strength. Though the ASME had long given the impression of youth and liberalism in comparison with the older and more conservative ASCE, forces of conservatism within the Hydraulic Division made very rapid change undesirable. It took place instead through the introduction of new committees, new types of meeting format, and publications which attracted the interest of the younger generation. The situation evolved in this way for roughly a decade before adoption of the new name, Fluids Engineering Division, in 1970. A number of individuals played an effective role in this evolution, including James Daily, Howard Emmons, and George Wislicenus, whose names have already appeared in these pages, as well as Robert Charles Dean Jr (1928-. . . .) of Georgia, a part-time professor at Dartmouth and president of his own consulting firm there at Hanover, and Stephen Jay Kline (1922-. . . .) of California, on the Stanford faculty since 1952 and an authority on diffuser flows, separation, and rational channel design. Significant is the fact that it was Wislicenus more than any other who bridged the gap between the old timers and the new and was ultimately decisive in the move for change. To complete the gradual transition begun in the Fifties, a separate *Journal of Fluids Engineering* came into being in 1974, with Dean as its first editor.

Probably the best example of interdisciplinary collaboration that has resulted from the advent of fluid mechanics is found in the biomechanics field. Despite its great upsurge in the past decade or so, application of the principles of mechanics to the study of the body fluids is in no sense new. Leonardo was interested in eddies, whether produced by heart valves or channel constrictions. Guglielmini taught not only hydraulic engineering but medicine as well. And the physician Poiseuille estimated the resistance of blood flow from tests with water and oil in glass capillaries. More recently, wartime cadiovascular researchers at Iowa called on Philip Hubbard for instruments to measure blood flow in the living body. Not long after, Antoine Craya of Grenoble, who replaced John McNown during a Fulbright year abroad, lectured on the analogy between water hammer and blood hammer (i.e. the pulse), later showing physicians the reason for arterial failure at bifurcations. What the physicians actually needed as much as instrumentation was appreciation of the fact that further progress could be made only if medical and mechanical principles were equally well understood, and that to this end doctors and engineers would have to work together in an atmosphere of mutual respect. Beginning in the late Fifties, such an atmosphere was produced at Carnegie Tech by George Bugliarello, who applied to analysis of the flow of blood the principles which he had developed under James Daily at MIT for nonNewtonian fluids such as paper stock. With the support of the National Institutes of Health, and with the involvement of a series of graduate students, he proceeded to study the detailed characteristics of blood flows in glass tubes of small diameter, including simulation of the movement of plasma between the red blood cells. Some 40 research papers on hemodynamics were produced by this group in the next ten years, in the course of which Bugliarello assumed the deanship at Chicago Circle (and more recently the presidency of the Polytechnic Institute of New York).

One of Bugliarello's early collaborators was Tin-Kan Hung, who had done his doctoral work with Enzo Macagno at Iowa. His principal contributions at Carnegie, and more recently at Pittsburgh, had to do with the effect of arteriolar bends, the details of the aortic flow and motion of plasma and blood cells, the non-linear mechanics of peristaltic pumping, and the role of secondary flow in membrane oxygenation. Richard Skalak (1923-. . . .) of New York, Boris Bakhmeteff's successor at Columbia, developed his interest in biofluids in 1962, when one of his hydraulics students proposed to study some aspect of blood flow for his doctoral dissertation; this led to the investigation of wave propagation in the blood circulation of the lungs. Skalak has since given attention to problems of both micro- and macrocirculation, including such aspects of the red-cell behavior as their membrane elasticity. A nonlinear analysis of wave propagation in a femoral artery was pioneered by Victor Streeter in the middle Sixties. Another ex-Iowan, Sung-Ching Ling of Catholic University, utilized his hot-film anemometer in the late Sixties for the measurement not only of the velocity distribution in the aorta of a dog but of other blood-flow characteristics as well. In 1968 Macagno and Rouse recommended at a hemorheology conference that principles of hydraulic similitude be given greater attention in problems of biomechanics. That same year Macagno's interest advanced from blood circulation to the induced flow of the contents of the small intestine; this, in fact, was the subject of his student Singerman's dissertation which received the 1974 Lorenz Straub award. The subject matter of such investigations is obviously of too specialized a nature to warrant further description. The point that is essential to this account is that hydraulicians have a role to play in professions that are at first glance far afield. Conversely, what is learned from flows in living systems can aid in the development of more sophisticated hydrotechnical systems, as proposed by Bugliarello and his collaborators.

With but few exceptions, general fields of research have been discussed in this chapter without citation of specific papers, simply because so many have been published since the War that the list of references would have to be either prohibitively long or grossly incomplete. The Waterways Experiment Station, for example, released in 1975 a compilation of its report titles that was several hundred pages in length. The MIT, Iowa, Minnesota, Colorado State, and Caltech laboratories, moreover, have issued printed lists of available reports and reprints that extend well into the hundreds, and other institutions have followed suit in proportionate numbers. The issuance of such summaries is a good step in the direction of recording an institution's history of accomplishment, and it is to be hoped that every organization with something to contribute will eventually do the same. The publication of research digests accomplishes much the same thing on a profession-wide scale, and the journal *Applied Mechanics Reviews* and the *Annual Review of Fluid Mechanics* are noteworthy in this regard. Books, of course, have their own special role.

Though the production of undergraduate texts began to taper off with the reduction in engineering enrollments, the momentum of the previous years was still apparent. If one undergraduate text deserves mention for this period, it is Daily and Harleman's *Fluid Dynamics* of 1966 (two years after Daily moved to Michigan), noteworthy as much as anything for the fact that its wealth of material made it almost more suitable for intermediate students. That same year the book *Estuary and Coastline Hydrodynamics* appeared as an Engineering Societies Monograph, edited by Ippen and written by those teaching the subject at MIT as well as several other authorities. The year thereafter, Streeter and Wylie published *Hydraulic Transients*, reflecting the senior author's specialty of many years. This was followed in 1968 by the translation from the Latin of Daniel Bernoulli's *Hydrodynamica* and Johann Bernoulli's *Hydraulica* at the hands of two Iowa doctoral students, Thomas Carmody (1928-. . . .) of Connecticut, who then went to the University of Arizona, and Helmut Kobus (1937-. . . .) of Germany, who eventually joined Eduard Naudascher at Karlsruhe. In 1969 Chia-Shun Yih published his second book, *Fluid Mechanics*, an advanced study which well displayed the author's elegance of both mathematical analysis and the written word.

Following Knapp's death, his manuscript notes for the book *Cavitation* were turned over to Daily, and with the coauthorship of Frederick Gnichtel Hammitt (1923-. . . .) of New Jersey, a professor of nuclear engineering at Michigan, the book was finally published as an Engineering Societies Monograph in 1970; it is easily the most authoritative work on the subject. That same year, before leaving California, Warren Hall published with a younger colleague a systems approach to water-resources management. On the 65th anniversary of Rouse's birth the following year, John Kennedy and Enzo Macagno paid him the distinct compliment of publishing a book containing 57 of his papers and articles under the title *Selected Writings*. The year 1971 also saw the release of the first American book on the *Hydraulics of Sediment Transport* by Walter Hans Graf (1936-. . . .) of Austria, a former student of Albert Einstein's then on the faculty of Lehigh University, who later went to the University of Lausanne. That same year brought Einstein's retirement at Berkeley, the ocasion being marked by a symposium organized by another former student, Hsieh Wen Shen; the papers—including Einstein's dissertation and 1950 paper—were published at Fort Collins in 1972 under Shen's editorship. (Mention should also be made of some 20 volumes containing lectures presented at Fort Collins during conferences and intensive summer courses and released by CSU's Water Resources Publications in the early Seventies.) For its distinctive subject matter, note should be taken of the 1974 book on computers and water resources written by George Bugliarello and a research assistant at Chicago Circle. In 1975 there finally appeared the 745-page ASCE manual on sedimentation, over the compilation of which Vito Vanoni had presided for some two decades; published first as a series of reports in the Hydraulics Division's *Journal,* these were then gathered together and the numerous references systematized; because of its multiple authorship and extensive review prior to final publication, it should long be the definitive work on American practice. Currently the Bureau of Reclamation is preparing to reissue its Engineering Monograph No. 18 under the title *Hydraulic Laboratory Techniques.*

As early as 1955 it had been proposed within the Agricultural Research Service to establish a new laboratory for studying the severe overland-flow erosion problems of the Yazoo-Tallahatchie Basin in northwestern Mississippi, much as the Soil Conservation Service had done elsewhere just before the War. By 1958 funds had been allocated, 10 acres of land had been acquired at Oxford not far from the University of Mississippi, and construction of a central test facility had begun. A year later the USDA Sedimentation Laboratory, built at a cost of half a million dollars, was dedicated; Russell Woodburn (1907-. . . .) of Kentucky, a civil engineer with the USDA since 1933, was named director; and an initial staff of 25 was assembled. The principal item of experimental equipment was a 100x4x2-foot tilting flume and appurtenances, but a number of watersheds in the vicinity were available for test purposes, and the facilities of both Mississippi and Mississippi State Universities were at the staff's disposal. Initial studies dealt with sediment erosion and transport, eventual attention being given to sediment suspension and discontinuities in the rating curves of alluvial streams. Woodburn was succeeded in 1961 by Carl Richard Miller (1920-1964) of Massachusetts and New Hampshire. His place was taken in 1963 by Donald Parsons (1901-. . . .) of Iowa, who had served with the SCS since 1934, first at the National Hydraulic Laboratory and then at St. Anthony Falls. Under Parsons a proposal was made for an increase in the size of both laboratory and staff, and in 1968-69, while August Robert Robinson Jr (1921-. . . .) of Texas was director, the physical facilities were nearly doubled.

Although the land area occupied by the laboratory remained the same, the central building was greatly enlarged, a 250x9x7-foot outdoor test channel was constructed, much supplementary equipment was purchased, and a number of additional watersheds were instrumented. At the time of writing, the USDASL staff has been increased to some 50 people, and the laboratory possesses two additional tilting flumes and a water tunnel, several test basins, hot-film anemometers and miscellaneous measuring instruments, and a very flexible modular computer system. Research efforts have been devoted to improvement in methods and instrumentation for measuring soil moisture and related characteristics. More recently attention has been given to means for preservation of the environment beyond simply the reduction of erosion by improved tillage practices—for example, investigation into the transport of herbicides, insecticides, and fertilizers that are adsorbed onto sediment. In the fall of 1975, under its most recent director, Donn Gene DeCoursey (1934-. . . .) of Indiana, the laboratory held a research review and planning conference. The dozen staff presentations ranged from details of the many needed research projects and outlines of how they would be carried out, to a discussion of how the USDASL could serve as a knowledge center not only to regional agencies but to the entire Agricultural Service. Within the past five years, it should be noted, the Water Resources Division of the USGS has undertaken a similar development. Its new Gulf Coast Hydroscience Center is located at NASA's National Space Technology Laboratories near Bay St. Louis, Mississippi. Facilities presently include an indoor hydraulics laboratory with 35,000 square feet of floor space which houses a tilting flume and a towing tank, and an outdoor flood-plain-simulation area of about 30 acres. The laboratory program is intended to include both applied and basic research.

An appropriate way to end this chapter—if not the book as a whole—is by endeavoring to give the applied phase of hydraulics at least some semblance of its just due. It was clearly stated at the outset, of course, that the science would receive primary attention, while its application would have secondary regard at best. The two can obviously not be wholly separated, for an engineering science must adapt itself to the designer's needs, and a good designer in turn must keep himself abreast of current advances. The writer has frequently been criticized for not maintaining a better balance between the two (as well as for not providing a more extensive treatment of hydraulic machinery, hydrology, naval hydrodynamics, etc), even though this would have required much more space and a much more knowledgeable author. For the latter reason, private engineering firms, which assuredly play a large role in the construction of hydraulic works both here and abroad, will still have to be ignored. Instead, the discussion will necessarily be restricted to the three federal agencies which give emphasis to both model testing and design—the Tennessee Valley Authority, the Bureau of Reclamation, and the Corps of Engineers—all of which have been treated so far solely from the laboratory point of view.

During the past decade it was probably inevitable that the ire of the militant ecologists would be directed against organizations carrying out vast construction projects. Whereas the TVA had long emphasized its aim of preserving the region's natural resources, the other two agencies were accused of public-works construction for its own sake, so to speak, without regard for preservation of the environment. The Bureau, it was claimed, built unnecessary dams or placed them in unjustifiable locations. The Corps, perhaps because of its lengthier history of public controversy, was subjected to a series of allegations: first, that it showed little regard for the effects of its works upon the land; second, that it was in league with the many members of Congress having pork-barrel inclinations; third, that it habitually underestimated costs and overestimated benefits of any project that it undertook; fourth, that it gave little more than lip service to the opinions of the public of which it was supposed to be the agent. As in any controversy, there was surely considerable justification on both sides of the issue, the good that the organizations had done being obvious, but the complaints being well documented. The reactions of the agencies were outwardly quite different. The Bureau (in apparent accord with the saying "If you can't beat 'em, join 'em!") almost claimed to have been the first to appreciate the importance of environmental protection. The Corps, on the contrary, either completely ignored or sought valiantly to rebut the criticism. In both cases, however, lawsuits prevented many controversial projects from being carried out; and, through a combination of administrative wisdom and public pressure, ever greater efforts were made to assess new undertakings from more than the purely technical point of view. For example, so-called Environmental Impact Statements became obligatory before any major construction projects could begin.

By far the largest of the three agencies, the Corps of Engineers is composed of 30 or 40 thousand civilians under the administrative supervision of a hundred or so military officers. The annual expenditure by the Corps for the construction of civil works approaches two billion dollars. While there is a constant temptation to measure excellence by the amount of money spent, even if reduced by several orders of magnitude this would still represent a considerable acquirement of expertise. Much of the criticism of the Corps has been directed against its military leadership, but it should be realized that the technical supervision is wholly civilian. (On the other hand, it is the officers who provide the contact with Congress, so that the question of reciprocal influence is still moot.) Though the smallest of the three agencies, the

TVA has acquired almost more prestige abroad than in the States for its introduction of multiple-purpose planning (what better field for systems research?) and for its involvement of state, county, and municipality rather than the formation of a powerful central administration.

While the writer continues to decry their prevalent emphasis upon development to the near exclusion of research, the fact remains that these three agencies together probably do more experimental work than all the rest of the country, much as their engineers are probably responsible for more hydraulic construction than the rest of the world. Although their contribution to the science is perhaps small compared with that of the universities, their influence on the profession as a whole can in no way be denied. So far as cross-fertilization between laboratory and field is concerned—a matter essential to both development and research—an excellent example is found in the problems of the Mississippi River: reference is made to the report *Improvement of the Lower Mississippi River and Tributaries, 1931-1972,* by Norman Robert Moore (1900-. . . .), former Chief of the Engineering Division of the Mississippi River Commission, from the viewpoint of the field engineer; and the complementary report *Review of Research on Channel Stabilization of the Mississippi River, 1931-1962,* by Joseph Tiffany, from the viewpoint of the experimenter. A parallel accomplishment on the part of the Bureau of Reclamation was the publication in 1973 of the second edition of the 1960 volume *Design of Small Dams,* under the editorship of Harold Gilbert Arthur (1914-. . . .); though it made extensive use of information gained through the laboratory, it was in no sense a laboratory project.

Individual instances of salutary interchange between the several domains of engineering hydraulics are found in the recent migration of Rex Elder from the TVA and of John Cassidy from the University of Missouri to the Bechtel Corporation in San Francisco; and of Victor Koelzer from the Harza Engineering Company to Colorado State University by way of the National Water Commission in Washington DC. Similarly, Joseph Frank Friedkin (1909-. . . .) of Texas and Mississippi State not only conducted an early series of meander studies at the Waterways Experiment Station, but he thereafter served various offices of the Corps and the Bureau of Reclamation in preparation for his position since 1962 as Commissioner of the International Boundary and Water Commission. Consider finally the case of Åke Ludvig Alin (1890-1976), a hydraulic engineer of Swedish origin, who was not only retained for many years as a consultant by private and federal agencies, but who long shared his practical experience with graduate students at Iowa on a part-time basis. Such instances are, to be sure, far too few.

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EPILOGUE

What Lies Ahead?

Since the Prologue to this record of hydraulics in the United States dealt with events that preceded the two centuries under discussion, it would seem only logical that the Epilogue should deal with those still to come. I have already attempted similar forecasts on three separate occasions: in a lead article for *Applied Mechanics Reviews,* which became the closing chapter of our *History of Hydraulics;* in a survey paper for a French-American meeting on hydraulic research; and in the keynote address at the First Australasian Congress on Fluid Mechanics. In each instance I sought to emulate Du Buat's 18th-century summary of the information then most needed by the profession, on the presumption that this was the direction in which progress would be made. I was as mistaken as Du Buat had been. Many of the gaps that he or I earmarked are still unfilled, and few of the accomplishments actually realized were foreseen by either of us.

Perhaps a safer course would be to attempt a limited extrapolation of current endeavors—such, for instance, as those in water-resource systems, biofluidmechanics, and the computer solution of the equations of motion for particular boundary conditions. The shorter the extrapolation, of course, the more accurate—and insignificant—the prediction. Moreover, each of these topics was barely a gleam in the hydraulician's eye a generation ago, and what new progeny are likely to appear a generation hence would be just as difficult to predict. Surely a wiser, more useful course will be to examine the interrelated events of the past from various points of view, in the hope that contemplation of their significance will provide some clue to our future behavior.

Vannevar Bush, in his article "The Builders," stressed the fact that it takes all kinds of workers to construct an edifice: those who create the original design, those who elaborate specific elements of it, and those who make or lay the individual bricks. The first of these are few and gifted, the second are skilled rather than creative, and the last may never even visualize the structure as a whole; yet all are equally important to its eventual completion. The analogy in the development of American hydraulics should be obvoius. In the foregoing pages upwards of 500 names have been mentioned; each one of these people contributed something useful to the profession, however small or repetitious, and there are countless others who must remain unnamed. Emphasis has already been laid on the fact that essentially all the basic principles had been recognized before our Colonies declared their independence, so that no early American except possibly Franklin can be said to have grasped and influenced the broad design. On the other hand, Franklin's compatriots were intensely practical men, and they and their successors contributed immeasurably to the art of hydraulics application. There are esoteric stories of a visit paid by the Göttingen mathematician Felix Klein to some of our Land-Grant institutions around the turn of the century, the impression made on him by their shops and laboratories having purportedly led to his employment of such men as Ludwig Prandtl in the applied field. On the other hand, our extensive use of analytical methods that had been developed abroad is reminiscent of the Japanese reproduction of Western methods of manufacture a generation or so ago. Like the Japanese, we have not only adopted what others have done before, but we seem to have made the methods our own and greatly improved upon them. However little we may have contributed to the most basic principles, we have surely extended and applied them in an unprecedented manner. And our contribution to sophisticated instrumentation has been fully commensurate with our advances in analysis.

Relatively speaking, our scientific progress was at first very slow. For generation after generation, American textbooks simply reproduced tables of French and German coefficients, and those eventually determined in our own early laboratories were much of a kind. True, the first industrial laboratories—at Lowell and Holyoke—and three of our earliest university laboratories—California, Worcester, and Cornell—produced new as well as stereotyped results; yet by and large the work was of the plodding, repetitive type that seems to be necessary in laying a solid, if not distinctive, foundation. With the advent of the present century, a few more bright spots began to appear and their rate of appearance also increased, though the change continued to be in quantity and quality rather than in kind. In brief, new discoveries were rare, and even as it grew in usefulness, hydraulic theory remained rather narrow in its viewpoint, for empirical insight is at best a one-track sort of approach.

At first the influence of John R. Freeman was simply an intensification of this trend. However, as certain hydraulicians began to adopt and publicize Prandtl's methods, a different type of change took place. With this advent of the fluid-mechanics approach, the profession's perspective broadened considerably. The stimulus provided by the urgencies of war then greatly accelerated the changeover, and the ultimate emphasis and amplification of the new discipline by the mechanical as well as the aeronautical engineers definitely established the mechanics of fluids as a broad, lasting branch of science. The methods of analysis were common to all, of course, and a unified sort of handling was apparent. The pool of knowledge about fluid motion now underlies many a profession—from astronomy to zoology—and hydraulics has contributed as well as utilized its full share. In the past two decades, on the other hand, a diversification has set in which completely belies the original narrowness of hydraulics itself. What could be more varied than the methods of computer analysis, biofluidmechanics, and water-resource systems already mentioned? Even age-old hydrology has changed its approach—though without solving the recurrent riddle of whether it has always been a part of hydraulics, or hydraulics a part of it!

Our profession has thus passed through a number of stages, each of which has had its effect upon the development of the country: the purely practical phases of water supply and disposal, westward expansion, and commerce; the education of engineers, at first through provision of cut-and-try methods and flow formulas, and then through recognition of a scientific basis for continued progress; the contribution to the war effort, and in the following years the deepening of the pool of fluids knowledge; finally, the manifold trend that the profession now exhibits in such diverse directions as ice formation and decay, diffusion of heat in the ocean and the atmosphere, the flow of body fluids, preservation of the environment, and so on and on. At times it seems that one or another phase of the general field has reached an end—empirical formulation, for instance, or potential theory—but no method ever really loses its usefulness: some problems are still solvable only by means of the experimental techniques introduced in the last century, and the classical hydrodynamics of that period went through a recent metamorphosis with the advent of the digital computer. All in all, the subject of hydraulics continues to grow in its breadth of coverage, giving rise to new phases of the fluids field which—like the many divisions of the engineering profession itself—then branch off on their own.

In one particular aspect of its progress, hydraulics is presently sharing a stage of development that is definitely profession-wide: the realization that an engineer must deal not only with materials but also with people, with the socio-humanistic sciences as well as the physical. This has, of course, always been the case, though the engineers were probably the last to react to the situation as a professional group. Such early scientists, engineers, and builders as Franklin, Washington, and Jefferson, who were statesmen as well, undoubtedly sensed that their powers of persuasion were even more important than their professional skills, and so it probably will always be. Some of the great hydraulic engineers—Latrobe, Eads, Freeman, and Durand, for example—probably accomplished at least as much through their dealings with their fellow men as by their work in laboratory and field. Only recently, however, has there been a widespread reflection in college curricula and the technical press of the importance of the sociological role that the engineer can and should play. A primary goal in these pages has been the tracing of our progress in hydraulics as a science, but there should always have been evident the interaction of hydraulicians as people: the passing of knowledge and enthusiasm from man to man, their role in professional-society affairs, and particularly the part that they have played in engineering education—whether from the viewpoint of innovative teaching or that of participation in the academic hierarchy. Even in local politics the hydraulician will be found to have made his mark, though it might usefully have been much bigger.

While hydraulicians are not unique in this respect, they have surely been among the leaders in promoting international exchanges of students, staff, and understanding. Chemists were perhaps the first to go to Germany for postgraduate study, and their numbers were appreciable even in the 19th century. Outstanding engineers, to be sure, had visited and even studied abroad at intervals through the 19th century and well into the 20th, but it was not till Freeman made such travel both readily possible and obviously fruitful that the trend was fully established. At the same time, foreign students began coming to the United States in increasing numbers, and again hydraulics took the lead. In fact, the first of Iowa's hydraulic alumni-to-be arrived from abroad in the very early Twenties—even before the first Freeman Scholars went to Europe—and the number per year has continued to grow. To date it is estimated that between one and two thousand hydraulicians from the various graduate schools of the United States are spread about the world.

This has by no means been a one-way street. In addition to the fifty Freeman Scholars, at least a comparable number of hydraulicians have studied or worked abroad under Fulbright, NSF, and other travel grants. Attention has already been called to international congresses and exchanges of visitors and to the strong part played therein by Americans. In addition, postdoctoral appointments have been received as well as given. At least three hydraulics laboratories have been designed in the States for foreign institutions (by several of us at Iowa for universities at Bogotá, Caracas, and Manila), and American specialists have collaborated with their foreign counterparts, particularly in the developing countries; participation in UNESCO and World Bank undertakings has been frequent. Outstanding in this regard has been the organization of the Asian Institute of Technology at Bangkok, a project initiated by staff members of Colorado State University under the leadership of Maurice Albertson; such American hydraulicians as Norbert Ackermann, Robert Banks, Robert Carstens, and John Roberson have served from two to a dozen or more years on the AIT faculty. Quite aside from the many hydraulic engineers who have been engaged in construction in the various parts of the world, American hydraulicians themselves have played a strong role in promoting both welfare and accord on an international scale. There is no apparent reason to expect this endeavor to lessen in the future.

As a matter of fact, it is our influence on the other nations of the world that may well control the outcome of one trend that can be predicted with considerable certainty: the continued growth of mankind's need for water. The problem of providing food for a world already overpopulated will surely be with us for an indefinite period. This in turn involves a two-fold approach: increasing our own production, and teaching the developing countries to increase theirs. From time immemorial, raising the agricultural output has involved not only the improvement of methods, seeds, and fertilizers, but also the provision of an adequate supply of water—no more and no less than needed by the crops. Since few regions have just the right amounts of rainfall, infiltration, and runoff, it is obvious that the continued improvement of agricultural productivity will involve the irrigation or drainage of ever-more-marginal land. Whether water is brought overland from distant sources, pumped out of the ground, or taken through desalination from the sea, the many ramifications of engineering hydraulics will surely be involved. As is invariably true, of course, a major difficulty will be nontechnical: obtaining the necessary accord among the people involved, which may require the greatest hydraulic expertise of all.

Even presuming that population growth can eventually be controlled and that agreement can be reached among nations about the allocation of water and food, it must still not be assumed that the demand for more water will cease, for there are other kinds of growth than the purely quantitative. I refer to the improvement of the material quality of life which we presently associate with civilization. The per-capita production of energy is probably the best measure of growth in this respect—a quality vaunted by the developed nations and decried by the developing (however much they want it for themselves). Developed and developing nations alike recognize that industrialization is the cause of pollution, that our waste of energy is almost profligate, and that in some ways the true quality of life is diminished thereby. Be that as it may, the probability is high that the need for water will continue to grow even after the population becomes stabilized, as it someday must.

Whether energy is eventually obtained from fossil fuels, from fission or fusion of the atom, from winds or tides, from solar or terrestrial heat, the flow of water (as well as other fluids) will be involved in some way. Add to these needs in connection with energy production, those of chemical and other industries as they continue to grow—not to mention the use of water in the home, office, and recreation sites—and it becomes clear that the end will never come into view. In some parts of the country unused water is still available. Elsewhere most supplies are at best second- or third-hand. (Long ago, for example, I read that every drop of Ohio River water was used on the average at least five times before it reached the Mississippi!) As our need for more frequent recycling of our limited supply of water continues to grow, the necessity of minimizing and then of completely preventing pollution of our streams and subsurface waters becomes obvious. This also involves hydraulics—and public collaboration to an extreme degree.

As one looks back over the history of hydraulics—even for the short two centuries covered by this book—one is tempted to conclude that we have merely come full circle, for we talked first of man's need for good water, and in the same vein we now seem to close. But our course has surely not been simply a circle, for our endeavors have burgeoned and our methods have continually gained finesse. Rather—as other nations have done before—we have completed another loop of a steadily ascending spiral. In so doing, we have witnessed a vast improvement of field and laboratory practice, growth of sophistication in flow analysis, diversification of fields of application on a very broad scale, and a gradual appreciation for socio-humanistic as well as purely physical aspects of hydraulic problems. Equally important matters are sure to arise as we pursue our upward course. In a word, our profession will undoubtedly continue to flourish in the centuries to come.

FREDERIC NIXON WEAVER

1899 - 1976

Frederic Nixon Weaver was born September 21, 1899, in Roxbury, the oldest of four children. He attended Dorchester High School for a year and a half, leaving school to work to support his family. After working a number of years, he decided at the age of twenty that he should further his education. Inquiries about admission to Tufts Engineering School on the basis of his incomplete secondary school record resulted in his admission in 1909, to the Bromfield-Pearson School on a trial basis. Four years later, Rick Weaver received his B.S. in civil engineering, *summa cum laude.*

Following graduation and after a trip to Europe with a classmate, he was employed for two years by the New England Structural Co.; he then taught in Passaic (N.J.) High School for two years. During World War I, Professor Weaver saw action with the 101st Engineers, 26th Division of the American Expeditionary Forces in France, and was wounded at Chateau-Thierry. He is coauthor of the history of this famous company. After the war ended, he chose to remain in France where he took some courses at the University of Caen, supplementing previous graduate study done at Columbia and Harvard universities. It may well be said that Professor Weaver was a self-educated man who took every advantage of his opportunities.

In 1919 he returned to Tufts as an instructor in the Department of Civil Engineering, where teaching and working with students became his career. His students knew him as a scholar, a dedicated teacher and above all, a willing and understanding listener. Promotions over the years advanced him to the rank of full professor and to the chairmanship of the Department of Civil Engineering for twenty-two years. In 1959, at the mandatory age of seventy, he retired. The Jumbo Book of that year in its dedication recognized Professor Weaver's forty years of service to the university.

He was the author of a textbook *Applied Mechanics,* and numerous technical and nontechnical papers. Always interested in the theater at Tufts, he actively participated in the Tufts Graduate Dramatic Society; he was the author of a one-act play and many written critiques. Unusual though it may seem, Rick's hobby was conversational French. He spent many hours speaking only that language with members of the Department of Romance Languages at the Tufts Faculty Club, and much of his leisure reading was in French.

His interests always extended beyond the classroom since it was his belief that in order to be an effective teacher in an engineering school, one should also be a practicing engineer. With this in view, he practiced the art of engineering all his life, and through his associations with many consulting engineering firms in the Boston area, he was able to help many of his students begin their professional careers. He was a past president of the Boston Society of Civil Engineers and of the Northeastern Section of the American Society of Civil Engineers and a member of Tau Beta Pi and Sigma Xi. Rick once remarked that he never retired, and to bear this out, his last assignment was in 1973, at the age of 83. He also gave generously of his time to community affairs, serving as a corporator of the Lawrence Memorial Hospital, Medford, and chairman of its School of Nursing for ten years.

In 1973, Professor Weaver received the Distinguished Service Award from the Tufts Jumbo Club in recognition of his years of interest and concern for Tufts athletes and the athletic programs. The same year, on the occasion of the 100th anniversary of the College of Engineering, he was honored with the Distinguished Service Award from the Department of Civil Engineering for his contribution to engineering education. On Alumni Day, 1974, he was to receive the Distinguished Service Award from the Tufts Alumni Association, but shortly before the event he suffered his first stroke. His son, Arthur, accepted it for him. He died two years later, on August 2, 1976.

He is survived by his wife, Ruth (Johnson), whom he married in 1923; a son, Arthur Sargent, who received a B.S. from the College of Engineering in 1945 with honors; a daughter, Dorothy Ruth, who graduated from Jackson in 1955, *summa cum laude;* and a sister, Mabel. His two brothers, Warren and Ralph, Engineering Class of 1925 and a former Tufts trustee, predeceased him.

Frederic Nixon Weaver has left his light on this Hill — a Tuftsman whom we shall always be proud to recall and identify with the Tufts tradition.

(Prepared By Earle F. Littleton
for use in the Memorial Service
at Goddard Chapel, October 23, 1976)

PROCEEDINGS

BOSTON SOCIETY OF CIVIL ENGINEERS SECTION AMERICAN SOCIETY OF CIVIL ENGINEERS

Meetings Held

BSCE Section

November 18, 1976. The Boston Society of Civil Engineers Section, ASCE, held a joint meeting with the Boston Post of the Society of Military Engineers, the Massachusetts Society of Professional Engineers, and the Boston Chapter of the Society of Women Engineers. This was a luncheon meeting at Pier 4 Restaurant. Speaker, Mr. Thomas M. Sherry of the Yankee Atomic Electric Company, now Construction Manager of the proposed nuclear generating station at Seabrook, New Hampshire. Attendance: 170.

Technical Groups

Computer Group

November 17, 1976. An evening meeting (no dinner) at the Ralph M. Parsons Laboratory, MIT, Chairman Lewis H. Holzman presiding. Speaker, Dr. James M. Dillingham, President of Dillingham Associates, Inc. Subject: Water Distribution Automation, How practical? Attendance: 11.

Construction Group

November 30, 1976. Luncheon meeting at the Red Coach Grill, Chairman Norman W. Bennett presiding. Speaker, Mr. Wilford A. Rose, Vice President of Perini Corporation and Board Chairman of Majestic-Wiley, a Perini subsidiary in pipelines and heavy construction. Subject: the Alaska pipeline; illustrated with a sound film. Attendance: 17.

Environmental Group

November 10, 1976. Dinner meeting at Purcell's Restaurant, Chairman Paul A. Taurasi presiding. Speakers, Mr. Frank McManamon, Archaeologist, Massachusetts Historical Commission, and Mr. Edward Bayon, Chief Engineer, Tighe & Bond, Easthampton, Massachusetts. Subject, Archaeological Surveys and Environmental Construction Projects. Attendance: 36.

Geotechnical Group

November 2, 1976. Afternoon meeting (4:30 PM) at Room 3-370, MIT, Chairman Zoino presiding. Speaker, Professor Doctor H. Borowicka of the Institute for Earth Structure and Soil Mechanics, Technical University of Vienna, Austria. Subject, Relationships of Soil Structure to the Engineering Properties of Soils. Attendance: 40.

December 8, 1976 meeting at Duke's in the Park, Chairman Zoino presiding. Speakers, Dr. Gonzalo Castro, Principal, Geotechnical Engineers, Inc. and Dr. Alfred Hendron, Professor, University of Illinois. Subject, Liquefaction of soils. Attendance: 58.

Structural Group

December 1, 1976. Evening meeting (no dinner) at the MIT Faculty Club Penthouse, Cambridge, Chairman Kentaro Tsutsumi presiding. Speaker, Dr. E. V. Leyendecker, Research Structural Engineer, National Bureau of Standards. Subject: Progressive Collapse. This was also an official business meeting of the BSCE Section. Attendance: 57.

Transportation Group

November 4, 1976. A morning session and a luncheon was held jointly with the Boston Transportation Group and the American Institute of Planners at Pier 4 Restaurant. Presiding at luncheon, Chairman Marvin W. Muller; at morning seminar, Mr. Alfred R. Howard, Transportation Planning Director of the Boston Redevelopment Authority and Mr. James Brown, Chairman AIP. The seminar program included a panel discussion on delivering transit service, by MBTA staff: Mr. Ronald J. Tober, Ms. Susan S. Richardson, Mr. Richard L. Barber, Mr. Joseph F. McDonald and Mr. Edward P. Collins; then a discussion on budget review, priorities, and citizen input by Ms. Carla Johnson, budget analyst of MBTA Advisory Board; and one on the Federal role by Mr. Louis Mraz of the Urban Mass. Transportation Administration. Speaker at luncheon, Mr. Robert J. Kiley, Chairman, Massachusetts Bay Transportation Authority. Attendance: 160.

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January 1977

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ASSOCIATE MEMBER FORUM	David L. Freed
AUDITING	William S. Zoino and Paul J. Bourque
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HYDRAULICS GROUP AWARD	Edward P. Dunn
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INVESTMENT	Saul Namyet
KEY MAN	Robert M. Fitzgerald
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MASSACHUSETTS ENGINEERS COUNCIL REPRESENTATIVE	David E. Thompson
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BOSTON
SOCIETY
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AMERICAN
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CIVIL
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FOUNDED
1852