HYDROGRAPHIC AND TIDAL INVESTIGATIONS OF THE INTERNATIONAL PASSAMAQUODDY TIDAL-POWER SURVEY

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The author is a graduate of the University of New Hampshire and has studied in the graduate schools of engineering at the Massachusetts Institute of Technology and Harvard University. During the period 1933-37 Mr. FLOYD was engaged in design and construction of highways for the New Hampshire Highway Department. Since 1938 he has served in a civilian capacity in several offices of the U.S. Army Engineer Corps, including the position of Chief of the Foundations and Materials Branch of the International Passamaquoddy Tidal-Power Survey from 1956 to 1960.

Introduction

The highest tides in the world are found on the east coast of Canada in the Bay of Fundy. In the Minas Basin at the head of the bay the tides average over 40 feet daily with maximum tides reaching more than 50 feet. Passamaquoddy and Cobscook Bays, which join the Bay of Fundy at the international border of Canada and the United States, as shown in fig. 1, have average tides of about 18 feet. Generation of electric power from the rise and fall of these tides has intrigued engineers in Canada and the United States for over 40 years. Several different studies of tidal-power development have been made. Dexter P. COOPER made the first large-scale study of an international tidal-power project using Passamaquoddy and Cobscook Bays during the 1920's. The U.S. Army Corps of Engineers initiated a project entirely within the United States in 1935, but construction was stopped when financial support was withdrawn.

The Governments of the United States and Canada in August 1956 directed the International Joint Commission to investigate the engineering and economic feasibility of harnessing the tides of Passamaquoddy and Cobscook Bays to produce electricity. The engineering studies were made primarily by the U.S. Army Corps of Engineers and by the U.S. Federal Power Commission, in cooperation with the Department of Public Works and other agencies of the Federal and Provincial Governments of Canada. A special engineering work group was established in the New England

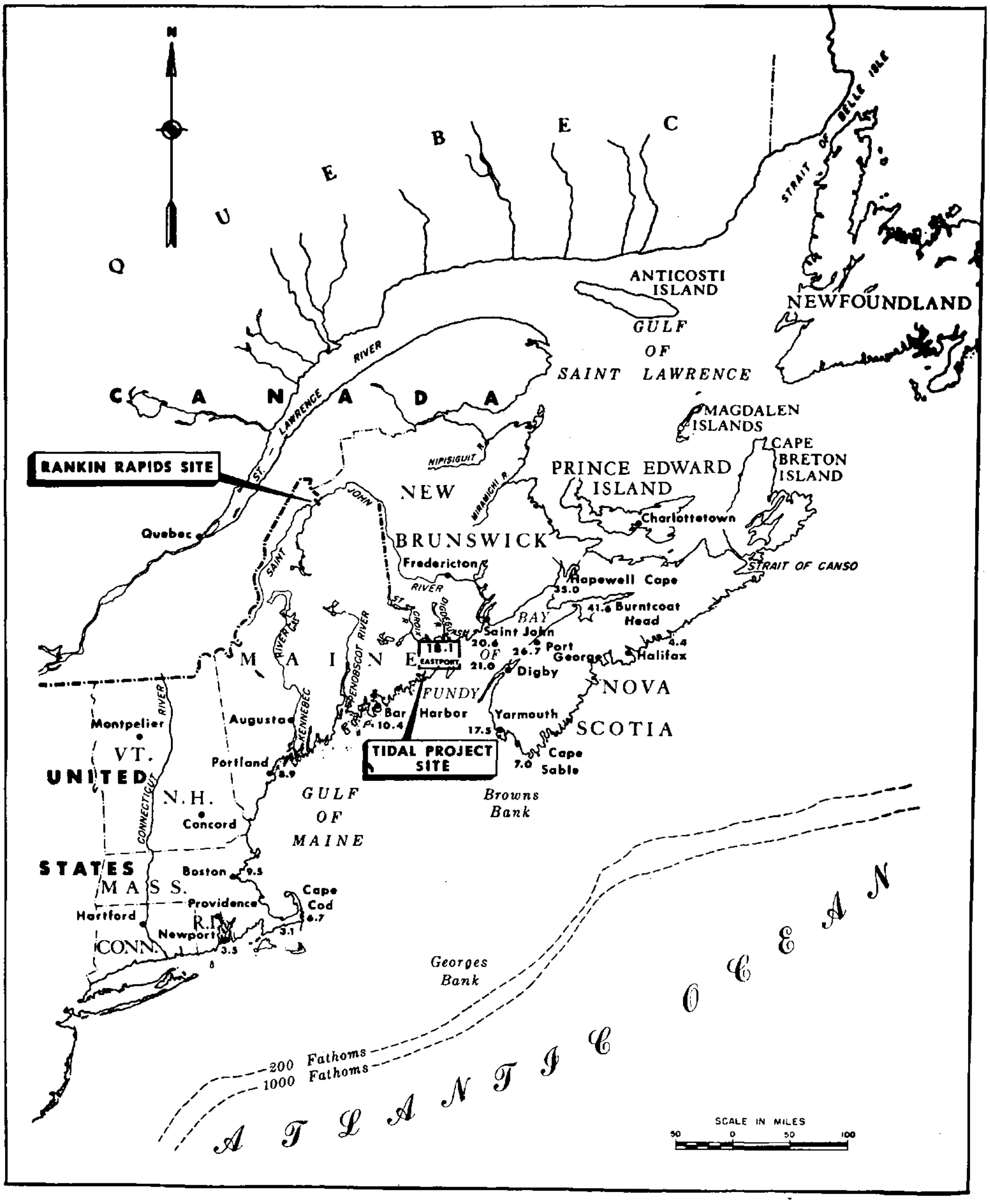

Figure 1. — Regional Map Showing Average Tidal Ranges in Feet.

Division of the U.S. Army Corps of Engineers to collect, compile, and analyze all pertinent technical data, and to develop the most feasible design of tidal-power project for the Passamaquoddy site. A field office was maintained in Eastport, Maine, from October 1956 to July 1959 for performing topographic and hydrographic surveys, observing tides and currents, conducting subsurface explorations, and gathering local data bearing on design and cost of the proposed international tidal-power project.

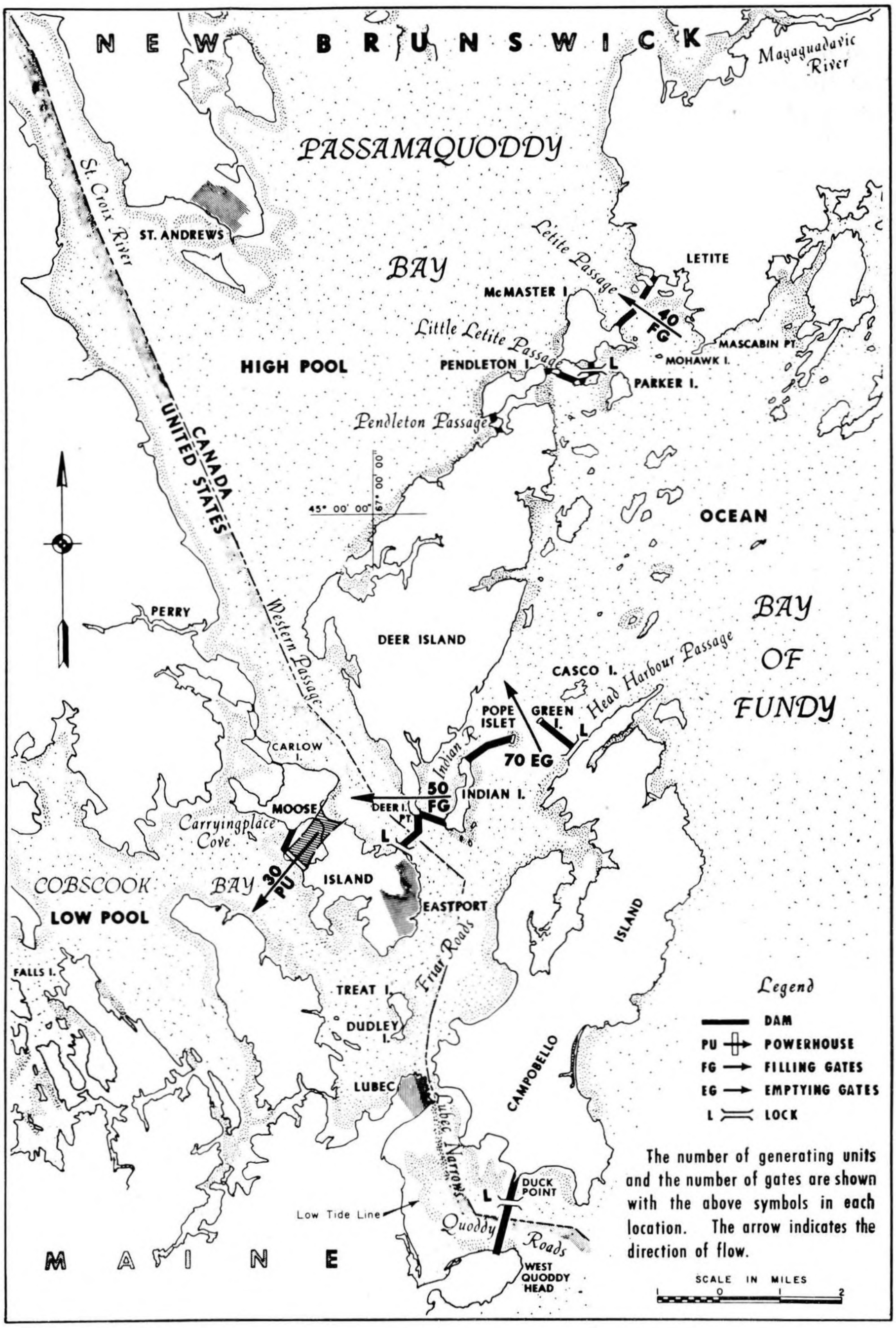

Figure 2. — Tidal-Power Project Plan.

The engineering report (1) * of the survey, submitted to the International Joint Commission in October 1959, established the most economical tidal-power development to be that shown in fig. 2 with an auxiliary river hydro plant at the Rankin Rapids site (see fig. 1) on the upper Saint John River to firm up the variations in tidal-plant output. The tidal project would include 2 pools with a combined area of 142 sq. mi.; 35 700 lin. ft of tidal dams; a 300 000-kw power plant, 2 540 ft long; 160 filling and emptying gates, each with 30- × 30-ft openings; and 4 navigation locks.

This discussion is limited to a review of the hydrographic engineering and observations of tidal phenomena conducted in the course of the international Passamaquoddy tidal-power survey of 1956-59.

Existing basic data

Previous studies of the general area of the proposed tidal project, and of the specific sites considered for development, have produced a great amount of basic data which were of considerable value in the 1956-59 study. Topographic and hydrographic surveys, and tidal observations, have been made by United States and Canadian agencies as part of the systematic coverage of the region. The entire area of the proposed tidal-power project has been surveyed for navigation purposes at various times since 1866 by the United States Coast and Geodetic Survey, the International Boundary Commission, the Canadian Hydrographic Service, and the British Admiralty. The results of these surveys, compiled as Hydrographic Chart 801 of the United States Coast and Geodetic Survey, were used for the initial general studies of the proposed international Passamaquoddy tidal-power project.

Hydrographic investigations specifically for a tidal-power project were made by Dexter P. Cooper in 1926-28, and by the U.S. Army Corps of Engineers in 1935-37. Underwater mapping by Dexter P. Cooper included reconnaissance of approach-channel areas, fairly complete data on prospective structure sites, and a careful survey of the Cobscook Bay shore in the tide range. During the 1935-37 investigations by the U.S. Army Corps of Engineers, new hydrographic surveys were made for the structures proposed at that time. In both the Cooper and Corps of Engineers investigations water depths were measured directly by sounding lines, and lateral positions were determined by transit sightings from reference points on shore or by sextant observations.

In the summer of 1951, the Water Resources Division of the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, made geological and geophysical studies designed to test the effectiveness of sonic methods to determine distribution and thickness of unconsolidated underwater sediments, and to discover as much as possible about such sediments in the Passamaquoddy Bay area. Eight areas were surveyed of which only two are structure sites of the selected plan developed in the engineering survey completed in October 1959.

(*) This and succeeding numbers apply to the list of references appearing at the end of this article.

Fathometric investigations were conducted from a converted cargo boat, 100 feet long with 22-foot beam. Horizontal positions of the survey boat were determined by sextant observations of previously established shore stations. The sounding equipment recorded only depth from the water surface which changes continuously and rapidly because of the large tides in the area. The soundings were corrected to mean-sea-level datum by reference to tide levels measured continuously at several tide gauges established locally. Two sounding units were used. One was a special unit developed in accordance with U.S. Geological Survey specifications. It emitted a high-power, low-frequency signal intended to penetrate underwater overburden. The other unit was a commercial instrument of less power and higher frequency which was used to determine water depths. In addition to the water-depth measurements, sufficient indication of the extent and thickness of the unconsolidated underwater sediments overlying bedrock was obtained to justify further application of the sonic method of exploration.

Various agencies have measured the tides in the Passamaquoddy Bay area over the past 100 years. The U.S. Coast and Geodetic Survey has measured the tides from 1929, the longest continuous period, at their station at Eastport, Maine. The U.S. Army Corps of Engineers observed the tides at several locations in Cobscook Bay for periods of about one month each during the 1935-37 period. Dexter P. COOPER made similar observations in the 1920's. Other short-term observations have been made on other occasions dating back to 1841. These early observations were made primarily for hydrographic surveys for navigation purposes.

Information on tidal currents in the Passamaquoddy Bay area is meager. The U.S. Coast and Geodetic Survey made a few current observations in 1861, 1887, and 1934. COOPER observed the currents in a constricted area of Cobscook Bay in 1927. The U.S. Army Corps of Engineers observed tidal currents in the area just south of Eastport, Maine, during the 1935-37 studies of a single-pool tidal-power project entirely within the United States.

All existing data were carefully reviewed and used where applicable in preliminary studies of tidal-project arrangement in the survey of 1956-59. These preliminary studies indicated the scope of additional data needed for a comprehensive analysis of the proposed international Passamaquoddy tidal-power project.

Subaqueous sonic survey of 1957

One of the important features of the international Passamaquoddy tidal power survey of 1956-59 was the investigation of foundation conditions for the deep tidal dams. The high cost of conventional core borings in deep water, with rapid tidal currents, led to the decision to use geophysical exploration for guidance in establishing a limited number of deep-water drill holes. The sonic exploration method was selected particularly in view of the apparent success of preliminary work of this type performed in 1951. The sonic explorations were performed by Fairchild Aerial Surveys, Inc., of Los Angeles, California, to determine top of overburden and top of bedrock, and to obtain and interpret all data indicating changes in character of overburden in several separate areas in the project vicinity. Approximately 100 range miles of profiles were surveyed. Principal technical equipment included an electronic positioning instrument to determine horizontal position of the soundings and a sonic exploration device of modern design.

Electronic positioning equipment, a Moran (moderate-range aerial navigation) instrument, was so arranged that the position of the survey boat could be determined continuously from two previously established shore stations. The boat positions were plotted on a control boat sheet by a mechanical tracking device. Within the limit of accuracy of $\pm$ 50 ft, the positioning system permitted rapid evaluation of the area covered by the survey operations. Using this information, immediate decisions could be made about the adequacy of coverage or the need for additional data.

The sonic exploration device used in the survey is the Marine Sonoprobe. This device is essentially a reflecting seismograph. Unlike most seismic instruments, which use an explosion as a sound source, the Marine Sonoprobe sound source is a pulsed vibrator. Sound waves of about 1 000 watts, generated at the rate of 12 pulses per second, are beamed downward, with approximately 50 percent of the energy contained in a cone of 30 degrees solid angle. The total energy of the sound wave is composed of a spectrum of frequencies from 900 to 9 000 cycles per second, with a dominant frequency of about 3 800 cycles per second. This equipment emits into the water a sound wave of sufficient energy to penetrate subaqueous materials. Part of the sound energy is reflected by the ocean bottom and part by each successive interface in the underlying materials in proportion to the contrast in acoustical properties of various formations encountered.

The reflected sound wave is converted to an electrical impulse by a receiving transducer. Through complex electronic circuitry the depths below water surface from which the sound waves reflect are permanently recorded on the Sonoprobe chart in the form of continuous profiles. The chart paper is 10 inches wide, ruled to delineate 10-foot intervals for a depth of 200 feet from water surface. As the trace goes off the bottom of the chart (when reflecting surface exceeds 200 feet) it automatically appears again at the top of the chart and continues down in the 200- to 400-foot depth range. Fig. 3 is a sample portion of a Sonoprobe chart showing a typical record taken in the Passamaquoddy Bay area.

A large portion of the Sonoprobe charts showed only one trace, that of the water bottom. The remainder showed two traces, or two diverging traces, the lower one of which became indistinct as its depth below the upper trace increased. In no case did more than two original traces appear. Repeated reflections of the sound wave produced multiples of the original Sonoprobe trace. These multiples were similar to the original traces but fainter, and were ignored in the interpretation. Where two original traces appeared it was assumed that the upper one represented the top of overburden and the lower trace indicated the boundary between overburden and rock. Where only one trace appeared, adjacent portions of the Sonoprobe chart were examined to determine whether a second trace had faded out of the zone in question. If this were the case, the material under the single trace was assumed to be overburden. Where only one Sonoprobe trace was in evidence, the depth of overburden was based on geologic inference supplemented by data from deep-water borings. The Sonoprobe was found to yield two traces consistently in areas where subsequent borings encountered soft clay as the top overburden stratum. In areas where core-drilling indicated a granular overburden, the Sonoprobe produced only one trace. On this basis, the existence of two traces was taken as indicative of a soft-clay overburden, and one trace of either granular material or rock.

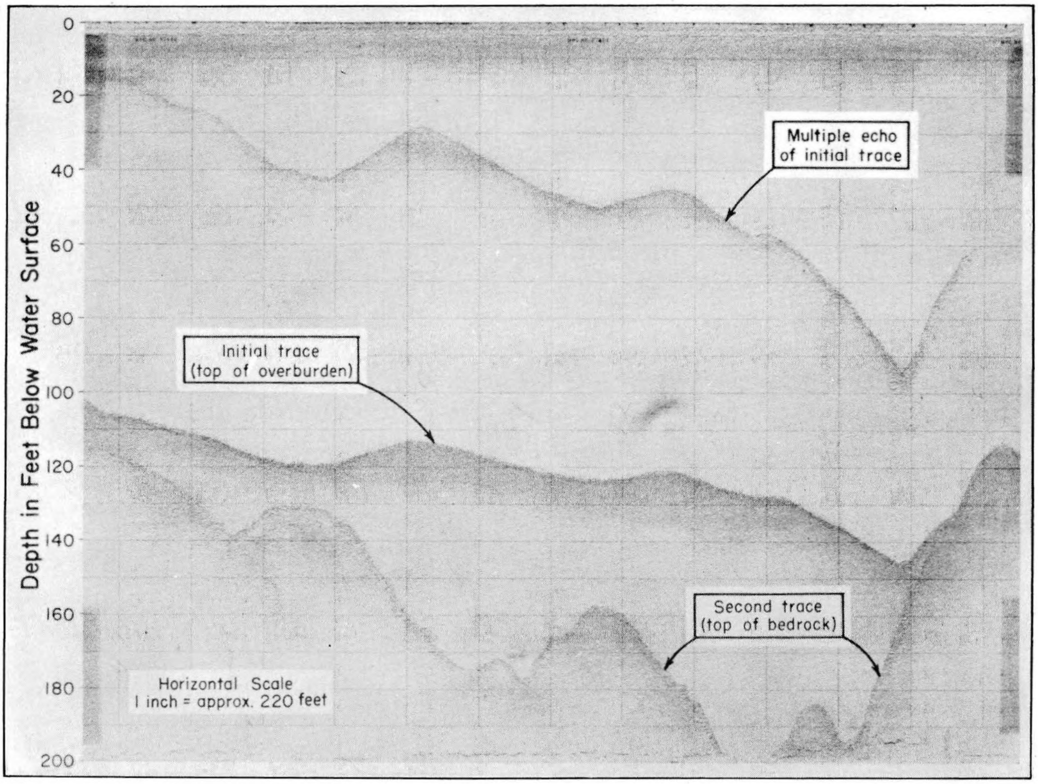

Figure 3. — Passamaquoddy Sonic Survey 1957.

The Sonoprobe is designed to record depths accurately on the calibrated chart if sound velocity through the transmitting medium is 4 800 feet per second, the speed of sound through sea water at 70° F. Thus the depth of water is accurately represented, but the velocity of sound in the material between the first and second traces is not accurately known for the particular materials existing at the site. Technical literature indicates that the velocity of sound in clay is generally about the same as in sea water. In granular materials, however, the velocity is substantially greater. Where two traces were recorded on the Sonoprobe chart, it was assumed that the material between the two reflecting surfaces was clay in which sound velocity is essentially the same as in sea water. Because the small differences in velocity which might exist would not affect the accuracy of the work, no correction of the apparent thickness of overburden indicated on the Sonoprobe chart was made in preparing the maps and profiles. The depths recorded on the Sonoprobe charts were reduced to mean-sea-level datum by adding or subtracting the tide level prevailing at the time of the sounding.

Supplementing the sonic survey by the Fairchild Corporation, additional soundings with a conventional Bludworth Marine Fathometer were made in several areas by the staff of the Eastport field office. Horizontal position of these soundings was determined by transit sightings from shore stations.

The underwater information from the Sonoprobe charts was added to maps of the shoreline and above-water topography with a scale of 1 inch to 400 feet, prepared from aerial photographs by the Aero Service Corporation of Philadelphia, Pennsylvania. The results of the survey shown on the maps and profiles developed by the Fairchild company furnish (*a*) accurate information on the bottom level; (*b*) relatively accurate indication of whether the bottom is or is not soft clay; (*c*) relatively accurate information on thickness of clay occurring as the top stratum of overburden; (*d*) speculative information on whether the water bottom is rock or granular overburden; (*e*) speculative information on thickness of granular overburden; and (*f*) no information to indicate whether layers of different materials may occur in the overburden. The ability of the Sonoprobe to indicate with reasonable accuracy the presence of soft clay was a considerable advantage because such material is inadequate as a foundation of deep tidal dams. The inability of the Sonoprobe to distinguish between rock and granular overburden was not as serious a handicap as was first thought, because either of these materials would be suitable as tidal-dam foundations.

Tidal observations

Planning of the proposed international Passamaquoddy tidal-power project required an accurate knowledge of the tides and tidal currents. Accurate tidal data were essential for (*a*) reducing soundings to a common datum to prepare maps of underwater areas, (*b*) establishing top level and water passages of all tidal structures, (*c*) determining the power available from the tidal project, and (*d*) estimating the effect of the tidal project on the tides of the region.

The basic tide-producing forces are the gravitational effects of the sun and moon. The moon exerts the major influence on the earth's tides. The sun is so much farther away from the earth that its greater mass affects the tides less than one-half as much as the moon. Since the lunar day is 24 hours and 50 minutes long, compared to the solar day of 24 hours, high tides, following the moon's phase, occur 50 minutes later each day. The earth, moon, and sun occur in line in that order once every 29.5 solar days. Two weeks later the moon, earth, and sun occur in line. Both of these conditions cause larger than average tides, or *spring* tides, the former condition causing somewhat larger tides than the latter. At the quarter phases of the moon, less than average tides, or *neap* tides, occur. The tide proceeds twice from spring to neap and back to spring again in the 29.5-day period.

Other conditions affecting the earth's tides include the distance of the moon and sun from the earth, the declination of both the moon and sun with respect to the earth, and the lesser effects of other astronomical bodies. The cycle of the resultant influence of all tide-producing factors is completed in approximately 19 years.

The fact that the tide-producing forces are astronomical makes it possible to predict tides accurately. The United States Coast and Geodetic Survey predicts the time and level of each high and low tide for a number of locations. The predictions for each calendar year are published in their *Tide Tables*; predictions at Eastport, Maine, are contained in the volume subtitled *East Coast, North and South America, including Greenland.* The Canadian Hydrographic Service also publishes tide predictions; the applicable volume is entitled *Tide Tables, Atlantic Coast of Canada.*

To supplement the regional coverage and the previous specific studies of tidal-power development, a new program of tidal observations was undertaken in 1957, particularly to investigate local variations in water surfaces in the proposed tidal-project area. Five automatic stage-recording tide gauges were installed at strategic locations in the project area. One gauge, at Eastport, Maine, was used for comparing other gauge records and for reducing soundings to a common datum. Continuous records of 1-year duration were obtained at four locations. At five additional locations records for at least one month were obtained.

During 1957 the Eastport field-office staff made tidal-current studies at eight locations in the vicinity of proposed tidal dams. In the same year, the Canadian Department of Fisheries also made tidal-current studies at 16 locations in the project area. Instantaneous maximum velocities were determined at several depths under various tide phases and stages. Maximum velocities up to 10 feet per second were recorded in the restricted passages. At any specific tide stage the velocities were found to be fairly constant from water surface to nearly full depth.

Existing tidal velocities were not extensively studied because the velocities under natural conditions are not critical with respect to design and construction of the proposed tidal-power project. However, as the natural channels are successively reduced by construction of tidal dams, the velocities in the remaining channels increase substantially and become an important consideration in design and construction of the tidal dams. Current velocities during the construction period can be evaluated only by hydraulic computations or by model studies.

Tides at Eastport, Maine, are characteristic of the tides within the proposed Passamaquoddy tidal-power-project area. Two well-defined high and low tides occur each lunar day, each high and low differing slightly.

In computing power from the tides the tidal range, the difference in elevation from a low tide to the following high tide, is most important. At Eastport, Maine, the average observed tide range for a 19-year period is 18.1 ft, the maximum is 25.7 ft, and the minimum is 11.3 ft.

Individual tide ranges vary somewhat from predicted values, principally due to variations of winds and barometric pressures which do not follow cycles as definite as other tide-producing forces. In a 1-year period when the predicted and observed mean tides were nearly the same, 5 percent of predicted tide ranges exceeded the observed by more than 1 foot, and 5 percent of predicted tide ranges were less than the observed by more than 0.9 foot. For longer periods of time the mean of the observed tide ranges agrees closely with the mean of the predicted values.

Water levels in Passamaquoddy Bay and in most of Cobscook Bay are essentially the same during the tide cycles. This condition permits the use of the Eastport gauge records in estimating tidal power. Exceptions occur at the Falls Island location in Cobscook Bay and at Lubec Narrows (fig. 2), where the water surface slopes considerably as the bays are filled and emptied by the tides. Specific studies of these two areas were required to determine the effects of sloping water surfaces on tidal-power output.

As shown in fig. 1, a comparison of the average tide ranges of shore areas open to the ocean (3.1 ft at Cape Cod, Massachusetts, and 4.4 ft at Halifax, Nova Scotia) with those at the head of the Bay of Fundy (41.6 ft at Burntcoat Head) suggests that the tides are influenced by the resonant system of the Bay of Fundy. Construction of the proposed tidal-power project would change this system by changing the timing and amount of flow into and out of Passamaquoddy and Cobscook Bays. A study of the effect of the proposed tidal project on the Bay of Fundy tides was undertaken by Drs. Arthur T. Ippen and Donald R. F. Harleman, Consulting Engineers, Massachusetts Institute of Technology, Cambridge, Massachusetts. The report of their study (unpublished) indicates that the tidal system of the Bay of Fundy is not highly resonant, and that construction of the tidal project would tend to increase the existing tide ranges. However, the amount of the change would be too small to measure. These conclusions were verified by independent studies by officials of the Canadian Hydrographic Service.

In view of the rapidly changing tides in the project area, the locations of the half-tide and low-water contours along the shores of Cobscook Bay were determined by infrared photography (2). This information was necessary in development of the depth-storage relationship in Cobscook Bay.

Conclusions

The engineering designs and tidal-power studies for the international Passamaquoddy tidal-power survey of 1956-59 required comprehensive hydrographic surveys and a thorough knowledge of the tidal phenomena applicable within an area embracing more than 200 square miles of tidal bays and channels. All available data obtained in systematic coverage of the region for general purposes and in previous studies of tidal-power development in the Passamaquoddy Bay vicinity were used where applicable. New hydrographic surveys, using recently developed sonic exploration methods, additional tide observations, and new tidal-current studies were made to provide the basis for reliable estimates of project cost and tidal-power output. Analysis of the tidal phenomena of the region included determination that construction of the proposed international Passamaquoddy tidal-power project would not affect the resonant system of tides in the Bay of Fundy.

REFERENCES

(1) *Investigation of the International Passamaquoddy Tidal Power Project,* report to the International Joint Commission, United States and Canada, by the International Passamaquoddy Engineering Board, October 1959.

(2) B. G. Jones. *Low-Water Photography in Cobscook Bay, Maine.* The International Hydrographic Review, Vol. XXXV, No. 1, Monaco, May 1958.