PROTECTION OF NARRAGANSETT BAY FROM HURRICANE TIDES

Hydraulic Model Investigation

Bostwick H. Ketchum

INTERIM REPORT

February 1957

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS.

PREFACE

The model investigation reported herein was initiated by the Waterways Experiment Station in November 1955 at the request of the U. S. Army Engineer Division, New England, CE. Design and construction of the model were accomplished during the period December 1955-January 1956, hydraulic adjustment of the model was carried out during February-March 1956, and the testing of the principal proposed improvement plans, which are discussed in this report, was accomplished during the period April-September 1956. Supplementary tests currently in progress will be reported in the comprehensive report to be issued on completion of the entire testing program.

The Division Engineer of the New England Division during the course of the investigation was Brig. Gen. Robert J. Fleming, Jr. Personnel of the New England Division who participated in planning the course of the model testing program were Messrs. H. J. Kropper, John B. McAleer, and Lincoln Reid. The model investigation was carried out under the supervision of the following engineers of the Waterways Experiment Station: Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division, Mr. G. B. Fenwick, Chief of the Rivers and Harbors Branch, and Mr. H. B. Simmons, Chief of the Estuaries Section, by Messrs. W. H. Bobb and E. B. Jenkins. This report was prepared by Mr. Simmons.

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PROTECTION OF NARRAGANSETT BAY FROM HURRICANE TIDES

Hydraulic Model Investigation
(Interim Report)

PART I: INTRODUCTION

Purposes of Investigation

1. The principal purposes of the model investiga on of plans for protection of Narragansett Bay from hurricane tides were to determine: (a) the effects of barriers installed at various locations in the bay on both hurricane and astronomical tide heights throughout the bay system, both landward and seaward from the various structures; (b) the magnitude of the tidal current velocities that would obtain in the navigation openings of certain of the barriers during both hurricane and astronomical tides; and (c) the effects of the barriers on tidal current velocities throughout the bay system for conditions of normal tides. Secondary purposes of the model investigation included determination of the effects of the barriers on salinities, temperatures, sedimentation, and flushing throughout the bay system.

Scope of This Report

2. A total of 36 proposed improvement plans were tested in the model during the course of the investigation; however, the more complete testing was limited to those plans found to be most practical as a result of partial model tests in combination with New England Division design and economic studies. Plans subjected to more or less complete testing include plans 27 through 36, and all pertinent data obtained during model tests of these plans are presented in this report. In addition, the results of several of the partial tests are reported herein, since these results have a direct bearing on conclusions or subsequent test procedures. It is planned to publish a

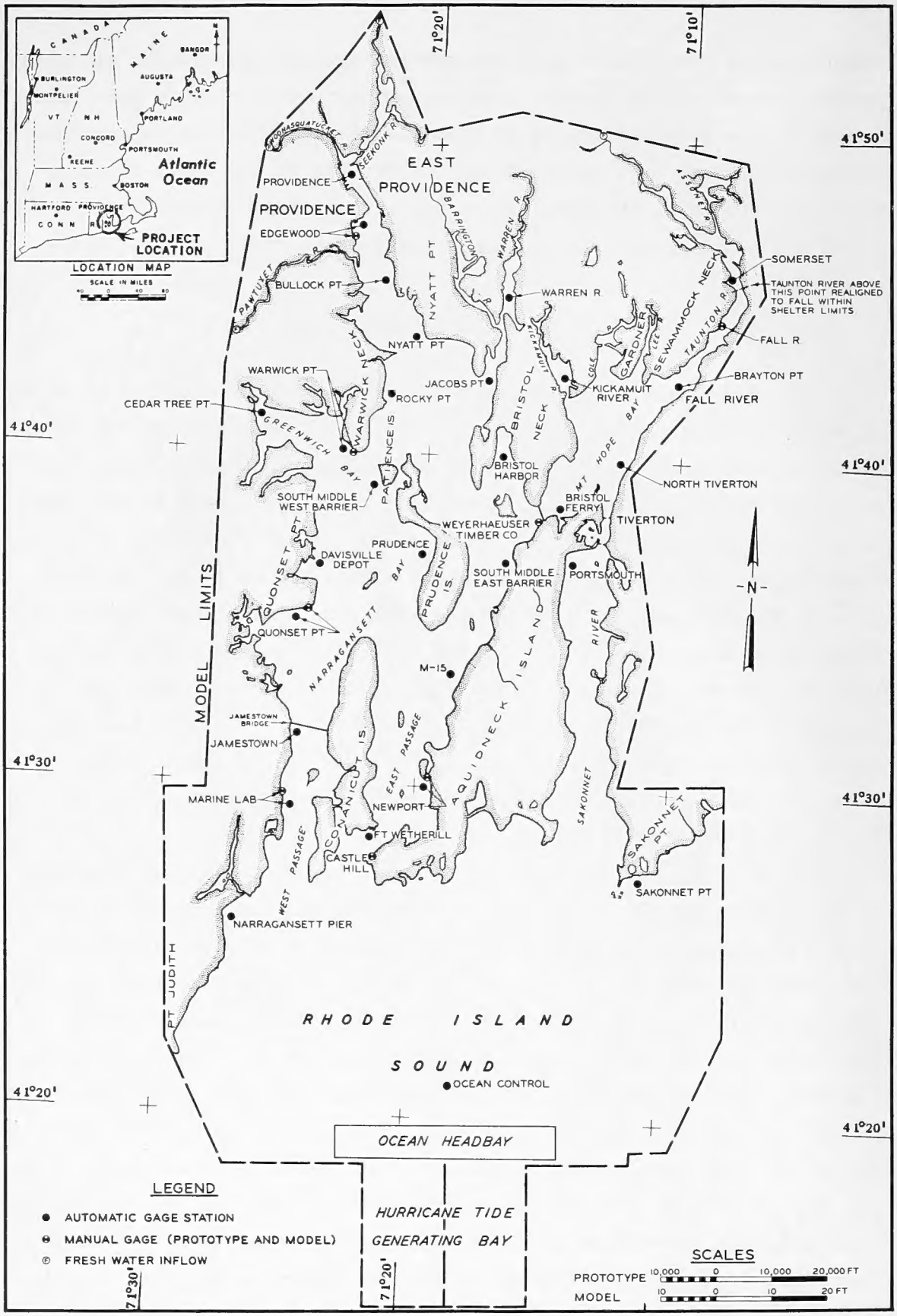

Fig. 1. Vicinity map showing location of tide gages

comprehensive report that will include the detailed results of all plans tested, regardless of whether complete or partial tests were made, since the test data obtained may be of value in planning and conducting future investigations of this type. Also, the results of the tests to determine the effects of the barriers on salinities, temperatures, sedimentation, and flushing will be included in the final comprehensive report.

The Prototype

3. Narragansett Bay is located on the coast of Rhode Island about 50 miles south of Boston (see location map, fig. 1). The bay system is about 30 miles long in a north-south direction and 15 miles wide in an east-west direction, the total area being about 450 square miles. The inner bay system is connected with the ocean by two major straits, East Passage and West Passage, and one minor strait formed by the Sakonnet River. The East Passage is about one mile wide at the mouth and has a controlling depth of about 70 ft; the West Passage is about two miles wide at the mouth and has a controlling depth of about 30 ft. The Sakonnet River is fairly wide and deep in its lower reaches; however, the control for flow into and out of the inner bay system is a bridge near Tiverton (see fig. 1) which has a navigation opening only about 100 ft wide and about 30 ft deep.

4. The terrain adjacent to the inner bay system ranges from high cliffs to low marsh areas which are partially inundated by normal spring tides. The principal cities and towns located on the bays include Jamestown and Newport, R. I., near the mouth of the bay system, and Providence and Bristol, R. I., and Fall River, Mass., near the head of the bay. The principal defense installations are the Newport Naval Base and Quonset Point Naval Air Station. There are numerous highly developed summer recreational facilities throughout the area, and a large number of the harbors are utilized by commercial fishing and pleasure craft.

5. The mean range of astronomical tides throughout the bay varies from about 3.6 ft at Newport to about 4.5 ft at Providence. Astronomical tides in the bay are principally of the stationary wave type, i.e., there

is no appreciable lag between the time of high tide at the entrance and at the head of the bay, the average time of high tide at Providence being only about 10 to 20 minutes later than at the entrance some 25 miles away. Tidal current velocities throughout the bay system produced by astronomical tides are quite moderate, ranging from maximums of about 2.5 ft per sec in the East and West Passages to less than 1.0 ft per sec in the wide sections. Only in a few restricted sections, such as that under the bridge near Tiverton, do current velocities of astronomical tides exceed about 2.5 ft per sec.

6. The tides generated by tropical hurricanes moving north along the Atlantic Coast are sometimes much greater in magnitude in the Narragansett Bay area than the largest astronomical tides, especially when the hurricane center moves inland to the west of Narragansett Bay, thus placing the bay in the path of the right front quadrant of the storm. When the time phasing of the hurricane-generated tide is such that its peak coincides with high water of the astronomical tide, as was the case in September 1938 and August 1954, the flooding of low-lying areas is especially severe and loss of life and damage to property may be extensive.

7. The tides generated by hurricanes moving inland on a coast such as that at the entrance to Narragansett Bay are made up of two major components: (a) the general rise in sea level produced by the low-pressure area associated with the hurricane center; and (b) the wind setup, or the additional rise in sea level produced by the mass transport of water shoreward by the onshore winds of the right front quadrant of the storm blowing over the fetch between the Continental Shelf and the shore. The height of the surge component generated by the wind is dependent on the wind velocity, fetch, the direction of the storm path with respect to the alignment of the shore, the bottom slope of the offshore region, and many other factors.

8. After a hurricane-generated tide enters a bay or estuary such as Narragansett Bay, the resultant heights attained at various locations are dependent on two major factors: (a) the gravitational component of the ocean tide which moves through the entrance and thence through the

bay system essentially as do the normal astronomical tides; and (b) the local setup caused by hurricane winds blowing over the bay proper. The first of these factors is usually the more significant, since few if any interior bay systems provide a sufficient fetch to permit generation of a large wind setup within the bay. Hurricane winds blowing along the axis of the bay depress the water-surface elevation near the bay entrance below that which would have been produced by the gravitational component alone, and raise the water-surface elevation at the head of the bay above that which would have been produced by the gravitational component alone. It may be stated, therefore, that local wind setup over the Narragansett Bay system could not increase flooding at localities near the bay entrance but could appreciably increase flooding at Providence and other localities near the head of the bay system.

PART II: THE MODEL

Design Considerations

9. Since the most important information desired from the model with respect to the feasibility of construction of barriers in Narragansett Bay concerned the effects of barriers at various locations on normal astronomical and hurricane tide heights and current velocities throughout the bay system (see paragraph 1), the principal consideration in design of the model was that it be capable of providing quantitative answers to these questions, or that the model test data be susceptible of adjustment by reliable analytical methods so that the final answers desired could be obtained.

10. Since the prototype forces involved in the generation of astronomical tides are gravitational forces, a model for study of such tides and the resulting tidal currents must be designed and operated in accordance with Froude's law of similitude. Since the major component of hurricane tides in an inner bay system is the gravitational component, the propagation of which is likewise governed to a major degree by gravitational forces, the Froude law is equally applicable to a model study of this component.

11. Model reproduction of the local wind-setup component of a hurricane tide is a different matter, and this difference was discussed in detail by all concerned during the planning and design phases of the model study. Since simulation of wind setup in a large model such as that of Narragansett Bay would be extremely difficult, time consuming, and expensive, and since local wind setup can be computed with acceptable accuracy by known analytical methods, the decision was reached that the model study would be confined to investigation of gravitational phenomena, and the wind-setup components would be computed by the New England Division. The model was therefore designed and operated in accordance with Froude's law of similitude.

Scale Relationships

12. The linear scales (model to prototype) selected for the model

were 1:1000 horizontally and 1:100 vertically. These scales were selected on the dual basis of providing the largest model that could be justified from a cost viewpoint, as well as the smallest model that could be tolerated from the standpoint of accurate reproduction and measurement of significant phenomena. Use of the above linear scales fixed the following significant scale relationships (model to prototype): velocity, 1:10; time, 1:100; plan area, 1:1,000,000; cross-sectional area, 1:100,000; discharge, 1:1,000,000; and volume, 1:100,000,000.

Description of Model

13. The prototype area reproduced in the Narragansett Bay model is shown on fig. 1. The ocean area reproduced outside the bay entrances extended from Point Judith on the west to Sakonnet Point on the east, and included most of Rhode Island Sound. Offshore hydrography in the ocean was reproduced in detail to the 100-ft contour of depth, and the ocean area beyond this contour was utilized for the astronomical tide and hurricane tide generators which are described subsequently. All of the inner bay system was included in the model, as well as the tidal portions of all streams tributary to the bays as far upstream as significant flooding by hurricane tides of record had occurred.

14. The model was of fixed-bed construction throughout, the bed and banks being molded of concrete. The hydrography of the bays and tributary streams was molded carefully in accordance with information shown on the latest hydrographic surveys made by the Coast and Geodetic Survey and the Corps of Engineers. The topography of the banks adjacent to the bays and tributary streams was molded in detail to el +32 ft mlw at Newport, R. I., in accordance with topographic surveys prepared by the Geological Survey, so that the extent of flooding by hurricane tides, as well as the storage effect of such flooding on water-surface elevations at upstream localities, could be reproduced with maximum accuracy. Fig. 2 is a general view of the model; a close-up of the Providence Harbor area is shown on fig. 3.

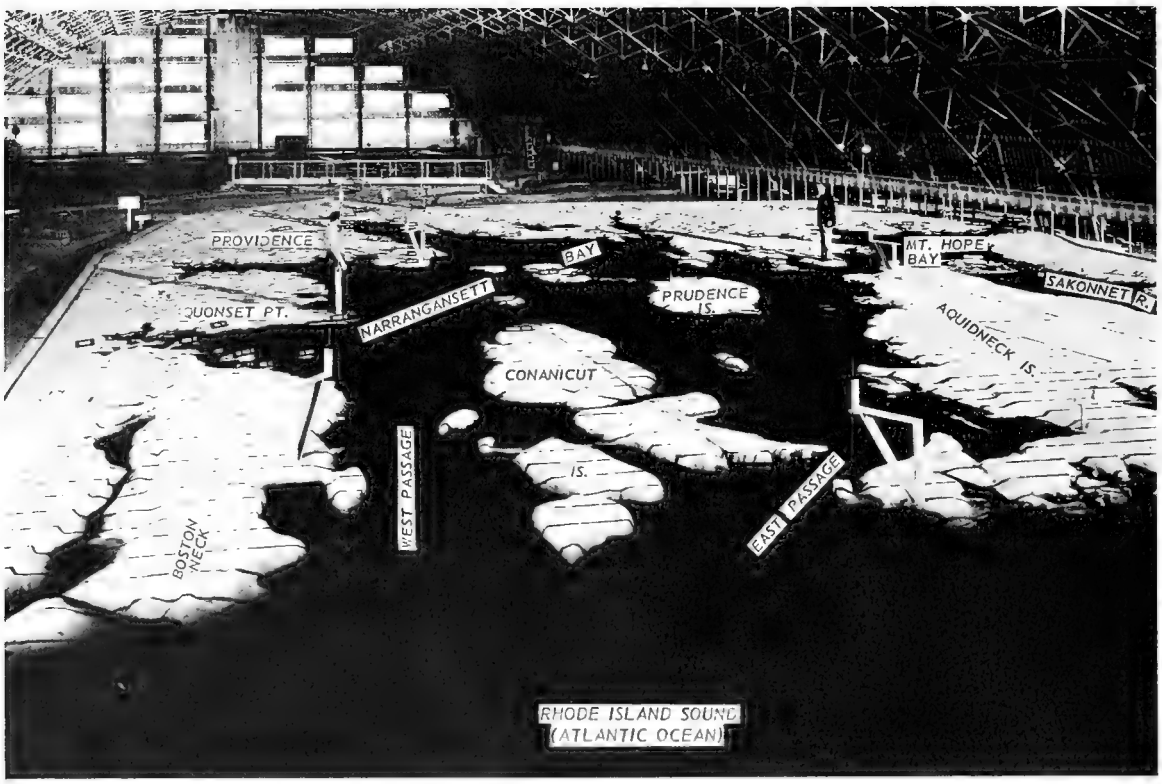

Fig. 2. The model

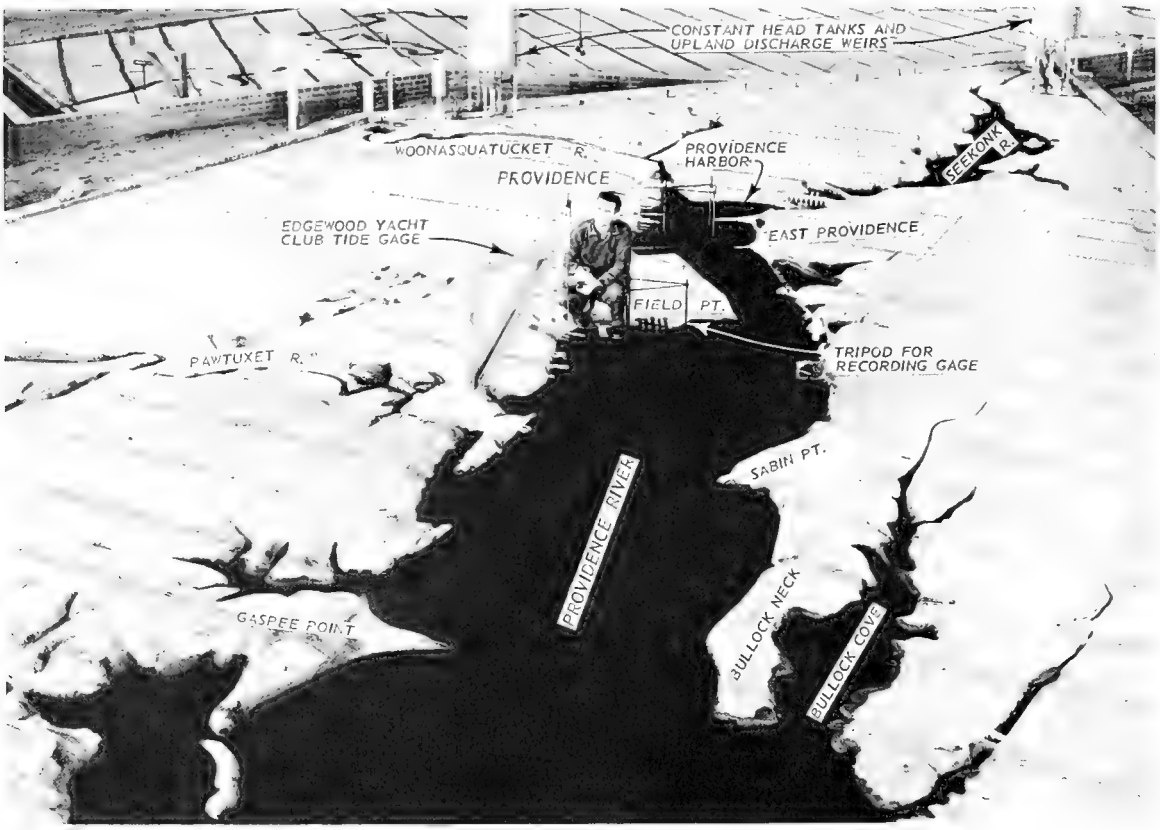

Fig. 3. Providence harbor and vicinity

Model Appurtenances

15. The major appurtenances utilized in operation of the model, and for measurement of the required phenomena therein, included astronomical and hurricane tide generators, recording tide gages, manually operated point gages, current velocity meters, and upland discharge weirs. These appurtenances and their uses are described briefly in the subsequent paragraphs.

16. The astronomical tide generator was of a conventional type used by the Waterways Experiment Station in connection with many estuary models. Its major components consisted of an underground water-supply sump located near the model, a large header connecting the sump and the ocean portion of the model, a mechanized valve installed in the header, a pumped-discharge line which entered the header on the model side of the mechanized valve, and an electromechanical control system which dictated the opening and closing of the mechanized valve. In operation, the control unit was adjusted to automatically cause precise opening and closing cycles of movement of the valve, which in turn maintained the necessary balance between a pumped flow of water to or a gravity flow of water from the model as required to duplicate the exact rate of rise or fall of the tide being reproduced. This apparatus consistently maintained correct water-surface elevations of the model ocean within an accuracy of about 0.001 ft (0.1 ft prototype). The mechanized valve and the valve-control unit are shown on figs. 4 and 5, respectively.

17. Hurricane tides could have been reproduced in the model with the same system used for generation of astronomical tides, or by an independent system of the same type, except that the large amplitude of the hurricane tides would have required the use of very large pumps, valves, and pipes. A study of possible methods of reproducing hurricane tides indicated that the most practical and economical solution would be to construct a reservoir (or basin) adjacent to and integral with the model ocean containing a volume of water somewhat greater than that required to reproduce the largest hurricane tide to be studied, and to reproduce the tide by means of a motorized bulkhead in the basin. This

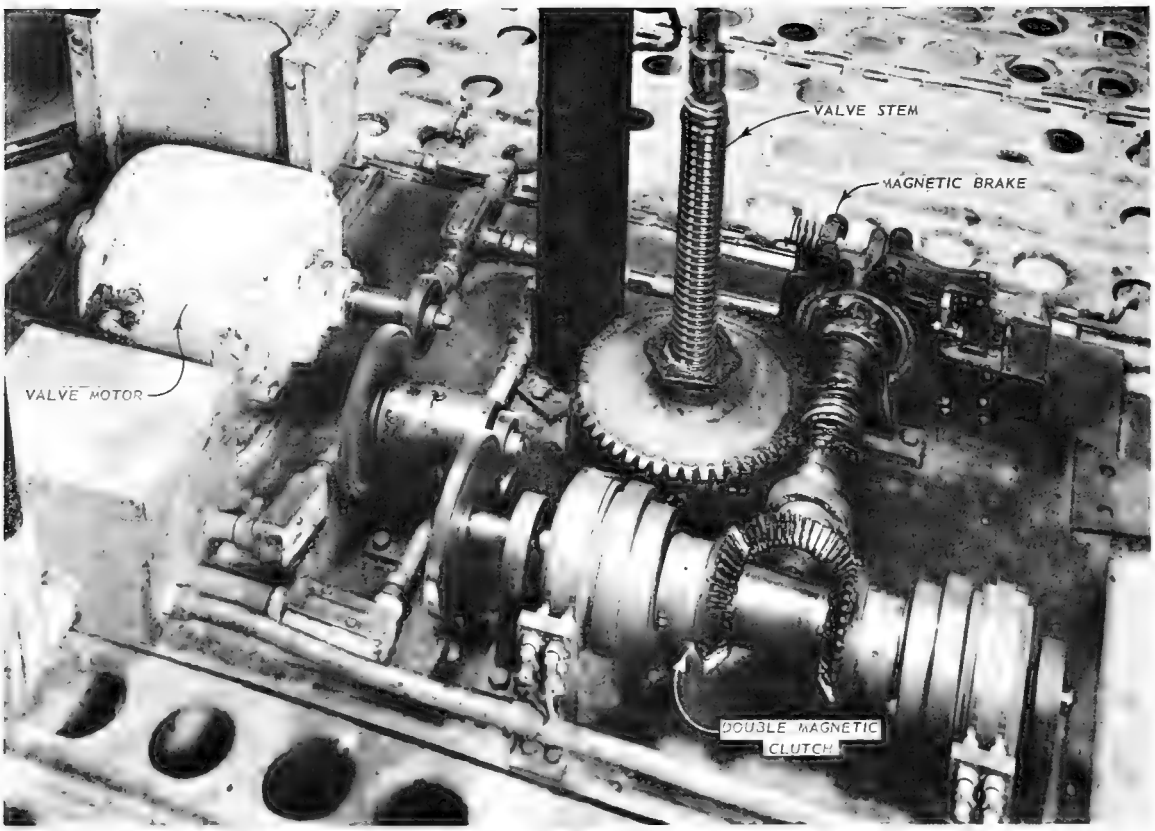

Fig. 4. Mechanized inflow-outflow valve

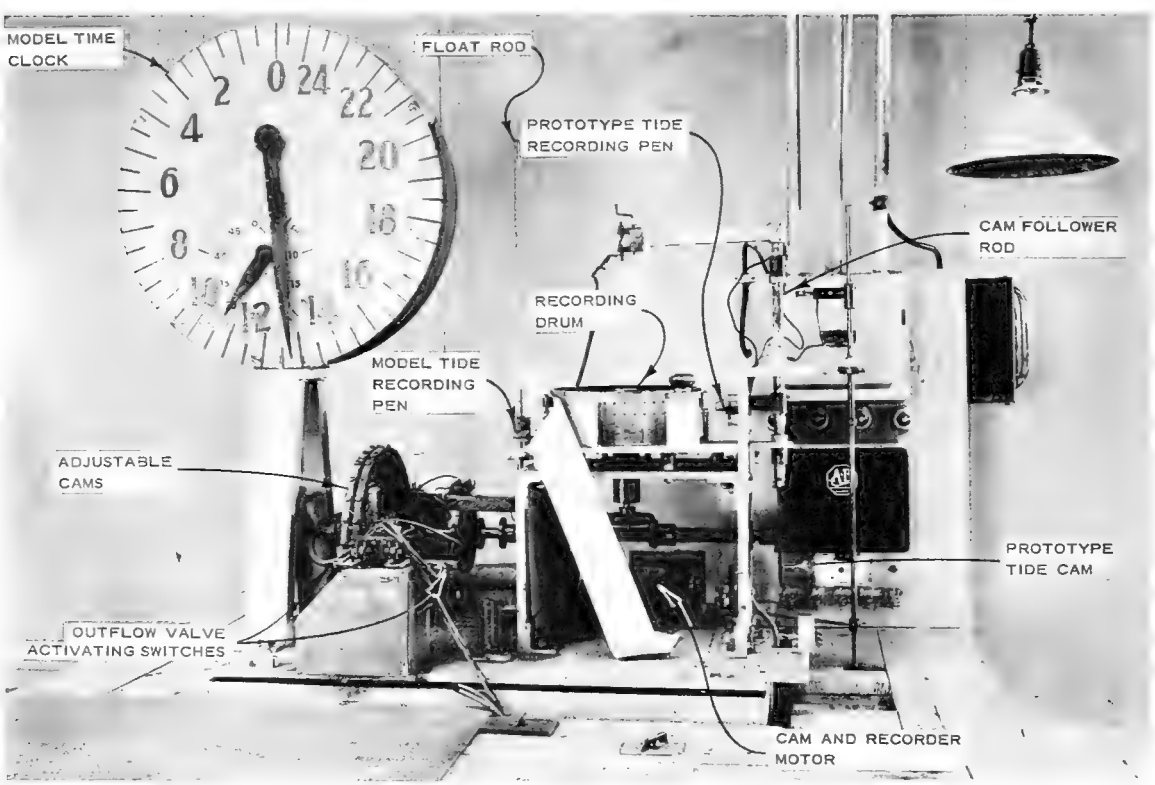

Fig. 5. Mechanized valve control unit and recorder

bulkhead was operated in such manner that its forward motion displaced water from the basin into the model, thus reproducing the rising phase of the hurricane tide, while its backward motion permitted water to flow from the model into the basin, thus producing the falling phase of the tide. The drive motor was of the three-phase type to permit the necessary reversal in direction of movement of the bulkhead, and a PIV (positive, infinitely variable) speed control unit was installed in the drive mechanism to permit a highly accurate control over the speed of the bulkhead. This system was found very satisfactory for generation of hurricane tides, in that the apparatus could be quickly adjusted to reproduce any desired ocean tide with a minimum of effort, and that tide could then be duplicated accurately as many times as necessary. The hurricane tide generator system is shown on fig. 6.

18. Because of the very rapid rate of rise and fall of hurricane tides, recording tide gages were utilized to measure and record these tides at various locations throughout the model. The gages consisted of a roll of recording paper moving on a drum which was revolved at a known and constant speed by a small synchronuous motor, and a float-supported pen which inked a continuous record of water-surface elevation on the

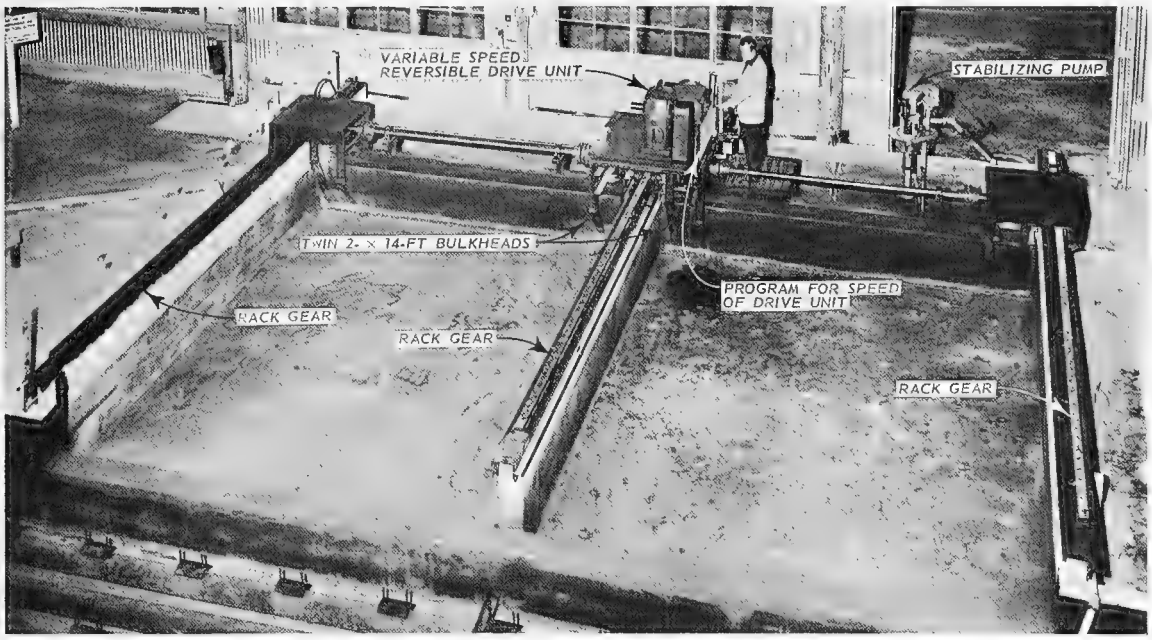

Fig. 6. Hurricane tide generator

recording paper. Pin points were projected through small holes in the recording drum so as to perforate the recording paper at time intervals equivalent to one hour (prototype), to maintain a permanent time check on each record. The recording gages were mounted on flat base plates, which in turn were mounted on tripods permanently located at all points in the model at which hurricane tide data were desired. The tripod mounts were all adjusted to a common reference plane, so that any recording gage could be moved from one location to any other location without loss of time for adjusting its reference plane. One of these recording gages is illustrated on fig. 7.

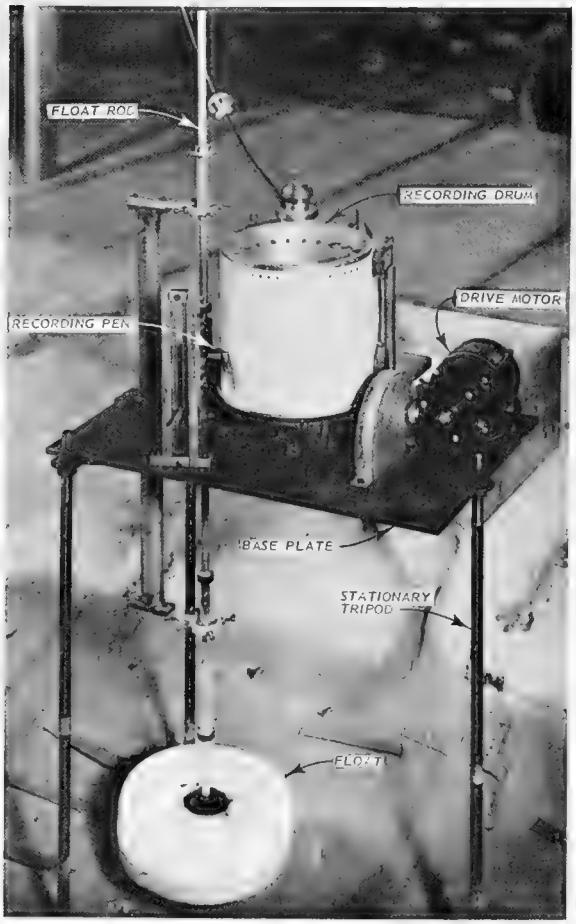

Fig. 7. Model recording tide gage

19. Manually operated point gages, permanently mounted at the locations of all prototype tide gages and at a number of additional locations, were used for measurement of astronomical tide elevations during most of the model tests; however, the recording gages described above were used for this purpose during a few tests in which time did not permit use of the point gages. More precise measurements were possible with the point gages than with the recording gages, since the measurement was a direct one and did not involve interpretation of a record. One of the permanent point gages used may be seen on fig. 3.

20. Most of the measurements of current velocities in the model were made with miniature Price-type current meters illustrated on fig. 8. The horizontal dimension of the cup wheel was about 0.083 ft and the vertical dimension about 0.03 ft. The meters were capable of accurate

measurement of velocities down to a minimum of 0.05 ft per sec (0.5 ft per sec prototype), and they were calibrated frequently to insure accuracy of operation.

Fig. 8. Model current meter

21. The upland discharges of the major tributaries to the bays were measured by means of Van Leer (California Pipe) weirs, each weir being supplied from a separate constant-head tank. One of the model weirs and its constant-head tank may be seen in the background of fig. 3. The upland discharges introduced in the major tributaries during all tests reported herein, unless stated differently in the description of a particular test, were as follows: Pawtuxet River, 700 cfs; Woonasquatucket and Moshasuck Rivers, 400 cfs; Seekonk River, 1500 cfs; and Taunton River, 1400 cfs.

PART III: VERIFICATION OF MODEL REPRODUCTION OF PROTOTYPE PHENOMENA

Astronomical Tides

22. The first step in preparing the model for testing consisted of verifying the accuracy with which it would reproduce observed normal astronomical tides. This was accomplished by adjusting the astronomical tide generator to reproduce a tide of mean range in the model ocean, then verifying the accuracy with which resulting mean tides were reproduced throughout the inner bay system. Prototype mean-tide data were available for a number of gages throughout the bay system, and data for Castle Hill, Newport, Narragansett Marine Laboratory, Quonset Point, Warwick Point, Weyerhaeuser Timber Company, and Edgewood Yacht Basin gages (see fig. 1) were selected for the initial comparison with model data.

23. An ocean tide of mean range was interpolated from observed records at Block Island (about 22 miles seaward from the bay entrance) and Newport, since no prototype tidal gaging station was in existence at a point approximating the location of the inflow-outflow system of the model astronomical tide generator (designated as ocean head bay, fig. 1). The tide generator was adjusted to reproduce the interpolated tide curve in the model ocean, and resulting tides at the seven locations listed in paragraph 22 were measured for comparison with observed prototype mean tide ranges and elevations. As shown on fig. 9, the high-water and low-water profiles at all corresponding model and prototype gaging stations were in close agreement, thus indicating that reproduction of an astronomical tide of mean range in the model ocean would result in accurate reproduction of the ranges and elevations of this tide throughout the bay system. This same procedure was repeated, using a spring tide having a range equal to that observed on 28 December 1955, and the agreement between model and prototype tidal ranges and elevations at Castle Hill, Narragansett Marine Laboratory, Weyerhaeuser Timber Company, and Edgewood Yacht Basin for this condition is also shown on fig. 9. These comparisons indicate satisfactory agreement between model and prototype with

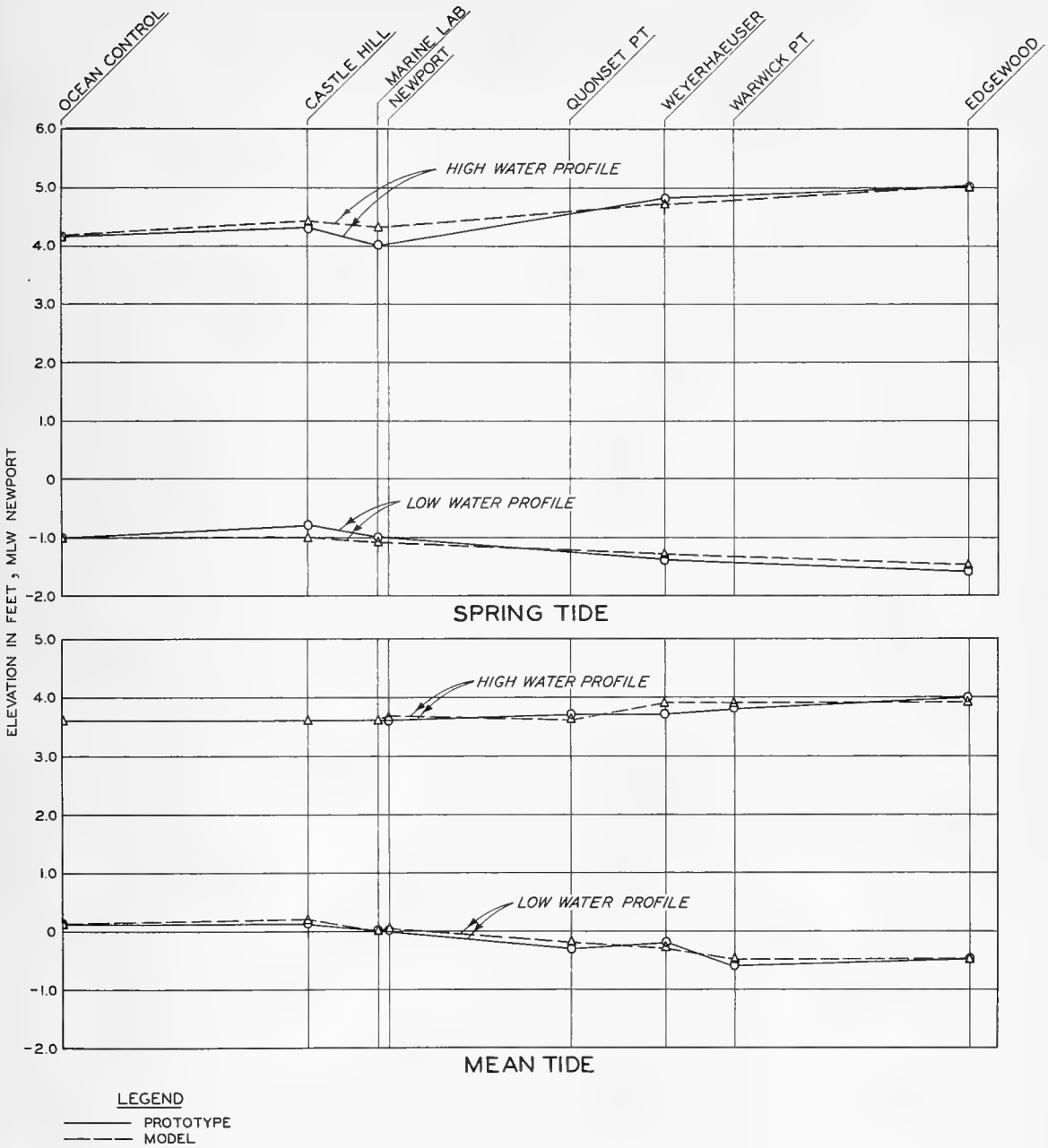

Fig. 9. Verification of astronomical tide heights

respect to ranges and elevations of both mean and spring astronomical tides throughout the area reproduced in the model.

Current Velocities

24. No attempt was made to obtain a detailed verification of

current velocities throughout the bay system for the tests reported herein; however, it was considered desirable to check the model reproduction of prototype current velocities in the principal channels of the bay system to insure that the distribution of flow among the several channels was approximately correct. Observed prototype current velocities for stations 1-6 shown on fig. 10, adjusted to conditions of mean astronomical tide, were obtained from Coast and Geodetic Survey Special Publication No. 208, entitled, Currents in Narragansett Bay, Buzzards Bay, and Nantucket and Vineyard Sounds, 1936. Observations were made at similar locations in the model for conditions of the mean astronomical tide described in the preceding paragraph. Comparisons between prototype and model current velocities for the six velocity stations are shown on figs. 11 and 12, and indicate satisfactory agreement between prototype and model current velocities at all stations.

Hurricane Tides

Hurricane tides of record

25. Gage records at Newport, Providence, and in some cases at Somerset, were available for the tides generated in Narragansett Bay by the hurricanes of September 1938, September 1944, and August 1954. Each of these hurricane tides was reproduced in the model to determine how closely the resulting model tides agreed with those of the prototype at the locations for which prototype gage records were available. However, the September 1938 hurricane tide was the only one used for model test purposes; therefore, the comparisons of model and prototype hurricane tides for conditions of the September 1944 and August 1954 hurricanes are not included in this report.

26. In the verification tests, the model astronomical tide generator was first adjusted to reproduce the astronomical tide predicted for 21 September 1938 (the date of the hurricane), which had a range of slightly more than 4.0 ft and a high-water elevation of +4.1 ft mlw at Newport.* The hurricane tide generator was then adjusted by a cut-and-try

* All elevations in this report are referred to mlw at Newport, R. I., which is 1.6 ft below msl.

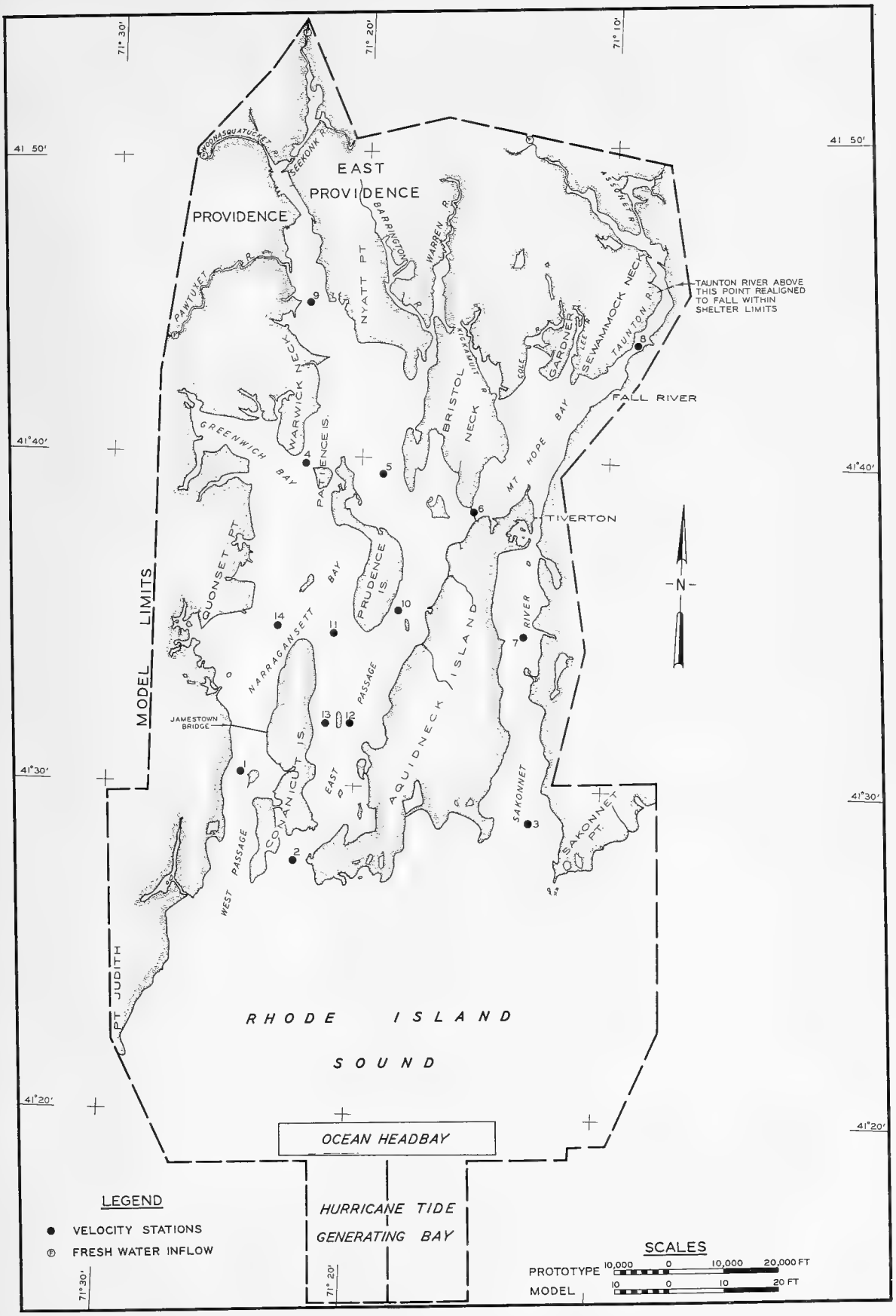

Fig. 10. Location of velocity stations

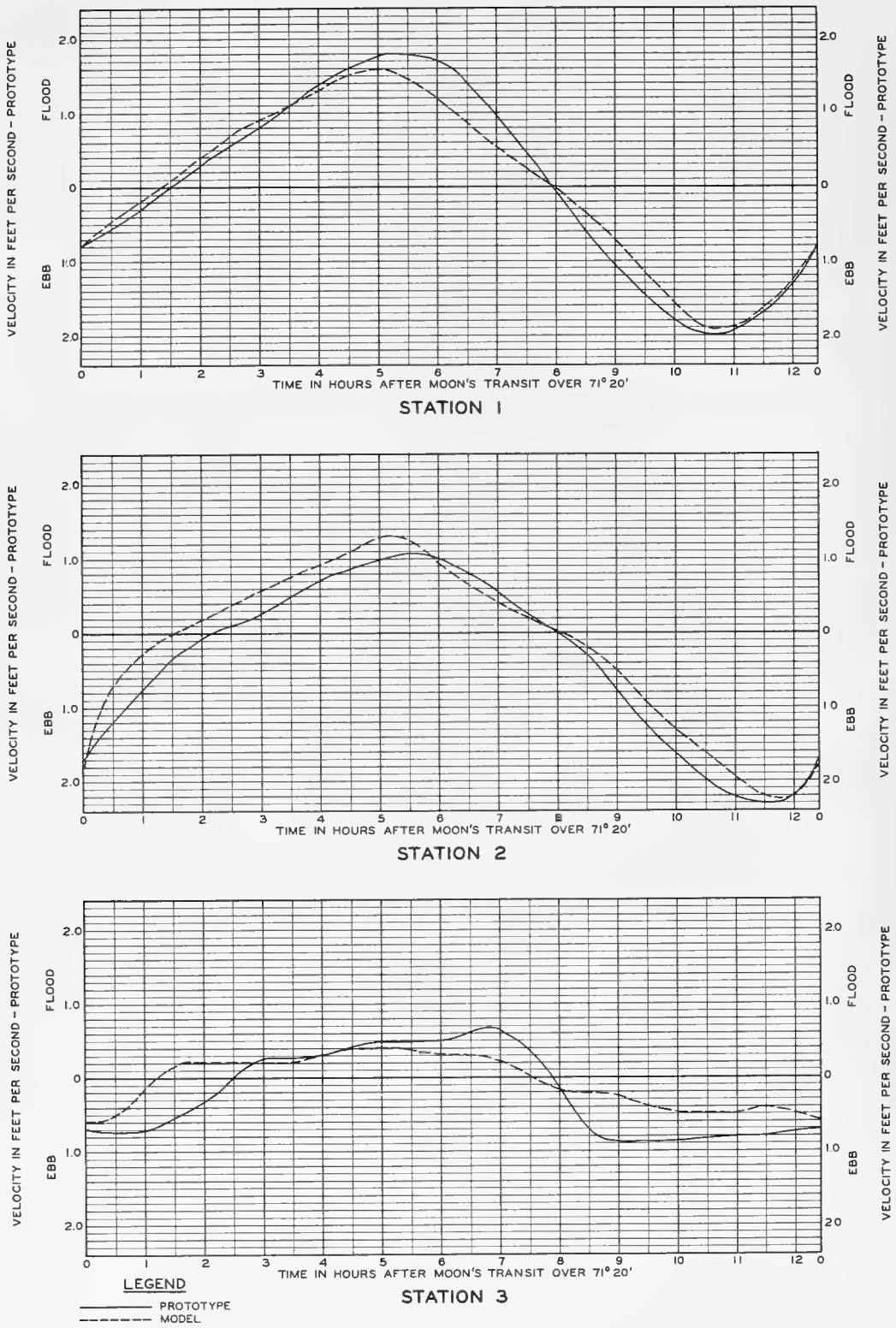

Fig. 11. Verification of velocities at stations 1-3

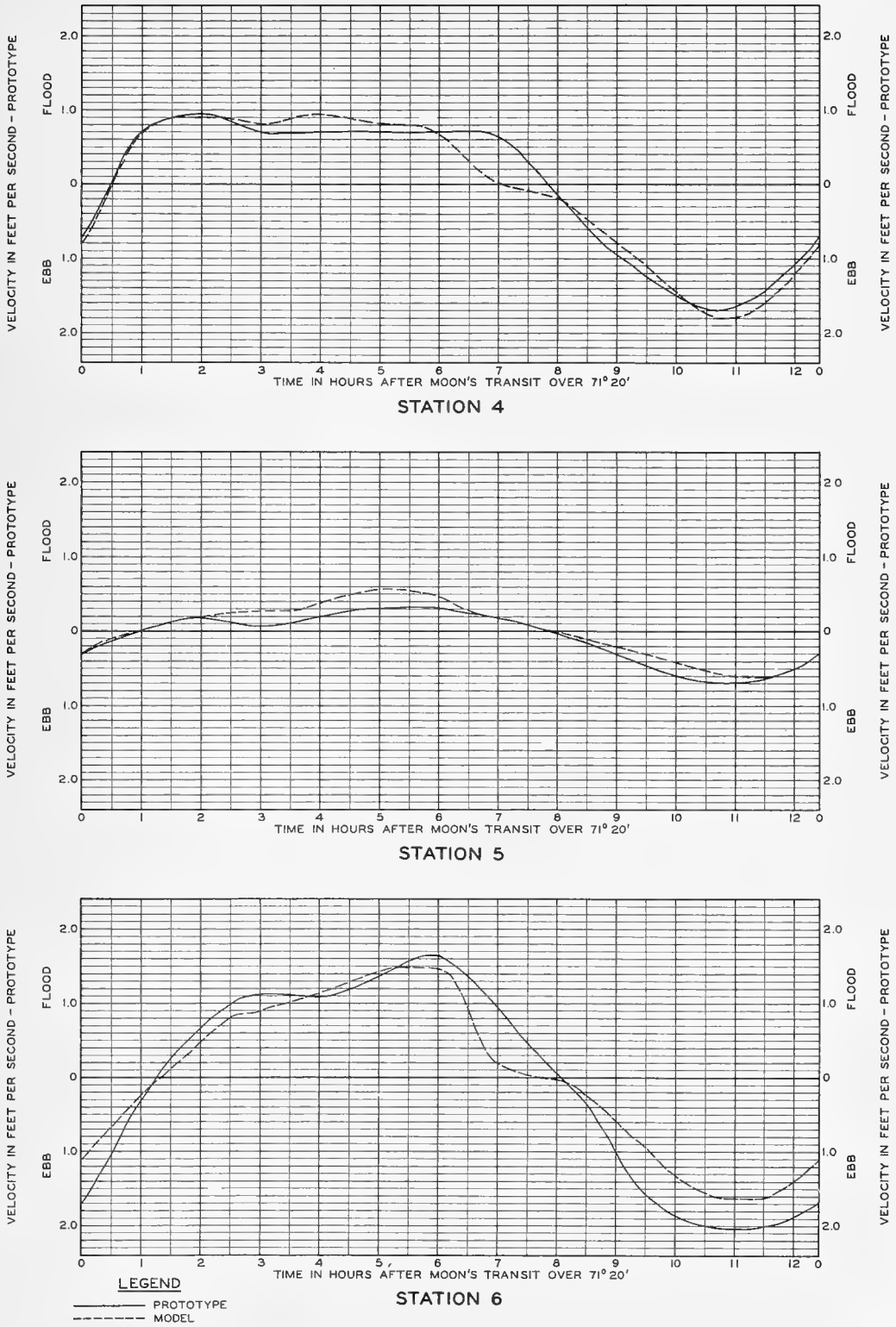

Fig. 12. Verification of velocities at stations 4-6

procedure until the resultant tide at Newport (astronomical tide plus hurricane tide component) was in agreement with the actual tide recorded for 21 September 1938. As soon as a successful reproduction of the Newport tide curve was attained, measurements of the resultant tides at Providence and Somerset were made for comparison with prototype records.

27. Maximum elevations reached by the September 1938 hurricane tide at Newport, Providence, and Somerset were 11.7 ft, 17.8 ft, and 14.8 ft, respectively, above mlw at Newport. The elevations reached at Providence and Somerset were therefore 6.1 ft and 3.1 ft, respectively, higher than at Newport, including both gravitational buildup and wind setup. Early computations of wind setup for the 1938 hurricane tide indicated this factor to be about 2.0 ft at Providence and less than 1.0 ft at Somerset, thus indicating the gravitational buildup to have been of the order of 4.0 ft at Providence and between 2.0 ft and 3.0 ft at Somerset. The initial test of the 1938 hurricane tide in the model, during which an elevation of +11.7 ft mlw was reproduced at Newport, resulted in maximum elevations of +15.5 ft at Providence and +14.8 ft at Somerset, or gravitational buildups of 3.8 ft and 3.1 ft at Providence and Somerset, respectively.

28. Since the results of the initial test were in close agreement with the results of initial computations of wind setup for conditions of the 1938 hurricane tide, a number of preliminary hurricane tide tests of proposed barrier plans (through plan 26 of the model study) were made for these conditions. However, the results of later and more refined computations of the wind-setup component of the 1938 hurricane tide indicated that the setup at Providence was of the order of 2.8 ft to 3.0 ft, instead of about 2.0 ft as indicated by the early computations. Use of the refined wind-setup computation indicated that the gravitational buildup of the 1938 hurricane tide between Newport and Providence was about 3.1 ft to 3.3 ft, instead of the 4.0 ft shown by the early computations and checked by the model during initial tests.

29. The excessive gravitational buildup of the 1938 hurricane tide in the model indicated a deficiency in model roughness, which consisted only of a rough brushed finish of the concrete bed at the time of

the initial tests. It was suspected from the beginning that the model roughness was deficient, but the very low current velocities throughout the model for astronomical tide conditions, plus the close reproduction of the gravitational buildup of the 1938 hurricane tide, had made additional roughness seem unnecessary. After the deficiency in roughness became apparent the Manning "n" of the prototype channels was estimated to be of the order of 0.026, and roughness elements were added to the model as required to effect a scale reproduction of this estimated prototype roughness. The model roughness elements consisted of three-fourth-inch-wide metal strips set vertically into the concrete bed of the model and extending to the water surface. An average of about one strip per two square feet of model area was required to duplicate the estimated prototype roughness.

30. Use of the refined wind-setup computations for the 1938 hurricane tide indicated that the gravitational buildup of this tide over maximum elevation at Newport was slightly more than 2.0 ft at Somerset and, as previously stated, was 3.1 to 3.3 ft at Providence. The 1938 hurricane tide was repeated in the model after completion of the roughness adjustment described above and with the hurricane tide generator adjusted to produce a maximum elevation of +11.9* ft mlw at Newport. It was found that maximum elevations at Providence and Somerset were 15.2 and 14.2 ft, respectively, above mlw, or a gravitational buildup of 3.3 ft at Providence and 2.3 ft at Somerset. Comparisons of prototype and model gage records at Newport, Providence, and Somerset for conditions of the 1938 hurricane tide are shown on fig. 13. Astronomical tide elevations and ranges shown on fig. 9, and current velocities at several of the stations for which data are presented on figs. 11 and 12 were rechecked to determine whether the change in model roughness had effected changes in astronomical tides and tidal currents. It was found that no measurable changes had occurred in astronomical tides and tidal currents

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* Model high tide was increased 0.2 ft over that recorded in the prototype to compensate for the effects of local wind setup which depress water-surface elevations near the bay entrance.

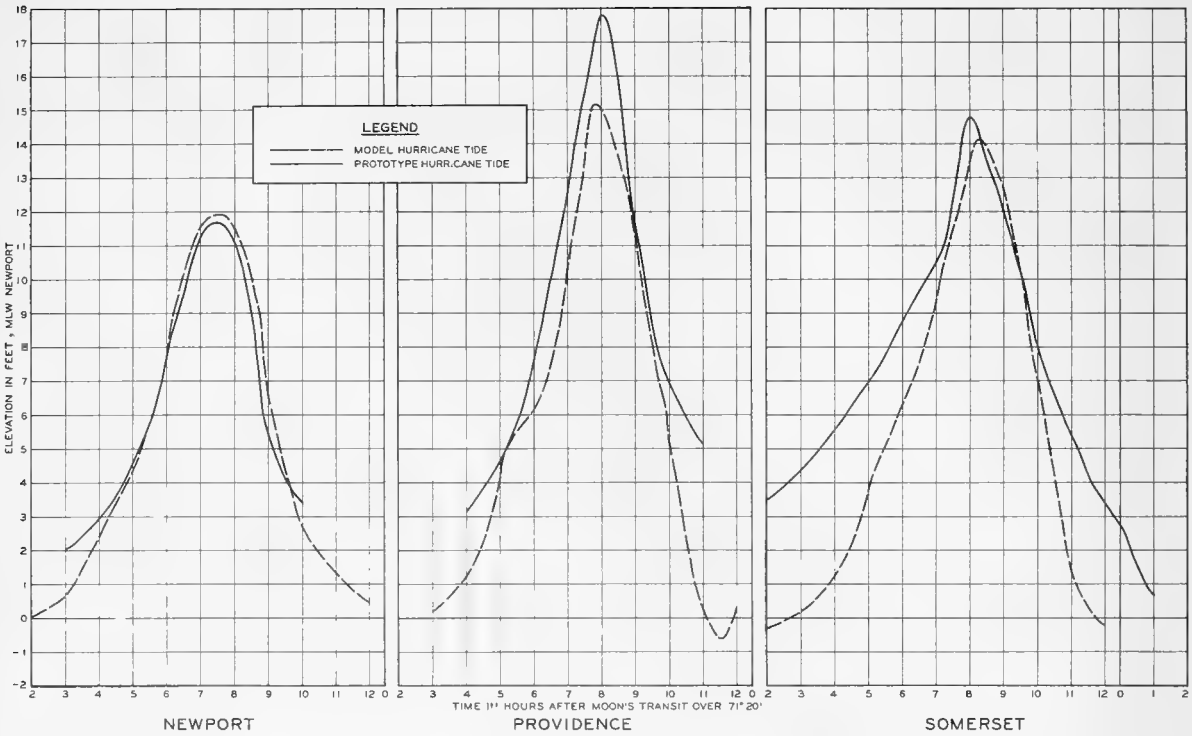

Fig. 13. Verification of 1938 hurricane tide heights

from the data shown on figs. 9, 11, and 12.

31. Prototype and model plots of the 1938 hurricane tide curves at Newport, Providence, and Somerset, shown on fig. 13, indicate that the time phasing of the peak of the hurricane tide was the same in the model as in the prototype. Some differences may be noted between prototype and model with respect to the slopes of the tide curves, especially at Somerset, but these differences are thought to be due to wind effects in the prototype. In addition to the comparisons between prototype and model tide curves shown on fig. 13, the maximum elevations reached by the 1938 hurricane tide at numerous locations throughout the bay system were checked against elevations at corresponding points in the model. High-water elevations at all points in the model were found to be lower than those at corresponding points in the prototype by amounts approximately equal to the computed wind setup for such locations. It was therefore concluded that the model would reproduce accurately throughout the entire bay system the gravitational component of any hurricane tide generated in the model ocean.

Design hurricane tides

32. The model hurricane tide generator was designed to reproduce hurricane tides of greater amplitude than that of September 1938, which was the greatest hurricane tide of record in the Narragansett Bay area, to take care of the possibility that later computations might indicate that tides of greater amplitude are likely to occur in that area. The hurricane of September 1944 was selected for design purposes, and the tides that would have been generated at Newport by this hurricane if it had reached Narragansett Bay at the peak of its intensity were computed for three assumed speeds of movement of the hurricane center, 20 knots, 30 knots, and 40 knots. These tides, referred to hereinafter as design tides, were computed by the New England Division and furnished to the Waterways Experiment Station for use in the model tests.

33. The model reproductions of the 40-knot and 20-knot design hurricane tides at Newport are shown on fig. 14. The computed tides do not contain an astronomical tide component as does the 1938 hurricane tide discussed previously, so adjustment of the model hurricane tide generator to reproduce the design tides at Newport was accomplished with

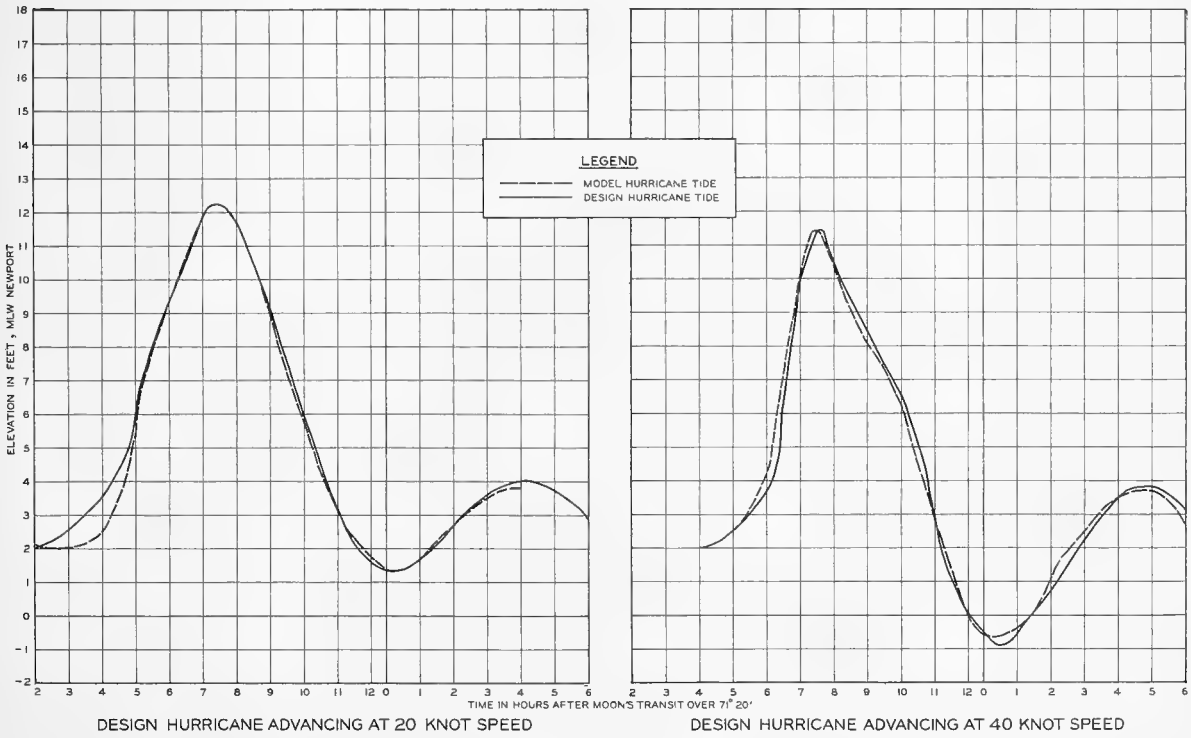

Fig. 14. Verification of design hurricane tides at Newport

the model water surface pooled at mean astronomical tide level (about +1.8 ft mlw). In later model tests involving use of the design hurricane tides, these tides were reproduced in combination with the astronomical spring tide range of 4.1 ft at Newport. The 40-knot design tide was used only briefly during the testing program since this tide was almost identical at the mouth of the bay with the 1938 hurricane tide used in all preliminary tests, and no test data for conditions of this design tide are included in this report. The 30-knot design tide was not used at all for model test purposes. All hurricane tide test data presented in subsequent parts of this report were obtained for conditions of the 1938 hurricane tide or the 20-knot design hurricane tide.

PART IV: TESTS AND RESULTS

Base Tests

34. Base tests, or tests of existing prototype conditions, are made in connection with hydraulic model studies to provide a direct basis for evaluating the results of subsequent tests incorporating proposed improvement plans. A measurement of some phenomenon during a plan test, when compared to a similar measurement made during the base test, will provide a direct measure of the effects of the plan on the phenomenon in question. Since it is usually desirable that improvement plans be tested for more than one basic condition, base tests are made for all of the conditions for which improvement plans will subsequently be tested. During the course of the Narragansett Bay model study, several astronomical tide and several hurricane tide base tests were made. The conditions established for these various base tests are described in the subsequent paragraphs.

Astronomical tide base tests

35. Two astronomical tide base tests were used for evaluation of the model test data. The first involved reproduction of a normal spring tide, which had a range of 4.1 ft at Newport, a high-water elevation of +4.1 ft mlw, and a low-water elevation of 0.0 ft mlw. All hurricane tide tests reported herein were made in conjunction with this astronomical tide, and supplemental current velocity data and astronomical tide data for all plans reported were obtained for conditions of this tide. In addition, certain current velocity data and astronomical tide data for plans 35 and 36 were obtained for conditions of a mean tide having a range of 3.6 ft at Newport, a high-water elevation of +3.7 ft mlw, and a low-water elevation of +0.1 ft mlw. Test data presented in subsequent parts of this report for plans 35 and 36 show which of the above-described astronomical tides was being used during the test in question.

36. Base test data for astronomical tides and tidal currents are not shown independently in the remainder of this report; instead, these data are included in data tabulations for direct comparison with similar

measurements made with the various plans installed in the model. The tables show whether the base test data presented were obtained for mean or spring astronomical tides. In all cases comparative plan data were obtained for the same tide range as were the base test data.

Hurricane tide base tests

37. Hurricane tide base test data presented in this report to assist in evaluation of plan test data were obtained for one or the other of the following conditions: (a) the astronomical spring tide range of 4.1 ft at Newport combined with the September 1938 hurricane tide; or (b) the astronomical spring tide range of 4.1 ft at Newport combined with the 20-knot design hurricane tide. As described above in connection with the astronomical base tests, each table presenting base test or plan test data shows whether the data presented were obtained for the condition described in (a) or (b) above, or both. Hurricane tide base test data were obtained at the 29 automatic gage locations shown on fig. 1 for each of the conditions described above.

Technique for Testing Improvement Plans

38. The testing of proposed barrier plans in the model involved some precautionary steps to insure that scale effects resulting from the distorted scales of this model did not adversely affect the accuracy of model test data, and to obtain all data required for evaluation of the plan in question. The detailed procedure followed in testing a proposed barrier plan is described below:

a. If one or more ungated navigation openings were incorporated in the design of the plan, each opening was modeled to the distorted model scales and also to an undistorted scale of 1:100. The openings and adjacent sections of the structures were then installed in two flumes in which depths were molded to conform with the depth at the location of the navigation opening in the prototype. The distorted and undistorted openings were next subjected to tests covering the full range of head differentials to be expected in the model, the discharge coefficients of the undistorted openings were determined for each increment of head differential, and the distorted openings were modified as required to adjust their discharge coefficients

to those of the undistorted openings. In all cases, the adjustments required consisted only of rounding the corners of the sills and abutment walls of the distorted openings to reduce contraction effects.

b. The proposed barriers were then installed in the model, and navigation openings (if any) were adjusted as found necessary during the flume tests so that their discharge coefficients were correct throughout the full range of head differentials.

c. Both the astronomical tide and hurricane tide generators were then readjusted to reproduce the same tides in the ocean portion of the model as occurred during the base test condition to be used for evaluating the effects of the plan in question. The readjustment procedure was necessary because installation of different plans in the model caused various changes in the tidal prism of the bay system, both for conditions of astronomical tides and hurricane tides, which in turn would have affected the range of the ocean tides in the model had not the generators been readjusted for each barrier plan.

d. The plan in question was then subjected to all astronomical tide and hurricane tide tests for which information was desired, and all necessary measurements of resulting tidal and current phenomena throughout the bay system were obtained. In the case of a few plans, it was desired to determine in detail the distribution of current velocities in one or more of the navigation openings for conditions of maximum hurricane tide head differential and maximum astronomical tide head differential across the structures. Because of the small size of the navigation openings in the distorted model, these data were obtained by observing the maximum head differentials in the model, establishing these head differentials in the flume containing the undistorted model of the opening in question, and obtaining the necessary measurements of velocity distribution therein.

By following this sequence of steps, all errors in model results that would have been caused by the distorted model scales were eliminated, and the test results presented herein may be considered quantitative with respect to the effects of the various structures in the prototype.

Middle Bay Barriers

39. The elements of the Middle Bay barrier plan are shown on fig. 15.

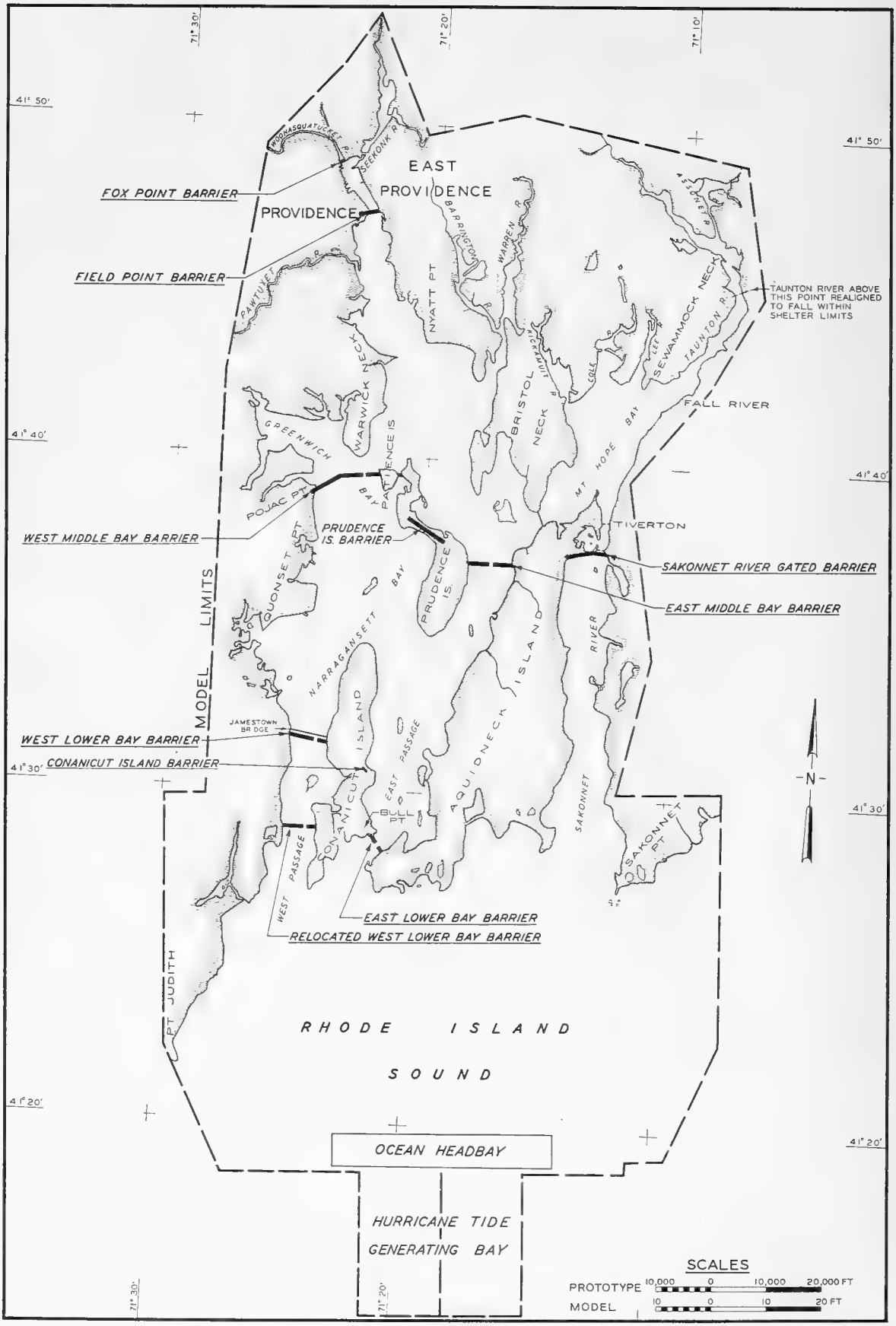

Fig. 15. Location of barriers

This plan involved a structure across the West Passage between Pojac Point and Patience Island (designated West Middle Bay barrier), a structure closing the gap between Patience and Prudence Islands, a dike across the Prudence Island marshes, and a structure across the East Passage between Prudence and Aquidneck Islands (designated East Middle Bay barrier). The model structure in the West Passage was equipped with 33 sluice gates, each 100 ft wide, and that in the East Passage with 34 similar gates (see fig. 16), in addition to navigation openings in each passage. A number of preliminary hydraulic tests were made to determine the maximum current velocity that would obtain in both navigation openings with various numbers of sluice gates open in each barrier. The data from these tests were to be used to determine the total area of openings (both sluice gates and navigation openings) required to hold current velocities in the navigation openings to a maximum of about 4.25 ft per sec for conditions of an extreme astronomical spring tide range of 5.4 ft at Newport. It was found that a total opening area of about 114,000 sq ft would be required to meet this criterion. No structure was installed in the Sakonnet River during these tests.

40. Two degrees of closure of the Middle Bay barrier were tested to determine the effects of the structures on hurricane tides. The first of these, designated plan 22 of the model study, involved complete closure of the West Passage, complete closure of the Sakonnet River at Old Stone Bridge, closure of the channel between Patience and Prudence Islands, and a navigation opening in the East Passage barrier having a sill elevation of -40 ft mlw, a sill width of 600 ft, abutment side slope of 1 on 1.5, and a crest elevation of +24 ft mlw. Details of this navigation opening are shown on fig. 16. The hurricane tide test of plan 22 was made for conditions of the 1948 hurricane tide superimposed on the astronomical spring tide having a range of 4.1 ft at Newport.

41. The effects of plan 22 on maximum elevations of hurricane tides throughout the bay system are shown in table 1, together with the effects of the plan on the times of hurricane high tides. Only a few reliable measurements of astronomical tide ranges and elevations were made during the test of plan 22; these measurements indicate that tidal

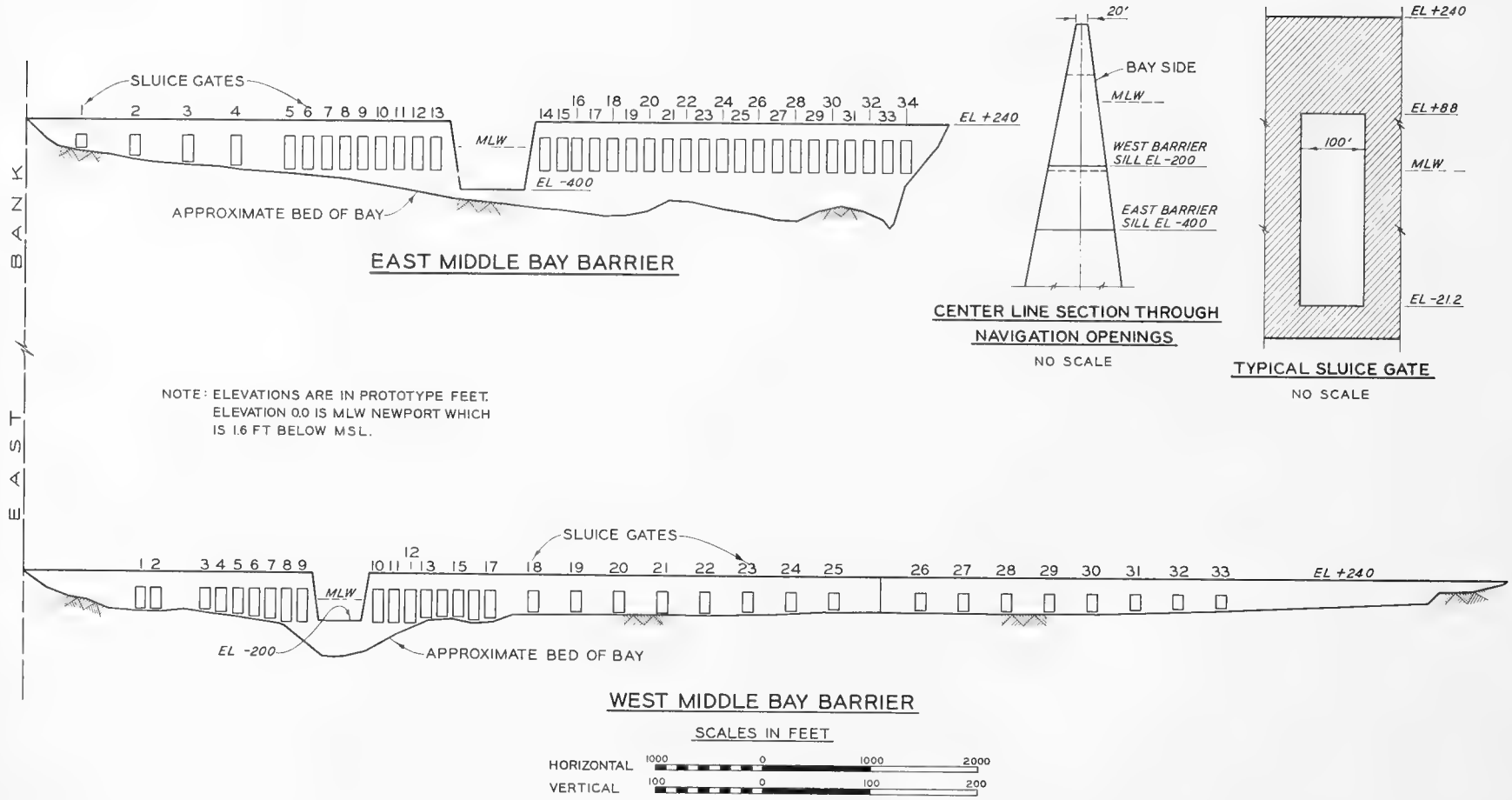

Fig. 16. Location of navigation openings and sluice gates in Middle Bay barrier plan

ranges and elevations at gages located downstream from the barriers were relatively unchanged, while tidal ranges at stations upstream from the structure were reduced by about 45 to 50 per cent (the elevations of high water being lowered and those of low water being raised). The maximum elevations of hurricane tides upstream from the structure were lowered by amounts ranging from about 9.0 ft at Warwick to about 11.1 ft at Providence. Downstream from the structures, however, the elevations of hurricane tides were increased by amounts ranging up to about 1.4 ft. The results of this test indicate that barriers located in this region of the bay would reduce hurricane tide elevations at all locations upstream from the barriers but would cause an appreciable buildup downstream from the structures over elevations without barriers.

42. Tests of the Middle Bay barriers were also made with the East Passage navigation opening closed, thus completely closing off the upper part of the bay. This condition was designated plan 23 of the model study, and the same conditions of astronomical and hurricane tides were used for this test as for tests of plan 22.

43. The effects of plan 23 on hurricane tide heights at gages located downstream from the structures are also shown in table 1, together with the effects on times of high tide. No tidal data are presented for gages located upstream from the structures, since that portion of the bay system was not subject to tidal influence for conditions of complete closure of the structures. As in the case of plan 22, reliable measurements of astronomical tide ranges and elevations were made at only a few locations; these measurements indicate that tide ranges and elevations at gages located downstream from the barriers for plan 23 were essentially the same as for the base test. The maximum elevations reached by hurricane tides were increased over those of the base test at gages located downstream from the barriers, the maximum increases being just downstream from the West Passage and East Passage structures and in the Sakonnet River. These measurements show that the buildup downstream from the barriers would be slightly more severe for plan 23 than for plan 22 (maximum of about 2.0 ft for plan 23, compared to about 1.4 ft for plan 22).

44. Prior to the above-described model tests, the Middle Bay barrier site had been generally considered to be the optimum location for barriers in Narragansett Bay for the following reasons: (a) the Middle Bay site would afford protection to those portions of the bay system which had experienced the greatest loss of life and property during hurricane tides of record; and (b) provisions for navigation through the structures by large naval vessels would not be involved, since the major naval bases in the bay are located downstream from the Middle Bay barriers. Because of the buildup downstream from the structures indicated by the model tests, which amounted to as much as 2.0 ft for tests involving the 1938 hurricane tide, the Middle Bay barriers were excluded from further consideration and were not subjected to as detailed testing as were some of the barrier plans tested subsequently. For example, the Middle Bay barrier tests reported herein were made prior to and were not tested with the refined model roughness adjustment described in paragraph 29 of this report, nor were these barrier plans subjected to hurricane tide tests for conditions of any of the design hurricane tides. The deficiency in model roughness existing at the time of the Middle Bay barrier tests probably resulted in slightly higher hurricane tides throughout the bay system than would have occurred had the roughness been correct (the addition of roughness lowered the 1938 hurricane tide peak at Providence by about 0.5 ft). However, since the roughness deficiency would have affected hurricane tide elevations in the same degree for both base test and plan test conditions, it was concluded that the buildup downstream from the model structures indicated by the model tests was of the proper order of magnitude, and the Middle Bay barrier tests were not repeated.

Lower Bay Barriers

45. The locations of the various elements of the Lower Bay barrier plan are shown on fig. 15. The general features of the plan included closure of the West Passage just downstream from the Jamestown Bridge (West Lower Bay barrier), closure of East Passage at Bull Point (East

Lower Bay barrier), either complete or partial closure of the Sakonnet River at Old Stone Bridge, and the diking of low marsh areas on Conanicut Island. Navigation openings of various depths and widths were considered for the East Passage, West Passage, and Sakonnet River structures, and each combination of openings was assigned a test number for identification purposes.

46. As in the case of the Middle Bay barriers, initial tests of the Lower Bay barriers were made for conditions of the extreme astronomical spring tide range of 5.4 ft at Newport to determine an approximate arrangement of navigation openings to satisfy the conflicting requirements of (1) reduction in hurricane tide elevations at Providence, (2) minimum width of opening specified by the Navy, and (3) reduction of maximum current velocities to those that can be tolerated by navigation. Inasmuch as all these criteria were varied over a wide range during the course of the model study, this report makes no reference to the widths and/or velocities that would be acceptable but only presents data for the various conditions tested in the model. On the basis of the preliminary tests, a Lower Bay barrier plan (designated plan 29 of the model study) was devised and subjected to complete testing. It is pointed out that the refined model roughness adjustment was accomplished prior to the testing of plan 29 as well as all subsequent plans reported herein.

47. The locations of the various components of plan 29 were as described in paragraph 45, and openings for navigation were provided in the West Passage and East Passage structures as shown on fig. 17. The Sakonnet River closure at Old Stone Bridge also had a navigation opening. The West Passage opening had a sill elevation of -40 ft mlw and a sill width of 600 ft; the East Passage opening had a sill elevation of -50 ft mlw and a sill width of 1000 ft; and the Sakonnet River opening had a sill elevation of -30 ft mlw and a sill width of 100 ft. The abutment slopes of the East and West Passage openings were 1.0 vertical on 1.5 horizontal, the slope of the ocean side of the structures was 1.0 vertical on 2.0 horizontal, and the slope of the bay side was 1.0 vertical on 1.5 horizontal. The Sakonnet River opening had vertical sides and was equipped

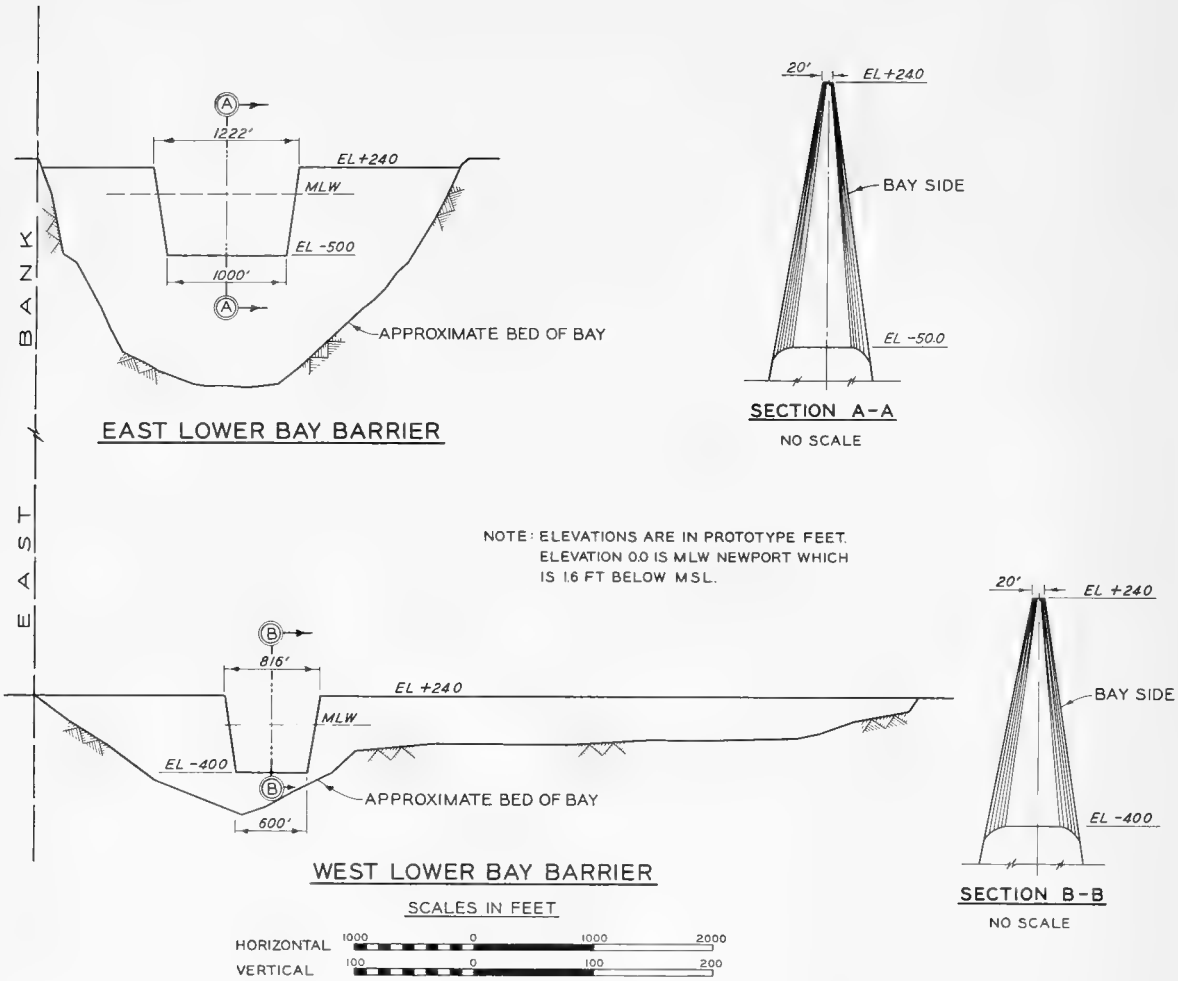

Fig. 17. Details of lower East and West Barriers for plans 29 and 30

with a gate for complete closure or complete opening. All of the structures had a crest elevation of +24 ft mlw. The Sakonnet River opening was closed completely for all astronomical and hurricane tide tests of plan 29.

48. The astronomical tide test of plan 29 was made for conditions of the normal spring tide range of 4.1 ft at Newport, and hurricane tide tests were made for conditions of this astronomical tide in combination with the 1938 hurricane tide and the 20-knot design hurricane tide.

49. The effects of plan 29 on astronomical tide ranges and elevations throughout the bay system are shown in table 2, together with the

effects of the plan on maximum elevations of the 1938 hurricane tide and the 20-knot design hurricane tide. The effect of the plan on times of high tide are shown in table 3. Astronomical tide ranges were reduced at all gages upstream from the barriers, the average reduction being of the order of 25 to 30 per cent, while the times of high water at upstream gages were delayed by as much as 1.8 hours. The peak of the hurricane tide at Providence was lowered from +15.1 ft to +7.8 ft mlw for conditions of the 1938 hurricane tide and from +17.2 ft to +9.1 ft for conditions of the 20-knot design hurricane tide. The maximum elevations of hurricane tides at all other gages upstream from the barriers were appreciably reduced, while the times of high water at these gages were delayed by as much as 2.0 hours. No measurements of current velocities were made in the navigation openings of the East and West Passage structures during model tests of plan 29.

50. It is emphasized that data contained in this report showing the effects of barriers on hurricane tide elevations throughout the bay system apply only to the gravitational component of the hurricane-generated ocean tide; the effects of local wind setup must be added to elevations presented herein to arrive at maximum elevations that would obtain during a hurricane. The reductions in hurricane tide elevations effected by plan 29 at Providence and other points throughout the upper bay appear quite large, but it must be remembered that some damage by hurricane tides begins when the water-surface elevation at Providence exceeds about +6.6 mlw, and this elevation would be exceeded appreciably by adding the wind component to the model test data presented herein.

51. The width of the East Passage navigation opening for plan 29 was considered at that time to be about the minimum that could be tolerated by the Navy. A further reduction in widths or depths of the navigation openings of the plan, which obviously would have been required to reduce the absolute elevation of hurricane tides at Providence below that at which damage begins, was considered untenable at the time. It was therefore concluded that a Lower Bay barrier plan alone, having ungated openings for navigation, could not simultaneously meet the requirements

for complete hurricane tide protection at Providence and at the same time provide a minimum width of ungated opening for navigation that would meet the requirements of the Navy. It was tentatively concluded, therefore, that one of the proposed Upper Bay barrier plans (discussed below) for the complete protection of Providence, in combination with a Lower Bay plan for partial or complete protection of the remainder of the bay system, might provide the most feasible and economical solution of the over-all problem. Testing of Lower Bay barriers was therefore suspended, and testing of the Upper Bay barriers was undertaken to determine which of those proposed would be best for consideration in combination with a Lower Bay barrier plan.

Upper Bay Barriers

52. The two Upper Bay barrier sites investigated in the model were at Field Point and Fox Point (see fig. 15). Provisions for navigation past the Field Point site would be required, since the Providence River navigation project extends upstream beyond Field Point, but no provisions for navigation would be required at the Fox Point site. For the purpose of model tests, it was assumed that proposed barriers at both Field Point and Fox Point would represent complete closures, since the navigation passage through the Field Point structure would be designed for complete closure in event of a hurricane. Provisions would also be made at both barrier sites for pumping upland drainage over the structures, although this feature of the plans was not considered during model tests. The crest elevation of both structures was +24 ft mlw.

53. The Field Point and Fox Point barriers were designated plans 28 and 27, respectively, of the model study. Tests of plans 28 and 27 were made for the same conditions of astronomical and hurricane tides as used for plan 29. The effects of these plans on astronomical tide ranges and elevations, and the effects on hurricane tide heights for conditions of the 1938 hurricane tide and the 20-knot design hurricane tide, are shown in table 2. Their effects on times of astronomical and hurricane high tides throughout the bay system are shown in table 3.

54. The results of the model tests indicated that both the Field Point and Fox Point barriers would provide complete protection to areas upstream from the barrier sites, since no overtopping of the structures by hurricane tides occurred. The effects of these barriers on astronomical and hurricane tide elevations throughout the bay system were negligible. No significant buildup of hurricane tides downstream from the barrier sites occurred for conditions of either of the hurricane tides tested. Elevations observed downstream from the Field Point barrier (plan 28) were slightly lower for the plan tests than for the base tests; however, this small reduction in elevation was caused by the absence of the discharge of the Seekonk River during the tests of this structure (the discharge was introduced during the base tests, but provisions for pumping the discharge over the structure were not provided in the plan tests, so the inflow weir on the Seekonk River was cut off for the plan tests). The Fox Point barrier tests were not affected by river discharge since this barrier was located upstream from the mouth of the Seekonk River.

55. Evaluation of the two upper Bay barriers showed that the Fox Point barrier would not only afford protection to the critical portions of Providence in which maximum damage has been caused by hurricane tides of record but would also be much less costly than the Field Point barrier because of the much greater width of channel and the need for navigation facilities at this latter site. The Fox Point barrier was therefore selected for testing in combination with Lower Bay barrier plans.

Combination Barrier Plans

Preliminary combination barrier plans

56. A total of five preliminary combination barrier plans (plans 30 through 34) were proposed for testing in the model to determine the effects of size of navigation openings in the East and West Passages on astronomical and hurricane tide elevations throughout the bay system. All of these plans incorporated the Fox Point barrier in addition to Lower Bay structures at the locations of those of plan 29, described in

paragraph 45. The locations of the structures of these plans are shown on fig. 15; the details of the West Passage and East Passage navigation openings of plan 30 are shown on fig. 17 and those of the other plans are shown on fig. 18. The navigation opening in the Sakonnet River barrier was similar to that of plan 29 (opening 100 ft wide by 30 ft deep); however, this opening was completely closed for all tests of plans 30 through 34.

57. In plan 30, the first plan including the Fox Point and Lower Bay barriers, the Lower Bay barriers and navigation openings were identical with those of plan 29. The astronomical tide test of plan 30 was made for conditions of the normal spring tide range of 4.1 ft at Newport, and hurricane tide tests were made for this tide in combination with the 1938 hurricane tide and the 20-knot design hurricane tide. The effects of plan 30 on astronomical tide ranges and elevations and on hurricane tide elevations, and its effects on times of high water for both astronomical and hurricane tides are shown in tables 4 and 3, respectively. The effects of this plan on both astronomical and hurricane tides throughout the bay system were almost identical with those of plan 29 described previously. Astronomical tide ranges at gages located upstream from the Lower Bay barriers were reduced by an average of about 23 per cent, and hurricane tide elevations at Providence were lowered from +15.1 ft to +7.9 ft mlw for conditions of the 1938 hurricane tide and from +17.2 ft to +9.1 ft for conditions of the 20-knot design hurricane tide. No current velocity measurements were made in the navigation openings of plan 30.

58. The locations of the barriers in the other plans of this series (31 through 34) were identical with those of plan 30, the only difference between plans in this series being the arrangement and size of navigation openings in the East and West Passages (see fig. 18). The combined areas of the East and West Passage navigation openings for this series of plans, measured at approximately mean-tide level at Newport (+2.0 ft mlw), were as follows: 104,700 sq ft for plan 33; 94,300 sq ft for plan 32; 73,500 sq ft for plan 31; and 71,060 sq ft for plan 34. The comparable area for plan 30 was 83,900 sq ft. The model test conditions (astronomical and

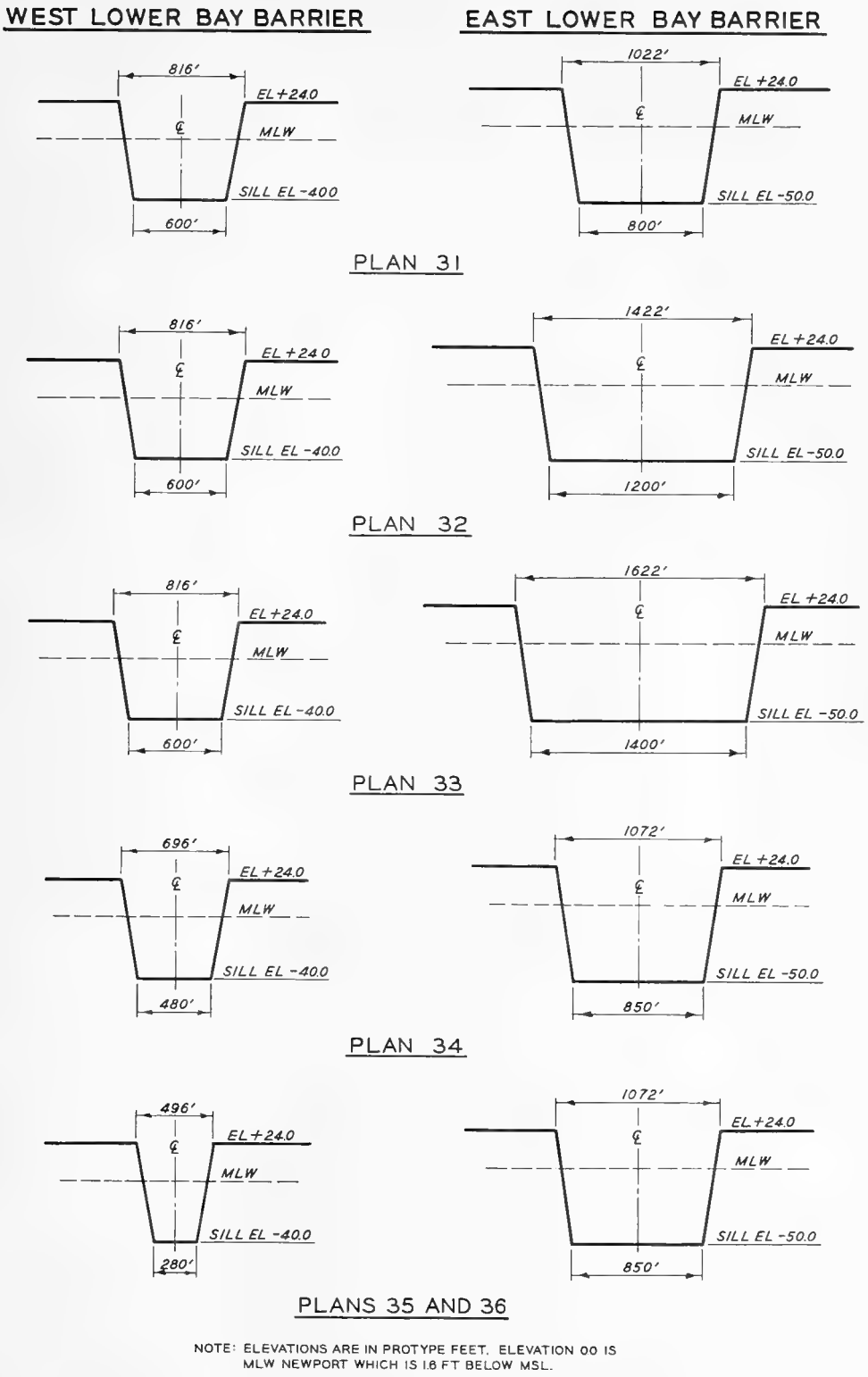

Fig. 18. Details of navigation openings, Lower East and West barriers, plans 31-36

hurricane tides) for these plans were identical with those of plan 30. The results of tests of these plans are presented in numerical order in tables 3 and 4; however, in the interest of clarity, the test results are presented in the following discussion in the order of descending total area of the navigation openings (plan 33, 32, 31, and 34, in that order). Plan 32 was not subjected to tests in the model; instead, the effects of this plan on tidal ranges and elevations were interpolated from the results of tests of other plans in this series.

59. The effects of the plans on astronomical tide ranges and elevations, and on hurricane tide elevations, are shown in table 4, and their effects on times of high tide for both astronomical and hurricane tides are shown in table 3. All of the plans reduced astronomical tide ranges at gages located upstream from the Lower Bay barrier, the average reduction being of the order of 16 per cent for plan 33, 32 per cent for plan 31, and 37 per cent for plan 34; the average reduction in range indicated by plan 30 was about 23 per cent. Based on equivalent areas of navigation opening, it was interpolated that plan 32 would have reduced astronomical tide ranges upstream from the structure by an average of about 19 or 20 per cent.

60. Maximum hurricane tide elevations at Providence for conditions of the 1938 hurricane tide were +8.7 ft mlw for plan 33, +7.2 ft for plan 31, and +7.1 ft for plan 34. The maximum elevation for plan 30 was +7.9 ft, and the interpolated elevation for plan 32 at Providence was about +8.3 ft. For conditions of the 20-knot design hurricane tide, the maximum elevations at Providence were +10.4 ft mlw for plan 33 and +8.6 ft for plan 31; a test of plan 34 for this condition was not included in the testing program. The maximum elevation at Providence for plan 30 for conditions of the 20-knot design hurricane tide was +9.1 ft mlw, and that interpolated for plan 32 was about +9.7 to +9.8 ft. No current velocity measurements were made in the navigation openings of the barriers during tests of this series of plans.

Final combination barrier plans

61. The results of tests of plans 30 through 34 indicated that the minimum size of navigation openings considered (71,060 sq ft for plan 34)

would not provide the desired reduction in hurricane tide elevations throughout the upper bay for conditions of the model tests. Two final combination barrier plans (plans 35 and 36) were proposed for testing in the model, both of which involved a total area of navigation opening somewhat less than that of plan 34 (total area of 62,660 sq ft at mean-tide level for plans 35 and 36 compared to a total area of 71,060 sq ft for plan 34). The barrier locations for plan 35 were identical with those of plans 30 through 34, while those for plan 36 were the same except that the West Passage barrier was moved about 3.0 miles downstream from the Jamestown Bridge. The barrier locations for these plans are shown on fig. 15, and the details of the East Passage and West Passage navigation openings are shown on fig. 18. The Sakonnet River navigation opening was completely open for all astronomical tide tests of plans 35 and 36 and completely closed for all hurricane tide tests of these plans.

62. Plan 35 was subjected to much more detailed testing in the model than were any of the previous barrier plans reported herein. Astronomical tide tests of this plan were made for conditions of the normal spring tide used for previous plan tests, and also for conditions of a mean astronomical tide having a range of 3.6 ft at Newport. Current velocities were measured at a total of 13 stations through the bay for conditions of the normal spring tide, and at surface, one-quarter depth, and one-half depth at three verticals in the East Passage navigation opening and at the same depths on the center line of the West Passage navigation opening for conditions of both spring and mean astronomical tides. In addition, the maximum head differentials across the East Passage navigation opening were observed in the model during astronomical tide tests; these maximum head differentials for both spring and mean tides were then established in the flume containing the undistorted scale models of the navigation openings, and detailed measurements of current velocity distribution in the openings were made. Hurricane tide tests of plan 35 were made for conditions of the normal spring tide combined with the 1938 hurricane tide and the 20-knot design hurricane tide. The maximum head differentials across the East and West Passage navigation openings during the hurricane tide tests were also observed in the model, and

were then established in the flume containing the undistorted scale models of the openings for detailed measurements of current velocity distribution in the openings for these conditions.

63. The effects of plan 35 on astronomical tide ranges and elevations for the two conditions tested are shown separately in table 4. The effects of this plan on hurricane tide elevations are shown in that part of table 4 which presents astronomical spring tide data, since the hurricane tide tests were run in combination with that tide. The effects of the plan on times of high tide for conditions of both astronomical and hurricane tides are shown in table 3. Spring astronomical tide ranges at gages located upstream from the Lower Bay barriers were reduced by an average of about 40 per cent, while mean-tide ranges were reduced by an average of about 37 per cent. The maximum elevations of hurricane tides at Providence were reduced from +15.1 ft mlw to +6.7 ft for conditions of the 1938 hurricane tide and from +17.2 ft to +8.0 ft for conditions of the 20-knot design hurricane tide.

64. The effects of plan 35 on tidal current velocities throughout the bay are shown in table 5. Base test current velocities in this table were obtained for conditions of the normal spring tide and no barriers, while plan test data were obtained for conditions of the same tide with plan 35 installed in the model. The velocity measurements presented in table 5 indicate that both flood and ebb current velocities at stations located upstream from the Lower Bay barriers were reduced, the maximum velocities being reduced by amounts ranging from about 20 per cent to about 60 per cent.

65. Current velocities were measured in the East and West Passage navigation openings of plan 35 for conditions of both spring and mean astronomical tides. Measurements were made at the surface, one-quarter depth, and one-half depth on the center lines of the openings and the centers of the sills. Two additional verticals, located halfway between the center lines and the abutments and also on the centers of the sills were used in the East Passage opening. Velocities observed at the three depths on the center lines of the openings for each hour of a complete tidal cycle are presented in table 6. The additional velocities

observed at verticals on each side of the center line in the East Passage were essentially equal to those on the center lines and are not included in this report. Table 6 includes velocity data for the East and West Passage navigation openings for conditions of both the astronomical tides described above. Maximum flood velocities in the East Passage opening for spring tide conditions ranged from 8.3 ft per sec at middepth to 7.4 ft per sec at the surface, while maximum ebb velocities ranged from 7.6 ft per sec at middepth to 7.3 ft per sec at the surface. For mean-tide conditions, maximum flood velocities ranged from 7.2+ ft per sec at middepth to 6.5 ft per sec at the surface, while maximum ebb velocities ranged from 7.8 ft per sec at middepth to 7.0 ft per sec at the surface. In the West Passage for spring tide conditions, maximum flood velocities ranged from 8.5 ft per sec at middepth to 7.8 ft per sec at the surface, while ebb velocities ranged from 8.3 ft per sec at middepth to 7.0 ft per sec at the surface; for mean-tide conditions, maximum flood velocities ranged from 8.0 ft per sec at middepth to 7.4 ft per sec at the surface, while ebb velocities ranged from 9.0 ft per sec at middepth to 7.5 ft per sec at the surface. An attempt was made to determine the maximum velocity in the Sakonnet River navigation openings for conditions of mean astronomical tide. Accurate velocity measurements in that opening were very difficult to obtain because of the small width of the opening in the model, but the results of measurements made therein indicated the maximum velocity to be of the order of 9.0 ft per sec.

66. Maximum head differentials observed across the East Passage structure for tests with astronomical tides were 1.8 ft for spring tide and 1.3 ft for mean tide. These head differentials were established in the flume containing the undistorted-scale models of the navigation openings, and detailed measurements of velocity distributions for both conditions were made. The lower portion of fig. 19 shows the results of velocity observations made on the center line of the navigation opening, from the upstream edge of the sill to the downstream edge and just above the sill, for conditions of the maximum spring tide head differential of 1.8 ft. These observations indicate that the point of maximum velocity

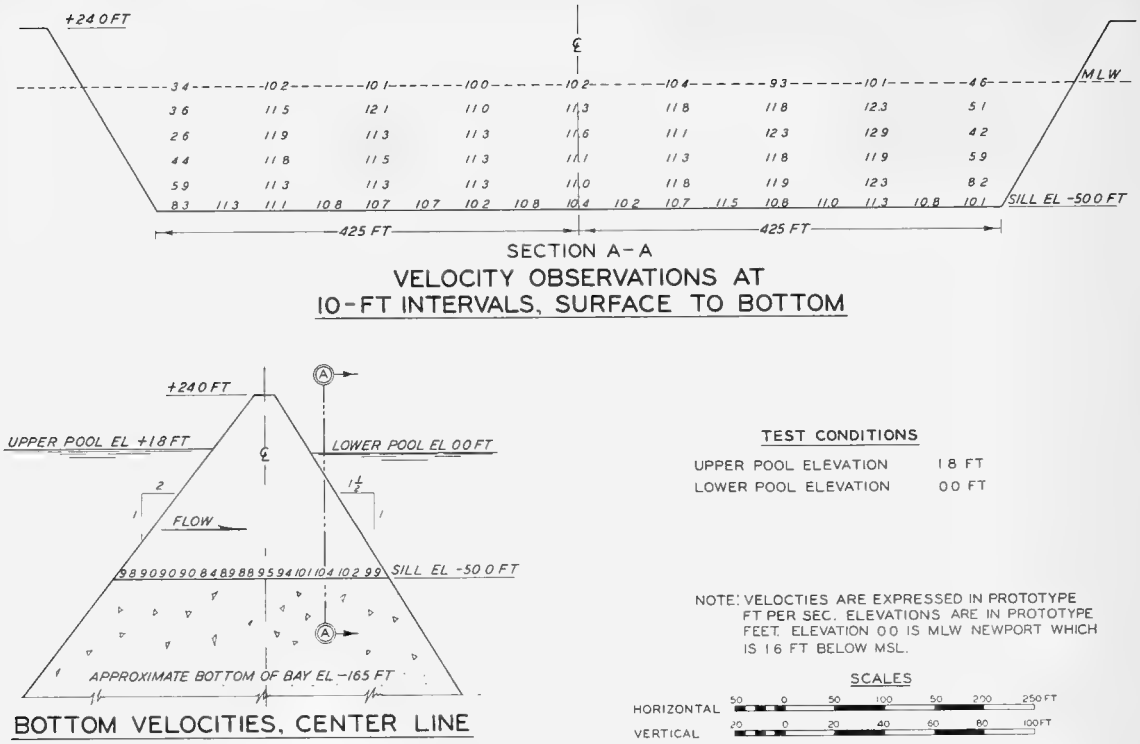

Fig. 19. Velocities in East Passage navigation opening of plan 35 for maximum head differential, astronomical spring tide with 4.1-ft range at Newport

just above the sill (10.4 ft per sec) was about 60 ft downstream from the center of the sill; therefore, detailed measurements were made to determine the distribution of velocities over this entire cross section. The results of these latter measurements are presented in the upper portion of fig. 19. Velocities were measured at 10-ft increments of depth from the surface to the sill at 100-ft increments of width across the navigation opening. These measurements indicate that velocities in the cross section ranged from a minimum of about 2.6 ft per sec to a maximum of about 12.9 ft per sec, the point of maximum velocity being at a depth of about 20 ft below the surface. Similar data for conditions of the maximum mean-tide head differential of 1.3 ft are presented on fig. 20. These data show that velocities in the opening ranged from a minimum of about 2.3 ft per sec to a maximum of about 11.0 ft per sec, the point of maximum velocity being also at a depth of about 20 ft below the surface.

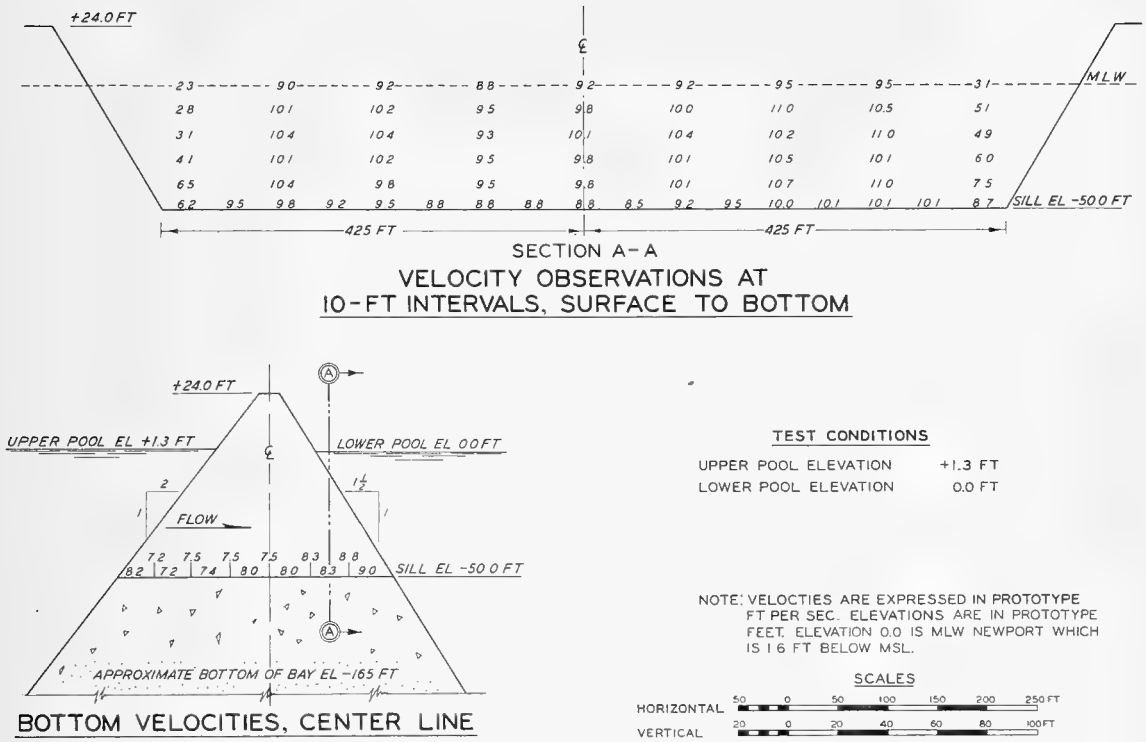

Fig. 20. Velocities in East Passage navigation opening of plan 35 for maximum head differential, astronomical mean tide with 3.6 ft range at Newport

67. Maximum hurricane tide head differentials across the Lower Bay structures of plan 35 occurred for conditions of the 20-knot design hurricane tide and amounted to 9.6 ft in the East Passage and 10.2 ft in the West Passage. These head differentials were established in the flume containing the undistorted scale models of both navigation openings, and detailed velocity measurements were made as described previously for maximum astronomical tide head differentials. Velocity data for the East Passage navigation opening are presented on fig. 21, and those for the West Passage opening are presented on fig. 22. Velocities in the East Passage opening ranged from a minimum of about 0.0 ft per sec near the abutments to a maximum of about 30.9 ft per sec, while those in the West Passage opening ranged from a minimum of about 24.0 ft per sec to a maximum of about 26.5 ft per sec. It was not possible to obtain accurate velocity measurements near the abutments of the openings

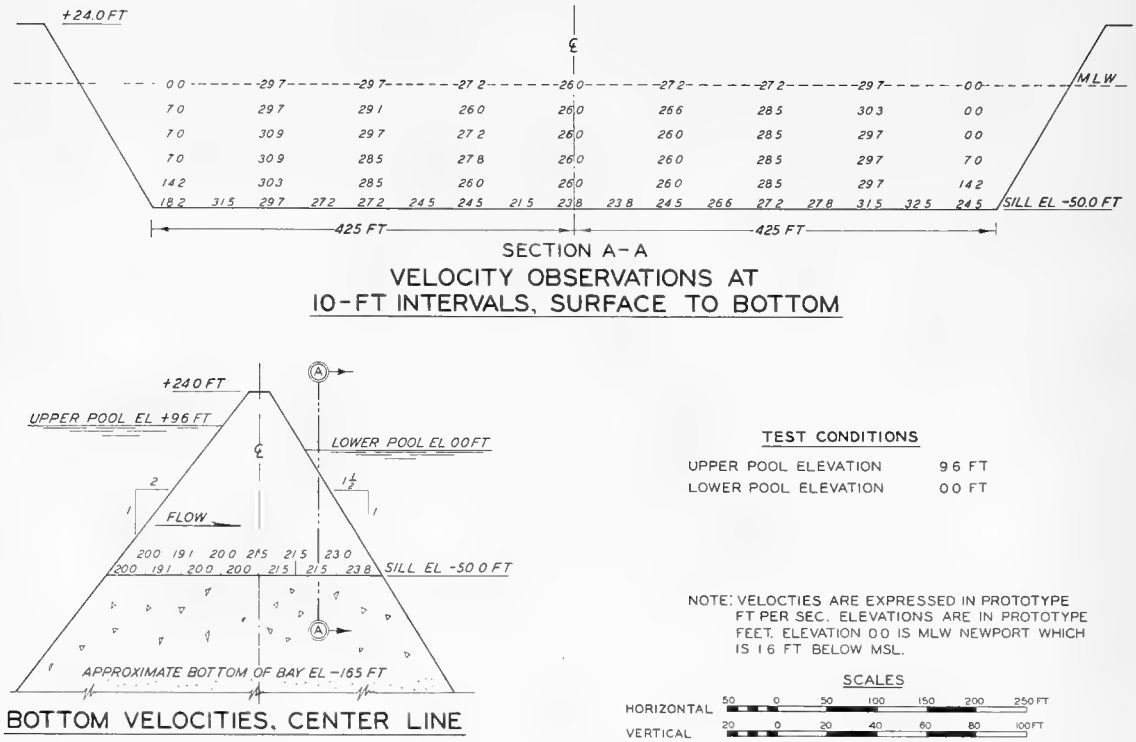

Fig. 21. Velocities in East Passage navigation opening of plan 35 for maximum hurricane tide head differential, 20-knot design hurricane

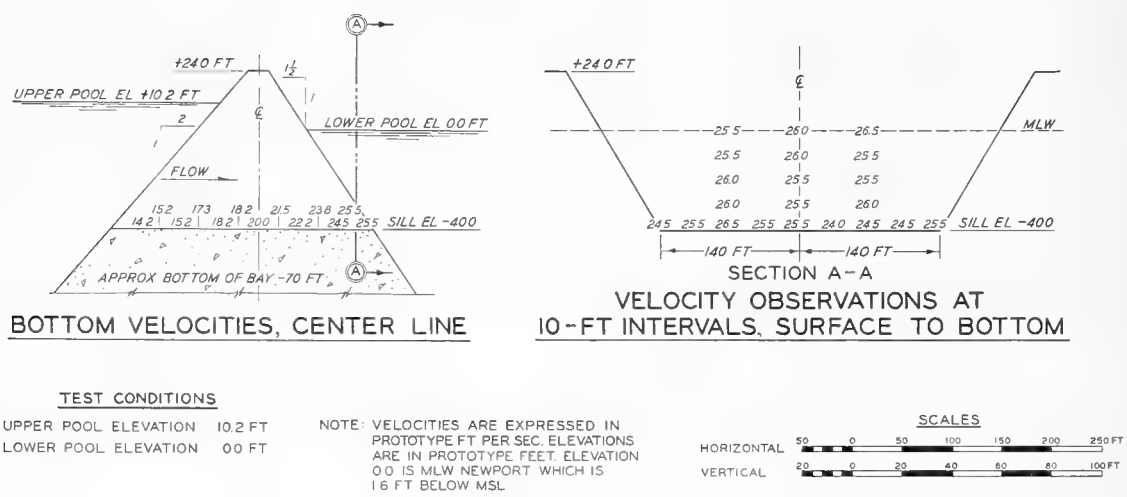

Fig. 22. Velocities in West Passage navigation opening of plan 35 for maximum hurricane tide head differential, 20-knot design hurricane

because of extreme turbulence in those areas.

68. Plan 36 was identical with plan 35 except that the West Passage barrier was moved downstream about 3.0 miles from the Jamestown Bridge (see fig. 15); the sizes of navigation openings for plan 36 were identical with those of plan 35 (see fig. 18). Astronomical tide tests were made of plan 36 for conditions of both spring- and mean-tide ranges, and hurricane tide tests were made for conditions of the astronomical spring tide in combination with the 1938 hurricane tide and the 20-knot design hurricane tide. Current velocities were measured in the East and West Passage navigation openings in the model for conditions of both spring tide and mean tide; however, velocities were not measured at stations throughout the bay for this plan, nor were supplementary velocity measurements made in the flume. Inasmuch as plan 36 was so similar to plan 35, it was considered that the detailed velocity measurements made for the latter plan would be adequate to show the effects of plan 36.

69. The effects of plan 36 on astronomical tide ranges and elevations for conditions of both spring and mean tides are shown separately in table 4; the effects on elevations of hurricane tides are shown in that portion of table 4 presenting astronomical spring tide data, since the hurricane tide tests were made in combination with that tide. The effects of plan 36 on the times of both astronomical and hurricane high tides are shown in table 3. Astronomical tide ranges at gages upstream from the Lower Bay barriers were reduced by an average of about 42 per cent for conditions of spring tide and by an average of about 40 per cent for conditions of mean tide. These average reductions in astronomical tide ranges upstream from the Lower Bay barriers are slightly greater than occurred for plan 35 and are believed attributable to the slight increase in surface area upstream from the barrier resulting from relocation of the West Passage barrier.

70. Plan 36 reduced hurricane tide elevations at Providence from +15.1 ft mlw Newport to +6.0 ft for conditions of the 1938 hurricane tide and from +17.2 ft to +7.1 ft for conditions of the 20-knot design hurricane tide. Hurricane tide elevations at Providence were slightly lower for plan 36 than for plan 35, and this effect is also believed attributable

to the increase in surface area upstream from the Lower Bay barriers.

71. Current velocities in the East and West Passage navigation openings of plan 36 for conditions of spring and mean tides were equal to or slightly greater than those of plan 35. Maximum flood and ebb currents on all verticals and at all depths were generally 0.1 to 0.3 ft per sec greater than for plan 35 because of the increase in tidal prism upstream from the barriers. The slightly greater reduction in astronomical tide ranges for plan 36 caused a minor increase in maximum astronomical tide head differentials across the East and West Passage barriers, which resulted in the minor increases in current velocities in the navigation openings for this plan over those of plan 35. Detailed current velocity data for plan 36 are not presented herein because of their similarity to plan 35 data.

PART V: CONCLUSIONS

Effects of Barriers on Tides

72. Model test data presented herein are considered to be quantitative with respect to the effects of barriers on astronomical tide ranges, elevations, and times, and also with respect to the effects of barriers on the gravitational component of hurricane tides. To obtain information on the absolute elevations that would be attained by hurricane tides at various locations throughout the bay for conditions of the barrier plans tested in the model, the effects of the local winds of the hurricane in question must be applied to the model test data. As pointed out above, all local wind-setup effects have been excluded from the model tests on the basis of computations of this phenomenon by the New England Division. Therefore, conclusions as to the absolute extent of the protection afforded by the barrier arrangements investigated will require consideration of local wind-setup effects which are beyond the scope of this report.

Effects of Barrier Locations on Buildup

73. The model tests indicated that barriers located in the central region of the bay (Middle Bay barrier plans) would cause an appreciable buildup in hurricane tide elevations downstream from the barriers. The tests showed that no appreciable buildup would occur downstream from barriers located near the upper extremity of the bay (Fields Point and Fox Point barriers) nor downstream from those located near the bay entrances (Lower Bay barrier plans). The effects of barrier location on buildup are illustrated on fig. 23, which shows the buildup in feet over maximum base test elevations that occurred immediately downstream from each of the proposed barriers for conditions of the 1938 hurricane tide (the negative buildup shown at the Field Point barriers was caused by cutting off the upland discharge, as explained in paragraph 54).

74. The degree of gravitational buildup or attenuation of an

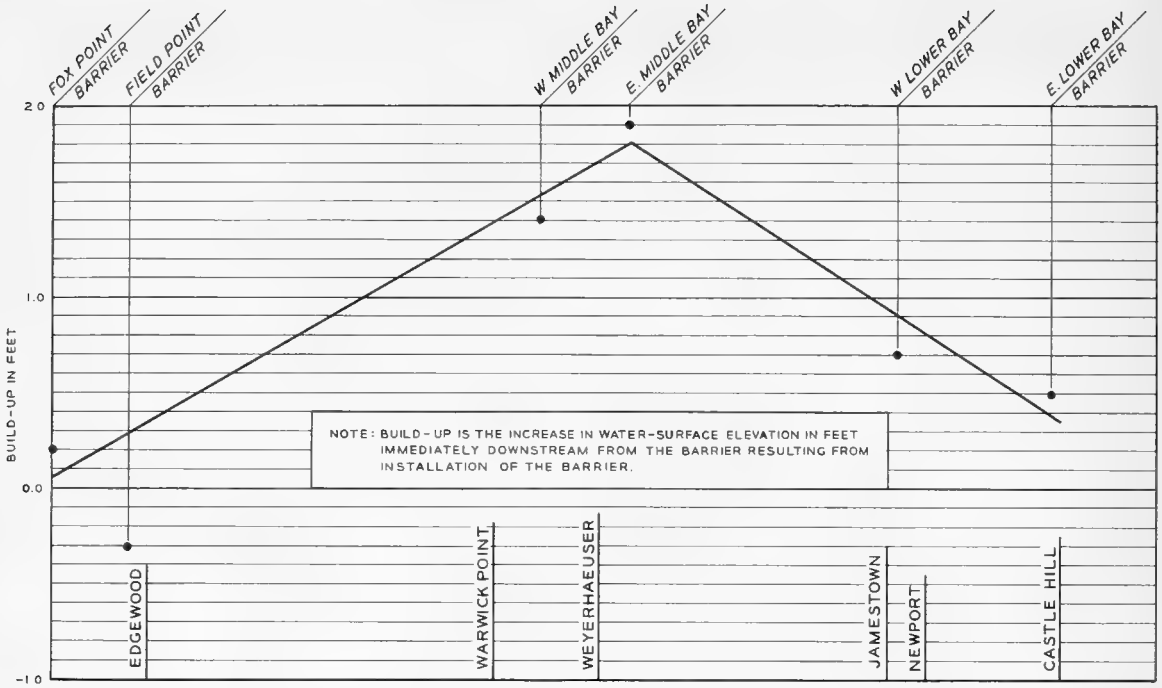

Fig. 23. Effect of barrier location on buildup for conditions of 1938 hurricane tide

astronomical or hurricane-generated tidal wave as it passes through a bay or estuary is affected by the depths, widths, shapes, and other physical characteristics of the system of channels involved. The extent of buildup of hurricane tides in Narragansett Bay for existing conditions may be illustrated by the fact that the gravitational component of the 1938 hurricane tide reached a maximum elevation at Providence (head of the bay) some 3.1 to 3.3 ft higher than at Newport which is near the bay entrance. This same phenomenon occurs for conditions of astronomical tides, since the mean elevation of high tide at Providence is about 0.5 ft higher than at Newport.

75. Construction of a barrier in the bay results in the loss of all or part of the storage (tidal prism) upstream from the barrier site, and the effects of this reduction in storage are reflected by increased elevations downstream from the barrier over those that would obtain without the structure. The reduction in storage effected by the Upper Bay barriers was so small in relation to the total volumes of hurricane tides in the entire bay that no measurable buildup occurred downstream from

these structures. In the case of the Middle Bay barriers, however, the reduction in storage upstream from the structures represented a large percentage of the total bay tidal prism occupied by the hurricane tides tested, and elimination of this storage area resulted in an appreciable buildup downstream from the structures. In the case of Lower Bay barriers, elimination of the entire storage area of Narragansett Bay would have only an infinitesimal effect on tides generated by hurricanes in the open ocean; therefore, no significant buildup occurred on the seaward side of the Lower Bay structures. Such minor buildup as was indicated by model tests seaward of the Lower Bay barriers is thought to be attributable to elimination of local drawdown effects caused by high velocities into the mouth of the bay under existing conditions.

Effects of Barriers on Tidal Currents

76. The effects of the barriers on tidal currents throughout that portion of the bay system upstream from the barrier site would be in almost direct proportion to the effects of the barrier on astronomical tide ranges; a reduction in tidal range of 30 to 40 per cent would be accompanied by similar reductions in tidal current velocities. In areas downstream from the barrier site, the mean velocities of tidal currents would be reduced by a factor representing the total reduction in tidal prism upstream from the area in question. The directions of tidal currents would be altered appreciably in the vicinity of barriers, since restriction of an existing wide channel to a single ungated navigation opening would result in funneling the entire flow through the ungated opening. The use of auxiliary sluice gates, similar to those considered in connection with the Middle Bay barrier plans, would probably prevent undesirable changes in current patterns. Current velocities in the ungated navigation openings of the plans investigated are affected by the design of the opening and the head differential across the structure. Reductions in total area of navigation openings to effect greater protection to upstream areas from hurricane tides increased head differentials across the structures and therefore increased current velocities

in the navigation openings. Undesirable current velocities in ungated navigation openings might also be prevented by use of auxiliary sluice gates as mentioned above.

77. It will be noted that current velocities measured in the navigation openings in the model are appreciably less than those measured in the flume containing the undistorted models of the navigation openings for comparable conditions of head differential. The major difference between velocities for the two conditions is attributable to location of the points of measurement; the verticals observed in the model were located on the center of the sills, while the cross sections observed in the flume were located in the most contracted portion of the jet. Measurements made at identical points in the model and flume for comparable head differentials indicate that use of steady state flows in the flume resulted in velocities about five per cent higher than occurred in the model under tidal flow conditions, for the reason that velocities apparently do not quite attain steady state values under tidal conditions. Velocity data presented on figs. 19 through 22 are therefore considered to be of the order of five per cent higher than can be expected in nature under tidal conditions.

Table 1

Effects of Middle Bay Barriers on Maximum 1938 Hurricane-tide Heights and Times

Location	Base Test		Plan	
	Elevation	Time	Elevation	Time
	Plan 22			
Narragansett Pier	12.1	7.3	12.5	7.3
Marine Laboratory	12.3	7.45	12.8	7.35
Portsmouth	14.9	7.6	16.3	7.6
Newport	12.1	7.45	13.3	7.45
Quonset Point	13.2	7.6	14.6	7.45
Warwick Point	13.7	7.7	4.7	8.9
Bristol Ferry	13.4	7.8	4.6	8.7
Somerset	14.6	8.2	5.3	9.1
Edgewood	15.4	7.9	5.1	9.05
Providence	16.3	7.95	5.2	9.1
Nyatt Point	14.2	7.8	5.0	9.0
Sakonnet Point	12.2	7.3	12.7	7.3
South Middle West Barrier	14.0	7.7	15.1	7.5
South Middle East Barrier	13.5	7.75	14.3	7.6
	Plan 23			
Narragansett Pier	12.1	7.3	12.7	7.3
Marine Laboratory	12.3	7.45	13.2	7.35
Jamestown	12.1	7.5	14.1	7.4
Portsmouth	14.9	7.6	15.9	7.6
Quonset Point	13.2	7.6	15.7	7.45
Davisville Depot	13.7	7.6	15.4	7.5
Newport	12.1	7.45	13.6	7.45
Sakonnet Point	12.2	7.3	12.5	7.3
South Middle West Barrier	14.0	7.7	15.4	7.5
South Middle East Barrier	13.5	7.75	15.4	7.6
Prudence	13.7	7.55	15.3	7.4

Note: Elevations are in prototype feet. Elevation 0.0 is mlw Newport which is 1.6 ft below msl. Times of high tide are expressed in terms of prototype hours after the moon's transit of meridian 71°20'.

Table 2

Effects of Barriers on Tidal Heights

Location	Base Test (Normal Tide)			Plan (Normal Tide)			Base Test (Hurricane Tides)		Plan (Hurricane Tides)	
	High Water	Low Water	Tidal Range	High Water	Low Water	Tidal Range	1938 High Water	20-knot High Water	1938 High Water	20-knot High Water
Plan 27 (Fox Point Barrier)										
Rocky Point	4.2	-0.4	4.6	4.2	-0.3	4.5	13.7	15.8	13.9	15.7
Edgewood*	4.4	-0.6	5.0	3.9	-0.8	4.7	14.9	16.8	14.7	16.8
Providence	4.4	-0.7	5.1	4.1	-0.6	4.7	15.1	17.2	15.3	17.4
South Middle West Barrier	4.2	-0.5	4.7	4.1	-0.4	4.5	13.4	15.7	14.0	15.8
Nyatt Point	4.2	-0.5	4.7	4.2	-0.4	4.6	13.6	15.6	14.2	15.6
Bullock Point	4.4	-0.4	4.8	4.2	-0.5	4.7	14.5	16.6	14.7	16.8
Plan 28 (Field Point Barrier)										
Rocky Point	4.2	-0.4	4.6	4.3	-0.4	4.7	13.7	15.8	13.7	15.7
Edgewood*	4.4	-0.6	5.0	3.8	-0.9	4.7	14.9	16.8	14.6	16.2
South Middle East Barrier	4.3	-0.3	4.6	4.6	0.0	4.6	13.0	15.3	13.6	15.5
South Middle West Barrier	4.2	-0.5	4.7	4.2	-0.2	4.4	13.4	15.7	13.7	15.6
Nyatt Point	4.2	-0.5	4.7	4.2	-0.6	4.8	13.6	15.6	14.2	15.7
Bullock Point	4.4	-0.4	4.8	4.6	-0.2	4.8	14.5	16.6	15.0	16.8
Plan 29 (Lower Bay Barriers)										
Jamestown	3.9	-0.2	4.1	3.9	0.1	3.8	11.9	14.3	14.7	15.7
Quonset Point*	4.0	-0.4	4.4	3.8	0.5	3.3	12.9	14.7	7.2	8.6
Warwick Point*	4.2	-0.5	4.7	3.8	0.4	3.4	13.5	15.3	7.2	8.8
Rocky Point	4.2	-0.4	4.6	3.8	0.4	3.4	13.7	15.8	6.9	8.7
Edgewood*	4.4	-0.6	5.0	3.8	0.2	3.6	14.9	16.8	7.2	9.0
Providence	4.4	-0.7	5.1	4.1	0.5	3.6	15.1	17.2	7.8	9.1
Fort Wetherill*	4.0	-0.1	4.1	4.1	0.1	4.0	11.5	13.7	13.5	15.3
Newport*	4.1	0.0	4.1	3.7	0.4	3.3	12.3	14.4	7.2	8.4
M-15	4.2	-0.5	4.7	3.6	0.5	3.1	12.5	14.5	6.9	8.4
South Middle East Barrier	4.3	-0.3	4.6	3.8	0.4	3.4	13.0	15.3	7.0	8.6
Bristol Harbor	4.4	-0.3	4.7	4.0	0.4	3.6	13.8	15.9	7.5	8.9
Nyatt Point	4.2	-0.5	4.7	3.9	0.4	3.5	13.6	15.6	7.2	9.0
Portsmouth	4.2	-0.2	4.4	3.9	-0.1	4.0	14.2	16.0	17.2	18.1
Somerset	4.7	-0.4	5.1	4.1	0.4	3.7	14.2	16.2	7.7	8.9

Note: Elevations are in prototype feet. Elevation 0.0 is mlw Newport which is 1.6 ft below msl.

* Base test astronomical tide heights were observed on permanent-type point gages and are accurate to less than 0.1 ft prototype. All other tide heights were obtained from recording-type tide gages and are subject to errors of ±0.2 ft prototype.

Table 3

Effect of Lower Bay Barriers on Times of High Water

Location	Base Tests			Plan		
	Normal	1938 Hurricane Tide	20-knot Design Hurricane	Normal	1938 Hurricane Tide	20-knot Design Hurricane
			Plan 27			
Rocky Point	7.8	7.7	7.6	8.3	7.7	7.6
Edgewood	7.8	7.9	7.7	8.5	7.8	7.7
Providence	7.8	7.9	7.8	8.5	7.8	7.7
South Middle West Barrier	7.8	7.7	7.5	8.3	7.7	7.6
Nyatt Point	7.8	7.8	7.6	8.4	7.8	7.6
Bullock Point	7.8	7.8	7.7	8.4	7.8	7.6
			Plan 28			
Rocky Point	7.8	7.7	7.6	7.8	7.7	7.6
Edgewood	7.8	7.9	7.7	7.9	7.9	7.6
South Middle East Barrier	7.7	7.7	7.7	7.7	7.7	7.7
South Middle West Barrier	7.8	7.7	7.5	7.8	7.7	7.5
Nyatt Point	7.8	7.8	7.6	7.8	7.8	7.6
Bullock Point	7.8	7.8	7.7	7.8	7.8	7.6
			Plan 29			
Jamestown	7.7	7.5	7.4	7.3	7.3	7.3
Quonset Point	7.7	7.6	7.5	9.1	8.7	9.0
Warwick Point	7.8	7.7	7.5	9.3	8.8	9.1
Rocky Point	7.8	7.7	7.6	9.4	8.9	9.2
Edgewood	7.8	7.9	7.7	9.6	9.1	9.4
Providence	7.8	7.9	7.8	9.7	9.2	9.5
Fort Wetherill	7.6	7.4	7.2	7.8	7.3	7.3
Newport	7.7	7.4	7.3	8.9	8.5	8.7
M-15	7.7	7.6	7.5	9.1	8.6	8.9
South Middle East Barrier	7.7	7.7	7.7	9.2	8.8	9.0
Bristol Harbor	7.8	7.8	7.7	9.3	8.9	9.1
Nyatt Point	7.8	7.8	7.6	9.5	9.0	9.3
Portsmouth	7.7	7.6	7.5	7.7	7.6	7.6
Somerset	7.8	8.2	8.0	9.7	9.2	9.5
			Plan 30			
Jamestown	7.7	7.5	7.4	7.3	7.3	7.3
Quonset Point	7.7	7.6	7.5	9.1	8.7	9.0
Warwick Point	7.8	7.7	7.5	9.3	8.8	9.1
Rocky Point	7.8	7.7	7.6	9.4	8.9	9.2
Edgewood	7.8	7.9	7.7	9.6	9.1	9.4
Providence	7.8	7.9	7.8	9.7	9.2	9.5
Fort Wetherill	7.6	7.4	7.2	7.8	7.3	7.3
Newport	7.7	7.4	7.3	8.9	8.5	8.7
M-15	7.7	7.6	7.5	9.1	8.6	8.9
South Middle East Barrier	7.7	7.7	7.7	9.2	8.8	9.0
Bristol Harbor	7.8	7.8	7.7	9.3	8.9	9.1
Nyatt Point	7.8	7.8	7.6	9.5	9.0	9.3
Portsmouth	7.7	7.6	7.5	7.7	7.6	7.6
Somerset	7.8	8.2	8.0	9.7	9.2	9.5
			Plan 31			
Jamestown	7.7	7.5	7.4	7.3	7.3	7.3
Quonset Point	7.7	7.6	7.5	9.3	8.9	9.2
Providence	7.8	7.9	7.8	9.9	9.4	9.7
Fort Wetherill	7.6	7.4	7.2	7.8	7.3	7.3
Newport	7.7	7.4	7.3	9.1	8.7	8.9
South Middle East Barrier	7.7	7.7	7.7	9.4	9.0	9.2
Somerset	7.8	8.2	8.0	9.9	9.5	9.8

(Continued)

Table 3 (Continued)

Location	Base Tests			Plan		
	Normal	1938 Hurricane Tide	20-knot Design Hurricane	Normal	1938 Hurricane Tide	20-knot Design Hurricane
			Plan 33			
Jamestown	7.7	7.5	7.4	7.3	7.3	7.3
Quonset Point	7.7	7.6	7.5	8.8	8.3	8.6
Providence	7.8	7.9	7.8	9.4	8.8	9.1
Fort Wetherill	7.6	7.4	7.2	7.8	7.3	7.3
Newport	7.7	7.4	7.3	8.7	8.2	8.5
South Middle East Barrier	7.7	7.7	7.7	8.9	8.5	8.8
Somerset	7.8	8.2	8.0	9.4	8.9	9.2
			Plan 34			
Jamestown	7.7	7.5	---	9.2	7.3	---
Quonset Point	7.7	7.6	---	9.4	9.0	---
Providence	7.8	7.9	---	9.9	9.5	---
Fort Wetherill	7.6	7.4	---	7.7	7.3	---
Newport	7.7	7.4	---	9.1	8.8	---
South Middle East Barrier	7.7	7.7	---	9.5	9.1	---
Somerset	7.8	8.2	---	9.9	9.6	---
			Plan 35			
Narragansett Pier	7.6	7.3	7.1	7.7	7.2	7.2
Marine Laboratory	7.7	7.4	7.3	7.8	7.3	7.3
Jamestown	7.7	7.5	7.4	9.3	7.3	7.3
Quonset Point	7.7	7.6	7.5	9.5	9.1	9.4
Davisville Depot	7.7	7.6	7.5	9.5	9.2	9.4
Cedar Tree Point	7.8	7.7	7.6	9.7	9.4	9.6
Warwick Point	7.8	7.7	7.5	9.7	9.3	9.6
Rocky Point	7.8	7.7	7.6	9.7	9.4	9.6
Edgewood	7.8	7.9	7.7	10.0	9.6	9.9
Providence	7.8	7.9	7.8	10.1	9.7	10.0
Fort Wetherill	7.6	7.4	7.2	7.8	7.3	7.3
Newport	7.7	7.4	7.3	9.3	9.0	9.2
M-15	7.7	7.6	7.5	9.5	9.2	9.4
South Middle East Barrier	7.7	7.7	7.7	9.7	9.4	9.6
Prudence	7.7	7.5	7.4	9.5	9.1	9.4
South Middle West Barrier	7.8	7.7	7.5	9.6	9.3	9.5
Bristol Harbor	7.8	7.8	7.7	9.8	9.5	9.7
Nyatt Point	7.8	7.8	7.6	9.8	9.5	9.7
Bullock Point	7.8	7.8	7.7	9.9	9.5	9.8
Sakonnet Point	7.6	7.4	7.3	7.6	7.4	7.4
Portsmouth	7.7	7.6	7.5	7.7	7.6	7.6
Bristol Ferry	7.7	7.8	7.7	9.8	9.5	9.7
Kickamuit River	7.8	7.9	7.8	10.0	9.7	9.9
North Tiverton	7.7	7.9	7.8	9.9	9.6	9.8
Brayton Point	7.7	8.0	7.8	9.9	9.6	9.8
Somerset	7.8	8.2	8.0	10.1	9.8	10.0
Ocean Control	7.6	7.2	6.9	7.6	7.2	7.2
			Plan 36			
Marine Laboratory	7.7	7.4	7.3	9.5	9.0	9.3
Jamestown	7.7	7.5	7.4	9.6	9.1	9.4
Warwick Point	7.8	7.7	7.5	9.7	9.3	9.6
Providence	7.8	7.9	7.8	10.1	9.7	10.0
Fort Wetherill	7.6	7.4	7.2	7.8	7.3	7.3
South Middle East Barrier	7.7	7.7	7.7	9.7	9.4	9.6
Somerset	7.8	8.2	8.0	10.1	9.8	10.0

Note: Times of high tide are expressed in terms of prototype hours after the moon's transit of meridian 71°21'. A spring astronomical tide having a 4.1-ft range at Newport was used for all tests.

Table 4

Effects of Lower Bay-Fox Point Barriers on Tidal Heights

Location	Base Test (Normal Tide) High Water	Base Test (Normal Tide) Low Water	Base Test (Normal Tide) Tidal Range	Plan (Normal Tide) High Water	Plan (Normal Tide) Low Water	Plan (Normal Tide) Tidal Range	Base Test (Hurricane Tide) 1938 High Water	Base Test (Hurricane Tide) 20-knot High Water	Plan (Hurricane Tide) 1938 High Water	Plan (Hurricane Tide) 20-knot High Water
				Plan 30						
Jamestown	3.9	-0.2	4.1	3.8	0.2	3.6	11.9	14.3	14.8	15.5
Quonset Point	4.0	-0.4	4.4	3.8	0.5	3.3	12.9	14.7	7.2	8.5
Warwick Point	4.2	-0.5	4.7	3.9	0.4	3.5	13.5	15.3	7.2	8.7
Rocky Point	4.2	-0.4	4.6	3.8	0.4	3.4	13.7	15.8	6.9	8.7
Edgewood	4.4	-0.6	5.0	4.0	0.2	3.8	14.9	16.8	7.2	9.0
Providence	4.4	-0.7	5.1	4.1	0.3	3.8	15.1	17.2	7.9	9.1
Fort Wetherill	4.0	-0.1	4.1	4.0	0.1	3.9	11.5	13.7	13.5	15.1
Newport	4.0	-0.1	4.1	3.6	0.6	3.0	12.3	14.4	7.2	8.3
M-15	4.2	-0.5	4.7	3.6	0.4	3.2	12.5	14.5	6.8	8.4
South Middle East Barrier	4.3	-0.3	4.6	3.7	0.4	3.3	13.0	15.3	7.0	8.5
Bristol Harbor	4.4	-0.3	4.7	3.9	0.3	3.6	13.8	15.9	7.4	8.9
Nyatt Point	4.2	-0.5	4.7	4.0	0.3	3.7	13.6	15.6	7.3	9.0
Portsmouth	4.2	-0.2	4.4	4.0	-0.4	4.4	14.2	16.0	17.2	18.0
Somerset	4.7	-0.4	5.1	4.0	0.1	3.9	14.2	16.2	7.5	8.7
				Plan 31						
Jamestown	3.9	-0.2	4.1	4.1	0.1	4.0	11.9	14.3	14.3	15.1
Quonset Point	4.0	-0.4	4.4	3.7	0.8	2.9	12.9	14.7	6.7	8.3
Providence	4.4	-0.7	5.1	3.8	0.5	3.3	15.1	17.2	7.2	8.6
Fort Wetherill	4.0	-0.1	4.1	4.0	0.2	3.8	11.5	13.7	13.2	14.8
Newport	4.0	-0.1	4.1	3.6	0.8	2.8	12.3	14.4	6.7	8.0
South Middle East Barrier	4.3	-0.3	4.6	3.7	0.7	3.0	13.0	15.3	6.6	8.2
Somerset	4.7	-0.4	5.1	3.8	0.4	3.4	14.2	16.2	6.9	8.6
				Plan 33						
Jamestown	3.9	-0.2	4.1	4.1	0.1	4.0	11.9	14.3	14.8	15.2
Quonset Point	4.0	-0.4	4.4	4.1	0.4	3.7	12.9	14.7	8.1	9.8
Providence	4.4	-0.7	5.1	4.3	0.1	4.2	15.1	17.2	8.7	10.4
Fort Wetherill	4.0	-0.1	4.1	4.2	0.4	3.8	11.5	13.7	13.3	14.7
Newport	4.0	-0.1	4.1	3.9	0.5	3.4	12.3	14.4	8.2	9.7
South Middle East Barrier	4.3	-0.3	4.6	4.2	0.3	3.9	13.0	15.3	8.2	9.8
Somerset	4.7	-0.4	5.1	4.2	0.1	4.1	14.2	16.2	8.8	10.1
				Plan 34						
Jamestown	3.9	-0.2	4.1	3.9	0.0	3.9	11.9	----	14.5	----
Quonset Point	4.0	-0.4	4.4	3.5	0.8	2.7	12.9	----	6.3	----
Providence	4.4	-0.7	5.1	3.7	0.5	3.2	15.1	----	7.1	----
Fort Wetherill	4.2	-0.1	4.3	4.0	0.1	3.9	11.5	----	13.3	----
Newport	4.2	0.1	4.1	3.3	0.7	2.6	12.3	----	6.6	----
South Middle East Barrier	4.3	-0.3	4.6	3.6	0.7	2.9	13.0	----	6.3	----
Somerset	4.7	-0.4	5.1	3.7	0.5	3.2	14.2	----	6.7	----
				Plan 35						
Narragansett Pier	3.8	0.1	3.7	3.8	0.0	3.8	12.4	13.7	11.3	13.8
Marine Laboratory*	3.9	-0.3	4.2	3.8	0.0	3.8	12.1	14.0	12.0	13.8
Jamestown	3.9	-0.2	4.1	4.0	0.0	4.0	11.9	14.3	12.7	14.1
Quonset Point*	4.0	-0.4	4.4	3.2	0.6	2.6	12.9	14.7	5.8	7.0
Davisville Depot	4.5	-0.2	4.7	3.3	0.7	2.6	13.2	15.7	6.2	7.2
Cedar Tree Point	4.2	-0.3	4.5	3.5	0.8	2.7	13.5	15.8	6.2	7.3
Warwick Point*	4.2	-0.5	4.7	3.4	0.5	2.9	13.5	15.3	6.0	7.4
Rocky Point	4.2	-0.4	4.6	3.6	0.7	2.9	13.7	15.8	6.1	7.3
Edgewood*	4.4	-0.6	5.0	3.3	0.3	3.0	14.9	16.8	6.0	7.2
Providence	4.4	-0.7	5.1	3.7	0.7	3.0	15.1	17.2	6.7	8.0
Fort Wetherill*	4.0	-0.1	4.1	3.8	-0.2	4.0	11.5	13.7	12.1	14.0
Newport*	4.1	0.0	4.1	3.3	0.8	2.5	12.3	14.4	6.1	7.5
M-15	4.2	-0.5	4.7	3.4	0.7	2.7	12.5	14.5	6.0	7.4
South Middle East Barrier	4.3	-0.3	4.6	3.4	0.6	2.8	13.0	15.3	6.2	7.4
Prudence	4.4	-0.2	4.6	3.3	0.6	2.7	13.4	15.5	6.0	7.1
South Middle West Barrier	4.2	-0.5	4.7	3.3	0.4	2.9	13.4	15.7	5.9	7.1
Bristol Harbor	4.4	-0.3	4.7	3.3	0.7	2.6	13.8	15.9	6.2	7.5
Warren River	4.8	0.3	4.5	3.5	0.7	2.8	12.7	14.8	6.0	7.2
Nyatt Point	4.2	-0.5	4.7	3.5	0.7	2.8	13.6	15.6	6.1	7.2
Bullock Point	4.4	-0.4	4.8	3.4	0.5	2.9	14.5	16.6	6.0	7.2
Sakonnet Point	4.4	-0.1	4.5	3.8	0.0	3.8	11.9	14.2	12.3	14.1
Portsmouth	4.2	-0.2	4.4	4.0	0.2	3.8	14.2	16.0	17.2	18.1
Bristol Ferry	4.2	-0.4	4.6	3.4	0.5	2.9	13.5	15.7	6.0	7.0
Kickamuit River	4.3	----	---	3.6	0.8	2.8	13.5	15.7	6.1	7.4
North Tiverton	4.3	-0.3	4.6	3.5	0.6	2.9	13.4	15.3	6.0	7.3
Brayton Point	4.3	-0.7	5.0	3.5	0.5	3.0	13.5	15.5	6.1	7.4
Somerset	4.7	-0.4	5.1	3.6	0.5	3.1	14.2	16.2	6.2	7.7
Weyerhaeuser*	4.2	-0.4	4.6	3.4	0.5	2.9	----	----	----	----
Fall River*	4.5	-0.5	5.0	3.4	0.3	3.1	----	----	----	----
Ocean Control*	3.8	0.0	3.8	3.8	0.0	3.8	12.3	13.6	12.0	13.7

(Continued)

Table 4 (Continued)

Location	Base Test (Normal Tide) High Water	Base Test (Normal Tide) Low Water	Base Test (Normal Tide) Tidal Range	Plan (Normal Tide) High Water	Plan (Normal Tide) Low Water	Plan (Normal Tide) Tidal Range	Base Test (Hurricane Tide) 1938 High Water	Base Test (Hurricane Tide) 20-knot High Water	Plan (Hurricane Tide) 1938 High Water	Plan (Hurricane Tide) 20-knot High Water
				Plan 36						
Marine Laboratory*	3.9	-0.3	4.2	3.2	0.8	2.4	12.1	14.0	5.3	6.6
Jamestown	3.9	-0.2	4.1	3.2	0.8	2.4	11.9	14.3	5.5	6.8
Warwick Point*	4.2	-0.5	4.7	3.2	0.6	2.6	13.5	15.3	5.8	6.6
Providence	4.4	-0.7	5.1	3.2	0.4	2.8	15.1	17.2	6.0	7.1
Fort Wetherill*	4.0	-0.1	4.1	3.8	-0.2	4.0	11.5	13.7	12.2	13.5
South Middle East Barrier	4.3	-0.3	4.6	3.3	0.7	2.6	13.0	15.3	6.0	7.1
Somerset	4.7	-0.4	5.1	3.5	0.7	2.8	14.2	16.2	6.2	7.3
	Plan 35 (Mean Astronomical Tide, 3.6-ft Range at Newport)									
Marine Laboratory*	3.7	0.1	3.6	3.5	0.1	3.4	----	----	----	----
Jamestown*	3.7	0.1	3.6	3.5	0.0	3.5	----	----	----	----
Quonset Point*	3.6	-0.2	3.8	2.8	0.4	2.4	----	----	----	----
Warwick Point*	3.8	-0.3	4.1	3.0	0.4	2.6	----	----	----	----
Edgewood*	3.8	-0.5	4.3	3.0	0.2	2.8	----	----	----	----
Fort Wetherill*	3.6	0.1	3.5	3.5	-0.1	3.6	----	----	----	----
Newport*	3.7	0.1	3.6	2.9	0.6	2.3	----	----	----	----
North Lower West Barrier*	3.8	0.1	3.7	2.9	0.6	2.3	----	----	----	----
North Lower East Barrier*	3.6	0.0	3.6	2.8	0.6	2.2	----	----	----	----
Weyerhaeuser*	3.9	-0.2	4.1	3.0	0.5	2.5	----	----	----	----
Fall River*	3.9	-0.5	4.4	3.2	0.3	2.9	----	----	----	----
Ocean Control	3.6	0.1	3.5	3.6	0.1	3.5	----	----	----	----
	Plan 36 (Mean Astronomical Tide, 3.6-ft Range at Newport)									
South Lower West Barrier*	3.7	0.1	3.6	3.2	-0.2	3.4	----	----	----	----
North Lower West Barrier*	3.8	0.1	3.7	2.8	0.6	2.2	----	----	----	----
Marine Laboratory*	3.7	0.1	3.6	2.9	0.7	2.2	----	----	----	----
Quonset Point*	3.6	-0.2	3.8	2.9	0.6	2.3	----	----	----	----
Warwick Point*	3.8	-0.3	4.1	3.0	0.6	2.4	----	----	----	----
Edgewood*	3.8	-0.5	4.3	3.1	0.5	2.6	----	----	----	----
Fort Wetherill*	3.6	0.1	3.5	3.3	-0.1	3.4	----	----	----	----
North Lower East Barrier*	3.6	0.0	3.6	2.8	0.7	2.1	----	----	----	----
Newport*	3.7	0.1	3.6	2.9	0.8	2.1	----	----	----	----
Weyerhaeuser*	3.9	-0.2	4.1	3.0	0.5	2.5	----	----	----	----
Fall River*	3.9	-0.5	4.4	3.2	0.6	2.6	----	----	----	----
Ocean Control*	3.6	0.1	3.5	3.6	0.1	3.5	----	----	----	----

Note: A spring astronomical tide having a 4.1-ft range at Newport was used for all tests. Additional tests of plans 35 and 36 were made using a mean tide having a 3.6-ft range at Newport. Elevations are in prototype feet. Elevation 0.0 is mlw Newport which is 1.6 ft below msl.

* Base test and plan astronomical tide heights for plans 35 and 36 at locations indicated were observed on permanent-type point gages and are accurate to less than 0.1 ft prototype. All other tide heights were obtained from recording-type tide gages and are subject to errors of ±0.2 ft prototype.

Table 5

Plan 35

Effects of Plan 35 on Current Velocities throughout Bay System (ft/sec, Prototype)

Spring Tide

Hour	Station 1		Station 2		Station 4		Station 5		Station 6		Station 7		Station 8		Station 9		Station 10		Station 11		Station 12		Station 13		Station 14	
	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan	Base	Plan
0.0	-1.3	-1.7	-2.5	-2.8	-1.3	-0.7	-0.5	-0.3	-1.5	-0.7	-0.8	-0.7	-1.0	-0.6	-1.0	-0.5	-1.3	-0.6	-0.3	-0.5	-0.7	-0.5	-0.8	-0.4	-0.5	-0.2
0.5	-0.9	-2.0	-2.2	-2.7	-1.0	-0.6	-0.5	-0.2	-1.4	-0.7	-0.6	-0.6	-0.6	-0.3	-0.9	-0.5	-1.2	-0.5	-0.4	-0.5	-0.5	-0.5	-0.7	-0.4	-0.5	-0.2
1.0	-0.5	-2.9	-1.4	-2.5	-0.5	-0.7	-0.4	-0.2	-1.1	-0.5	-0.2	-0.5	-0.4	-0.4	-0.7	-0.6	-1.1	-0.6	-0.3	-0.4	-0.2	-0.5	-0.4	-0.5	-0.4	-0.2
1.5	0.0	-3.0	-0.8	-3.2	0.0	-0.6	-0.5	-0.2	-0.8	-0.5	-0.0	-0.3	-0.3	-0.5	-0.3	-0.5	-0.6	-0.5	-0.1	-0.4	0.0	-0.4	-0.2	-0.5	-0.2	-0.2
2.0	0.2	-2.8	-0.3	-3.3	0.3	-0.6	-0.2	-0.2	-0.2	-0.6	0.3	0.0	-0.1	-0.4	0.0	-0.4	-0.3	-0.5	0.1	-0.3	0.2	-0.3	0.0	-0.6	-0.2	-0.2
2.5	0.6	-1.3	0.7	-2.7	0.5	-0.5	0.1	-0.2	0.2	-0.6	0.7	0.1	0.1	-0.4	0.3	-0.3	0.1	-0.5	0.4	-0.2	0.4	0.0	0.3	-0.6	0.2	0.0
3.0	1.0	0.5	0.8	-2.0	1.0	-0.3	0.4	0.0	0.6	-0.4	0.9	0.2	0.5	-0.3	0.6	-0.2	0.5	-0.5	0.5	-0.1	0.6	0.1	0.6	-0.5	0.4	0.0
3.5	1.7	1.0	0.9	-0.8	1.7	0.0	0.5	0.1	1.3	0.0	1.0	0.4	0.8	-0.1	0.8	0.0	0.8	-0.3	0.5	0.0	0.7	0.3	0.7	-0.3	0.6	0.2
4.0	1.9	1.0	1.0	0.6	1.9	0.4	0.4	0.2	1.5	0.2	1.1	0.5	0.9	0.0	1.0	0.0	1.2	-0.1	0.8	0.2	0.8	0.5	0.8	0.0	0.8	0.3
4.5	2.2	1.0	1.3	1.3	1.8	0.9	0.5	0.3	1.8	0.5	1.1	0.6	1.1	0.3	1.0	0.3	1.3	0.2	0.7	0.3	1.0	0.6	0.9	0.3	0.9	0.3
5.0	2.4	0.8	1.4	1.4	1.7	1.0	0.6	0.3	1.9	0.7	1.1	0.9	1.2	0.4	1.0	0.4	1.4	0.5	0.5	0.4	1.0	0.6	1.0	0.5	0.9	0.4
5.5	2.0	0.7	1.3	0.9	1.5	1.0	0.6	0.3	1.8	0.7	1.1	0.7	1.1	0.5	0.9	0.3	1.3	0.5	0.5	0.4	1.0	0.6	1.0	0.6	0.6	0.4
6.0	1.5	0.9	1.0	0.9	1.3	0.9	0.5	0.4	1.5	0.7	1.0	0.5	1.0	0.5	0.7	0.2	1.2	0.6	0.5	0.3	1.0	0.6	0.9	0.5	0.5	0.5
6.5	1.4	1.0	0.8	1.0	0.9	0.9	0.1	0.4	1.4	0.7	0.8	0.4	0.8	0.3	0.5	0.3	1.1	0.7	0.5	0.3	1.0	0.8	0.7	0.4	0.4	0.5
7.0	1.2	1.0	0.7	1.1	0.7	0.9	0.0	0.5	1.1	0.7	0.5	0.5	0.6	0.3	0.4	0.4	0.9	0.7	0.1	0.3	0.8	1.3	0.4	0.4	0.2	0.4
7.5	0.7	0.8	0.2	0.9	0.4	0.8	0.0	0.5	0.4	0.8	0.1	0.5	0.3	0.4	0.0	0.4	0.5	0.8	-0.1	0.4	0.6	1.8	0.2	0.2	0.0	0.4
8.0	0.3	0.7	0.0	0.5	0.0	0.8	0.0	0.4	0.0	0.8	-0.3	0.5	0.0	0.5	-0.2	0.4	0.2	0.8	-0.2	0.4	0.3	2.0	0.0	0.0	0.0	0.4
8.5	0.0	0.7	-0.4	0.5	-0.4	0.7	-0.1	0.3	-0.3	0.7	-0.6	0.5	-0.4	0.5	-0.3	0.3	0.0	0.7	-0.2	0.3	0.0	2.2	-0.2	-0.2	-0.2	0.5
9.0	-0.5	0.4	-0.7	0.6	-0.6	0.5	-0.3	0.2	-0.5	0.6	-0.7	0.0	-0.7	0.6	-0.5	0.3	-0.4	0.5	-0.4	0.4	-0.1	1.8	-0.3	-0.3	-0.2	0.6
9.5	-0.8	0.0	-0.9	0.2	-1.0	0.3	-0.5	0.0	-0.8	0.4	-0.9	-0.5	-0.8	0.5	-0.7	0.0	-0.7	0.3	-0.5	0.3	-0.3	1.2	-0.4	-0.4	-0.3	0.4
10.0	-1.2	-0.3	-1.2	-0.4	-1.3	0.2	-0.5	-0.2	-1.2	0.0	-1.0	-0.6	-0.8	0.5	-0.7	-0.1	-0.8	0.0	-0.7	0.0	-0.7	0.8	-0.7	-0.6	-0.4	0.0
10.5	-1.5	-0.5	-1.3	-0.8	-1.5	-0.2	-0.7	-0.2	-1.4	-0.5	-1.0	-0.5	-0.9	0.3	-0.9	-0.4	-1.1	-0.3	-0.7	-0.3	-0.9	0.8	-0.9	-0.7	-0.6	-0.2
11.0	-1.7	-0.7	-2.2	-1.2	-1.6	-0.5	-0.6	-0.1	-1.6	-0.7	-1.0	-0.8	-1.0	0.0	-1.1	-0.5	-1.3	-0.4	-0.7	-0.4	-0.9	0.7	-1.0	-0.8	-0.6	-0.3
11.5	-1.7	-0.8	-2.7	-1.7	-1.6	-0.6	-0.5	-0.3	-1.8	-0.7	-1.0	-0.7	-1.1	-0.4	-1.1	-0.5	-1.5	-0.5	-0.7	-0.4	-0.9	0.7	-1.0	-0.8	-0.5	-0.3
12.0	-1.6	-1.2	-2.7	-2.3	-1.4	-0.6	-0.5	-0.3	-1.6	-0.6	-0.9	-0.6	-1.0	-0.5	-1.1	-0.4	-1.4	-0.5	-0.6	-0.4	-0.8	0.3	-0.9	-0.8	-0.6	-0.3

Note: Minus signs indicate ebbing velocities. Velocities were determined by timing the travel of a 14-ft pole float. Times are expressed in terms of prototype hours after the moon's transit of meridian 71°21'.

Table 6

Plan 35

Current Velocities on Center Line of Navigation Openings (ft/sec, Prototype)

	Mean Tide						Spring Tide					
	℄ of East Barrier Navigation Opening			℄ of West Barrier Navigation Opening			℄ of East Barrier Navigation Opening			℄ of West Barrier Navigation Opening		
Hour	Surface	1/4 Depth	Middepth	Surface	1/4 Depth	Middepth	Surface	1/4 Depth	Middepth	Surface	1/4 Depth	Middepth
0.0	-6.7	-7.2	-7.5	-5.4	-7.4	-7.7	-7.0	-7.3	-7.6	-6.8	-7.3	-7.8
0.5	-6.4	-6.5	-6.9	-5.1	-7.2	-7.5	-7.0	-7.3	-7.6	-6.8	-7.5	-7.8
1.0	-5.7	-6.0	-6.2	-5.1	-6.4	-7.0	-6.6	-7.0	-7.6	-6.7	-7.1	-7.6
1.5	-5.1	-5.2	-5.2	-5.4	-5.5	-6.0	-6.3	-6.5	-6.8	-6.5	-6.7	-7.1
2.0	-3.7	-3.9	-3.9	-4.7	-4.1	-4.4	-5.4	-5.7	-5.7	-6.0	-5.7	-5.8
2.5	-2.3	-2.4	-2.3	-2.8	-2.8	-2.8	-4.5	-4.5	-4.6	-4.4	-4.4	-4.5
3.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.6	-2.4	-2.6	-2.4	-2.3	-2.4
3.5	2.8	3.1	3.2	3.6	4.1	4.1	0.0	0.0	0.0	0.0	0.0	0.0
4.0	4.7	5.1	5.2	5.2	5.7	5.9	3.9	4.1	4.0	4.5	4.4	4.4
4.5	5.9	5.9	6.2	6.4	6.2	6.7	5.7	5.9	6.5	6.2	6.5	6.3
5.0	6.2	6.5	6.9	7.2	7.5	7.5	6.6	6.6	7.3	6.8	7.5	7.5
5.5	6.4	6.7	7.2	7.4	7.8	7.8	7.1	7.4	7.9	7.5	8.3	8.5
6.0	6.5	7.0	7.2	7.2	7.5	8.0	7.4	7.6	8.3	7.8	8.5	8.3
6.5	6.5	6.9	7.2	6.9	7.2	7.7	7.3	7.6	8.1	7.5	8.5	8.5
7.0	6.5	6.7	7.0	6.7	7.0	7.5	7.3	7.3	7.9	7.1	7.8	8.1
7.5	6.2	6.2	6.5	6.2	6.4	7.0	6.8	7.0	7.6	7.0	7.5	7.8
8.0	5.2	5.2	5.5	5.4	5.4	5.7	6.0	6.3	7.3	6.3	6.5	7.0
8.5	3.7	3.6	4.1	4.2	3.6	3.9	4.8	5.1	5.7	5.2	5.2	5.5
9.0	1.6	1.3	1.8	0.0	0.0	1.3	3.3	3.3	3.9	3.2	3.4	3.4
9.5	-1.6	-2.3	-2.1	-3.9	-3.1	-3.2	0.0	0.0	0.0	0.8	0.8	0.8
10.0	-5.2	-5.4	-5.2	-6.0	-6.4	-6.4	-1.9	-1.9	-2.2	-2.6	-2.7	-2.9
10.5	-6.4	-6.4	-6.7	-6.9	-7.4	-8.4	-4.8	-5.1	-5.1	-5.2	-5.2	-5.8
11.0	-6.9	-7.2	-7.2	-7.5	-8.2	-9.0	-5.7	-6.3	-6.6	-5.8	-6.8	-7.8
11.5	-6.9	-7.4	-7.8	-6.7	-8.2	-8.9	-7.0	-7.0	-7.6	-6.8	-7.1	-8.3
12.0	-7.0	-7.2	-7.5	-5.7	-7.5	-8.8	-7.3	-7.4	-7.3	-7.0	-7.6	-8.3

Note: Minus signs indicate ebbing velocities. Times are expressed in terms of prototype hours after the moon's transit of meridian 71°21'.