# Chapter 42

# HURRICANE STUDIES FOR NARRAGANSETT BAY

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# ABSTRACT

Hurricane flooding has emerged as one of the major coastal engineering problems of the Atlantic and Gulf Coast areas of the United States. Engineering and scientific investigations have been made to determine the fundamental mechanics of the hurricane surges that cause inunda tion of coastal areas and to develop practical and economical protection. Mathematical models and large hydraulic models were used for the Narragansett Bay studies of two major projects.

The discussions presented herein are limited to the hydraulic studies of barriers at the mouth of the bay, known as the Lower Bay Barri Plan, and a brief description of this plan and the Fox Point Hurricane Barrier which is now under construction.

#### INTRODUCTION

Hurricane tidal surges generated in the Atlantic Ocean have flooded Narragansett Bay areas of Rhode Island and Massachusetts 10 to 14 feet above normal tide levels, and caused extensive inundation of business and residential properties. A map of the bay is given in Figure 1. Flood damages of about \$100 million occurred in the September 1938 hurricane a again in the August 1954 hurricane. Loss of life was 110 in 1938 but only 10 in 1954 owing mainly to better warnings. The ocean surges travel with the hurricane at speeds of 30 to 50 miles an hour, then build up in height as they cross the Continental Shelf and flow into bays and estuaries. Althoug records of occasional great hurricanes go back to 1635, it is the recent di astrous hurricanes that have attracted attention to the problem.

#### HURRICANE CHARACTERISTICS

Tracks of selected hurricanes are shown on Figure 2. Major storms have followed the coastline striking inland west of Rhode Island thi placing Narragansett Bay in the dangerous north-east quadrant of the stor



Fig. 1



Also important are the fast movement and short duration of the great hurricanes on the northeast coast in contrast to the slower storm movement farthe south.

The result is that a storm reported stalled or moving slowly along the South Atlantic coast may accelerate and strike Narragansett Bay 8 or 10 hours later; or it may completely miss the area and pass harmlessly out to sea. Forecasting, warning and evacuation of people from flood areas becomes extremely difficult under these conditions and there are bound to be many false alarms.

Maximum sustained winds in the great hurricanes have been generally above 75 miles per hour in the Narragansett Bay area, with 1-minute velocities of about 90 miles per hour and gusts recorded above 125 miles per hour. Minimum barometric pressures were recorded at about 28.50 inches of mercury (964.8 millibars). Significant wave heights in the bay entrances were about 25 feet, with 11 second period and waves within the bay areas were reported up to 9 feet in height with 7 second period.

## SCOPE OF IN VESTIGATIONS

As this was one of the first major hurricane studies in the United States, extensive engineering and scientific investigations were made over a 9-year period by the U. S. Army Corps of Engineers and many private and public agencies, including the Corps' Coastal Engineering Research Center and Waterways Experiment Station; other Federal agencies such as the Weather Bureau, Coast & Geodetic Survey, Public Health Service, Fish & Wildlife Service; and universities, including the Texas Agricultural & Mechanical Research Foundation, University of Rhode Island Oceanographic Department, and Massachusetts Institute of Technology. The purpose of these studies were: (1) to secure data on the behavior and frequency of hurricanes; (2) to determine the fundamental mechanics of hurricane surges and determine improved forecasting and warning methods, and (3) to develop practical and economical protection of life and property.

The investigations in Narragansett Bay included hydrographic and oceanographic investigations for hurricane and normal conditions as a basis for the studies by hydraulic models and mathematical models. Engineering studies and field investigations were made of 15 plans of protection.

# FLOOD CONTROL

# BARRIERS ACROSS THE ENTRANCES TO THE BAY

A plan of rockfill barriers, with large ungated navigation openings across the three entrances to Narragansett Bay, has been studied by hydraul model and computation methods. It was determined that satisfactory flood control, with reduction of 6 to 7 feet in flood levels over the 120 square mile bay area could be obtained by construction of barriers. The ungated navigation openings into the bay would have a total area of 122,000 square feet, whi is 23 percent of the waterway area of the natural openings into the bay.

# STUDIES OF HURRICANE SURGES

Historical records show 2 to 5 great hurricanes in each century since 1635 when the country was settled. Although 70 hurricanes have been recorded since 1900 as crossing or threatening the area, of which 13 caused major flooding in Narragansett Bay, reliable data are available on only a fehurricanes. (1) Studies of hurricane windfields and associated rainfall have been made of recent hurricanes and of maximum probable hurricanes by the Weather Bureau (2) (3). Using this wind data, the offshore surges were reproduced by Reid (4) in mathematical model studies. Surges within Narragansett Bay were reproduced in hydraulic models. Analytical methods were used to check model results and calculate local wind set-up effects.

# FLOOD CONTROL EFFECT

The 1938 hurricane surge at the Newport entrance to the bay (Ea Passage) and the flood control effect of the barriers is shown in Figure 3. will be noted that without barriers most of the rise to 10.8 feet mean sea le occurs in 2 hours and the entire surge has a duration of 6 to 8 hours. With barriers, the opening into the bay would be reduced from their natural 532,000 square feet to 122,000 square feet. The rate of rise is limited by the smaller openings and flood levels are reduced over the bay area.

Next considering the bay as a whole, profiles of flood levels, frc the mouth of the bay to the head of the bay at Providence are given in Figur 4 for the 1938 hurricane, with and without the Lower Bay Barriers. The ir crease in levels towards the head of the bay is caused by the combination o wind set-up and the dynamic effect of the surge, which builds up in much this same manner that the normal tide range increases towards the head of the bay.



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# FIG. 4 HURRICANE FLOOD LEVELS

NARRAGANSETT BAY HURRICANE PROTECTION

# DETERMINATION OF FLOOD EFFECTS

Navigation openings of various sizes were investigated. Openings were selected as large as practicable while retaining satisfactory flood reductions. The sequence of study was as follows:

(1) <u>Hurricane Windfields</u>. Charts of wind velocity, direction, barometer, and rate of travel were prepared by the Weather Bureau.

(2) Offshore Surge. Mathematical model studies were made by Reid (4) (5) employing the method of characteristics to reproduce floods of record and maximum probable floods. Storm track and speed were varied to determine the most severe conditions.

(3) <u>Storm Surge at bay entrance</u>. Observed for floods of record an computed for maximum probable hurricane.

(4) <u>Storm Surge in Narragansett Bay.</u> Observed levels for floods of record (1). Hydraulic model tests at Waterways Experiment Station (6) (7) reproduced floods of record and established maximum probable hurricane. This gave dynamic buildup within the bay, without local wind effects. Wind set-up was calculated in method outlined by Coastal Engineering Research Center (8), and added to the results of the model studies. Independent mathematical model studies were made by Reid (5).

# (5) Flood Control Effect within Narragansett Bay.

(a) Determined from Waterways Experiment Station model tests without local wind effects. Wind set-up calculated as in (3) above.

(b) Independent mathematical routings were made using the discharge characteristics of the navigation openings determined in hydraulic model tests, as described below, and storage of water in the 120 square mile bay area (1).

(6) Inflow of water from wave overtopping. The extra flow of hurricane waters into the bay area from storm waves overtopping the barriers was calculated by the method of Saville (8). Waves were determined from the hurricane windfields furnished by Weather Bureau (2) using method of Bretschneider (9). (7) Inflow from fresh water runoff. The additional water flowing into the bay during the hurricane surge period was determined from rainfall associated with hurricanes by Weather Bureau (3). Unit hydrographs were prepared of local runoff and river flood flow.

# EFFECT ON OCEANOGRAPHY OF BAY

A basic consideration in the design of Lower Bay Barriers was to avoid changing the normal conditions in the bay, insofar as possible, becauof the important recreational use and natural resources value of the area fo commercial and sport fishing.

The normal tides and currents were first reproduced in the hydra lic model of Narragansett Bay. In later tests tidal interchange, mixing, salinity, stratification and sedimentation were reproduced for natural conditions and with the barriers over a period of 600 tidal cycles (10) (11).

Opening sizes were varied to determine effect on the natural tide It was found that with openings totaling about one-third of their natural area there would be no reduction in the tidal prism or levels. Sluice gates, clos in hurricane periods, would provide the increase in area for the normal tid interchange. Narragansett Bay is a partly mixed estuary as river flow is small and stratification occurs only in the upper bay areas. The Lower Ba and entrance areas are well mixed. With full tidal interchange the barrier would not be expected to change the natural salinity, stratification, temper ture and sedimentation to increase the pollution problem, or to adversely affect finfish and shellfish. Extensive studies have been made of pollution and fishery effects by the U. S. Public Health Service (13) and U. S. Fish and Wildlife Service (14) assisted by other agencies.

#### EFFECT OF OPENINGS ON NORMAL TIDE RANGE

Barrier plans with openings varying from 63,000 square feet to 172,000 square feet were investigated (ll). The reductions in the present mean tide range of 3.6 feet at the Newport entrance, plotted against area c openings are given in Figure 5, as determined from the model tests and routings described in paragraph (5) (b) above, and in the section on Hydrau lic Design and Navigation Openings. It will be noted that an opening of abo 125,000 square feet is critical. If the openings are smaller than the critic area the tide range is reduced. For larger openings the tide range is not significantly affected and the recommended plan with 172,000 square feet would not change the present normal tide range. Sluice gates in the East



and West Passages would provide the additional 50,000 square feet of openi over the 122,000 square feet in the three navigation openings.

## EFFECT ON NORMAL TIDES AND CURRENTS

Tides at the entrance to Narragansett are semi-diurnal with two approximately equal tides having a period of 12 hours 40 minutes. It is a stationary type tidal wave with tide range increasing from 3.6 feet at the mouth to 4.6 feet at Providence, 25 miles away, where high water occurs only 10 minutes later than at the mouth. The tidal currents and levels are sensitive to offshore and local meteorological conditions.

Although the selected plan with 172,000 square feet of openings would not change the normal tidal range it would cause the phase of the bay tide to lag the ocean tide about 15 minutes as shown in Figure 6. As a resu the maximum currents in the East Passage would be increased from 1.5 to about 3.0 knots for a mean tide, as shown in Figure 7.

# EFFECT ON SALINITY AND TIDAL MIXING

At present the entrance and lower half of the bay are well mixed by tidal currents with very nearly constant salinity from the surface to the maximum bottom depth of 170 feet in the East Passage, as shown in Figure In the upper bay and river areas stratification is apparent with surface sal of about 22 parts per thousand dropping to 8 parts per thousand during the spring runoff season as illustrated by the salinity graphs for present condi in the Providence River.

For the bay as a whole the ratio of fresh water runoff (per tidal cycle) to the tidal prism is small with an average of about 1 to 150.

As the selected barrier plan will provide full tidal interchange, good vertical mixing will continue to be produced by tidal currents becaus the water is nearly constant density from surface to bottom. Flume tests show full vertical mixing at the East Barrier site although the sill, at elev tion-60, will be about 100 feet above the bottom. For the other passages t' sill of the navigation openings is near the natural bottom.

It is not anticipated that the normal salinity, mixing and flushin conditions would be changed by the barrier plan. However, detailed hydr: lic tests of the final plan with sluice gates have not been made in the bay model during the present survey report study.



NOTE MEAN TIDE EAST AND WEST PASSAGES

FIG. 6

NARRAGANSETT BAY, R.I. EFFECT OF HURRICANE BARRIERS ON TIDE LEVELS



<u>NOTE.</u> CURRENTS IN THE EAST PASSAGE FOR A MEAN TIDE

FIG. 7

NARRAGANSETT BAY, R.I. EFFECT OF HURRICANE BARRIERS ON TIDAL CURRENTS



# COASTAL ENGINEERING

# HYDRAULIC DESIGN OF NAVIGATION OPENINGS

The navigation openings studied included broad-crested and sharp crested weirs of varying sizes and different abutment configurations. The objective was to design openings (1) that would give parallel flow for normal navigation conditions (low head and low velocity), and (2) restrict the flow c abnormal tides and hurricane surges into the bay (sluice gates closed). Th are conflicting requirements.

The adopted design for the principal navigation opening, 1,720 fe x 60 feet in the East Passage, provided rounded abutments to obtain a satis factory current pattern for navigation and a sharp-crested weir type of sill in order to obtain effective flood control.

Extensive model tests were made of ship operations in the East Passage. A 1 to 150 scale model of an 1,100-foot long vessel/used in the hyc lic model of the East Passage to simulate present conditions with the barri The present mean tide current of about 1.5 knots would be increased to abo 3 knots by the barriers, as shown in Figure 7. For strong running tides (spring tide) the present maximum current of 2 knots would be increased to about 4 knots for a maximum ebb and flood in the immediate vicinity of the barriers (sluice gates open).

### DISCHARGE CHARACTERISTICS

The discharge characteristics of the navigation opening in the pr posed hurricane barrier for the East Passage were investigated by means both sectional and 3-dimensional models. Two sectional models reproduci the barrier at scales of 1:50 and 1:150 were used to determine the effect of approach depth, roughness of the barrier, model scale and weir design on the discharge characteristics of the structure for steady flow conditions. discharge characteristics of plans for both flood and ebb flows were determined with the 1:150 scale, undistorted, 3-dimensional model for the East Passage entrance.

As expected, the discharge capacity of the structure was greate with a deeper depth of approach. The roughness of the barrier due to the cover stone increased the discharge capacity of the navigation opening by reducing the effect of a contractive sill 10 feet high by 10 feet wide located on the oceanside of the weir crest. The model scale was found to have no significant effect on the discharge characteristics of the barrier. Tests revealed that the barrier surmounted by the 10 by 10-foot contractive sill v almost as effective as a 40-foot high vertical sill in contracting flood flow: The tests showed that discharge characteristics of navigation openings were highly sensitive to the design of sill and abutments. Good flood con trol demandsthe lowest practicable coefficient of discharge and this is normall associated with high contraction and high energy loss which can readily lead to a meandering jet with large eddies and unstable flow conditions. On the other hand if the transitions are rounded and eased to improve navigation conditions flood control effectiveness diminishes as the coefficient of discharge increase and little energy is lost.

The solution was the use of the contractive sills which formed a sharp-crested weir with high vertical contraction and dissipation of energy in vertical eddies which do not affect the steering of a vessel. These were combined with rounded abutments to give a smooth flow pattern in the horizontal plane.

The coefficient of discharge for representative weir sections that were tested (12) are shown in Figure 9. For the proposed plan the C is about 0.9 for flood and 1.0 for ebb flows, using the basic equation:

$$Q = CA\sqrt{2g} h$$

where the terms used in the equation are defined as follows:

- Q total discharge in cfs
- C submerged flow discharge coefficient
- A cross-sectional area of navigation opening with reference to tailwater elevation (00.0 mlw) above weir crest in sq. ft.
- h differential between total energy of approach channel flow and depth of tailwater with reference to weir crest in ft. (H-h)
- g acceleration due to gravity in  $ft/sec^2$

The mathematical routings for normal tides and for hurricane surges were predicated on storage in the 120 square mile area above the barriers and the above equations. The computations gave a good check on the test results of the bay model.



### NAVIGATION

Navigation currents in the barrier openings were investigated for plans with openings varying from 63,000 square feet to the 172,000 square fee total of the recommended plan, with sluice gates open. Estimated maximum current at strength of flood or ebb, for a spring tide, are given in Figure 10. It will be noted that increasing the openings from 122,000 square feet to 172,0 square feet by adding the sluice gates reduces currents about 30 percent, whi substantially improves navigation conditions. This is particularly important for recreational boating which is a major factor in the Narragansett Bay area. The maximum current velocities in the East Passage and West Passage, estimated at about 4 knots in a spring tide and about 3 knots in a mean tide would be confined to the immediate vicinity of the barriers. Figure 7 shows the variation of currents over the tide cycle. Although currents at the navigation openings would be strong, small recreational craft and fishing boats regularly use waterways on the East and West Coasts of the United States where stronge currents occur. Flood protection would be afforded for many dock and anchor age areas and marine facilities along the shoreline of the bay.

The East Passage model was also used to demonstrate navigation conditions in the vicinity of the East Barrier before and after construction of the proposed barrier, using a model ship having a prototype length of 1,100 feet.

(1) <u>Normal conditions</u>. Tests were made using the model ship whic satisfactorily transited the passage in both directions at speeds of 15, 10 and 7 knots.

At an engine speed of  $7\frac{1}{2}$  knots the ground speed of the vessel over the barrier was slow, without the sluice gates, because the vessel must buck the 4 knot current and also to climb the gentle slope to the higher pool level. There was no control problem with parallel flow normal to the axis of the barrier.

With sluice gates open, navigation conditions and maximum currents are considerably improved; operation was satisfactory.

(2) <u>Gale conditions</u>. Waves ll feet in height had little effect on a large ship. Some protection was afforded by the barriers. Windage on the vessel moving at low speed was very important -- with or without barrier. Engine speeds used were the same as for normal conditions. Operation was satisfactory.

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(3) Hurricane conditions. Navigation during hurricane conditions of current, 25-foot high waves, and 70 knot winds were simulated using vess speeds of 20 and 15 knots. The present maximum flood current of 5 knots would be increased to 11.5 knots with barrier, and the present maximum hurricane ebb current of 9.5 knots would be about the same with the barrier in place. Model operation under these conditions (which may in nature include low visibility) is difficult but can be accomplished either with or witho the barrier. It is definitely an emergency operation (sluice gates closed).

# PROJECT STUDIES

Planning and design studies include hydraulic, structural design and economic analyses for the Fox Point Hurricane Barrier at the head of the bay and the Lower Bay Barriers at the entrance (15) (16).

### FOX POINT HURRICANE BARRIER

One of the first hurricane flood control structures to be built in this country, the Fox Point Barrier is now under construction. It will affoi protection to the commercial and business section of downtown Providence against a design hurricane tide of 20.5 feet above mean sea level, which is 4.8 feet higher than the maximum flood on record. The barrier was design as a dam across the Providence River. Figure 1 gives the location of the p ject, and Figure 11 shows the layout.

The central structure is a concrete gravity dam about 680 feet lo with its top 25 feet above mean sea level. In the east section of the main barrier three 40-foot wide tainter gates will pass normal river and tidal flo These gates will generally be in a raised position to permit the passage of small boats and barges. When closed, the gates will prevent entry of tidal flood waters from Narragansett Bay.

The western section of the barrier includes a large pumping station to discharge the flood runoff of the Providence River when the gates an closed during hurricane emergencies. Intake gates at the pumping station permit the entrance of water to a cooling water canal along the west side o the river leading to large steam electric plants upstream of the barrier.

Dikes on either side of the main dam tie in to high ground so as prevent flanking by flood waters; each dike is about 800 feet long, 10 to 15 feet high, and composed of rolled earth faced by armor stone to protect against wave action. Steel swing gates are provided at street crossings, t be closed during hurricanes. The top elevation of 25 feet for the barrier





will contain the calculated waves of the design storm for the fetch of the Providence River fronting the barrier. Rock facing will effectively dissipate breaking wave forces on the front of the dikes, while rear faces are riprappe for protection against the moderate overtopping flow of maximum waves. Th concrete structures in the river are in relatively deep water so that the wave will not break and only wave runup has been provided for.

The tainter gates will pass a major river flood and prevent back-u into the city streets during normal tides. In the event of a hurricane tide the gates will be closed and the five 109-inch pumps of the pumping station will g into action. These pumps have a design capacity of 7,000 cfs at 20-foot heac which is adequate for any flood of record and for the maximum runoff of a transposed 1938 hurricane rainfall. The pumps would maintain the Providend River pool upstream of the barrier near mean sea level elevation. Sewers passing through the barrier will be gated and flow will be bypassed into the river upstream of the barrier in hurricane tide periods.

Foundation conditions include glacial till at elevation 80 feet below mean sea level, generally overlain by two layers of silt separated by a 10-foc sand-gravel layer. The upper silt layer was removed in the river section an replaced with sand fill; all river section structures will be supported by stee piling driven to till. The river sections are being constructed in the dry usin cellular cofferdams.

The estimated cost of the Fox Point project is about \$18,000,000, of which the non-Federal share is 30 percent. Local costs are being shared, two-thirds by the City of Providence, and one-third by the State of Rhode Island. Upon completion the project will be turned over to the local authorities for maintenance and operation. The project would prevent flood damage of about \$40 million in a recurrence of the 1938 hurricane.

#### LOWER BAY BARRIER PLAN

After consideration of numerous plans proposed by local interests involving 25 different sites, the specific locations of the barriers were selected after (1) extensive hydraulic model tests, (2) economic studies of alternative sites and structures, and (3) the evaluation of navigation conditions. Figure 1 shows the location of the structures. The plan of protection includes a system of three massive rock barriers with ungated openings large enough to meet navigation needs but small enough to control the entrance of hurricane tidal surges into the bay area. The component structures are described in more detail below.

# COASTAL ENGINEERING

The East Barrier would consist of a massive rockfill barrier acro the East Passage from Castle Hill to Fort Wetherill and provide for an unga navigation opening 1,718 feet wide at mean low water, and 1,500 feet wide at depth of 60 feet below mean low water; and 40 sluice gates 25 feet wide x 27, feet high. The maximum water depth near the barrier in the East Passage 200 feet. See Figure 12.

The West Barrier would consist of a massive rockfill barrier acr the West Passage at Bonnet Shores, with an ungated navigation opening 520 wide at mean low water, and 400 feet wide at a depth of 40 feet below mean water; and 40 sluice gates 25 feet wide x 27.5 feet high. The maximum wat depth at the barrier site is 60 feet.

The <u>Tiverton Barrier</u> would cross the third opening into the Narr gansett and Mt. Hope Bay area with an earthfill armored structure across t Sakonnet River providing for an ungated navigation opening 166 feet wide at mean low water, and 100 feet wide at a depth of 20 feet below mean low wate flanked by beach raising, widening and back-up dikes.

Dikes to complete the closure would include road raising combine with beach raising and widening at Mackerel Cove and dikes across the low lands at Bonnet shores and Castle Hill.

The present plan provides for substantially larger navigation ope ings and more effective tidal interchange than the original 1956 proposal wh had a total waterway area of about 63,000 square feet in the three navigatio openings. The larger navigation openings provide 122,000 square feet of op ing, and the sluice gates another 50,000 square feet for a total of 172,000 square feet open during normal tidal conditions.

Effect of Barriers on Natural Resources. A three year study of the fishery problems was made by the U. S. Fish and Wildlife Service, ass ted by the University of Rhode Island, the Rhode Island Fish and Game Depment, and other agencies (14). The problems of pollution and water quality effects were the subject of a two year study by the U. S. Public Health Serv (13) assisted by the University of Rhode Island and the Rhode Island Health Department. In both instances it was concluded that the Lower Bay Barrie would have very little effect on present conditions within the Bay. The effe of the barriers on navigation conditions has already been discussed.



Present Status. Studies are being completed for the system of Lower Bay Hurricane Barriers which would reduce flood levels 6 to 7 feet over the 120 square mile bay area. More than 90 percent of the design floo damages of \$126,000,000 in the area below the Fox Point Barrier would k prevented. The estimated cost of the plan is about \$90,000,000. A survey report is being prepared by the Army Engineers for submission to the Unite States Congress.

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