# Design of Hurricane Flood Protection Works


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# DESIGN OF HURRICANE FLOOD PROTECTION ON THE UPPER TEXAS COAST

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## INTRODUCTION

One of the recurring natural phenomena that causes enormous damages in the destruction of property and loss of lives on the upper Texas Gulf coast is the tropical hurricane. The terrific wind velocities, overflowing tide surges and tremendous waves that accompany these disturbances are overwhelming in their devastating effects on man made structures. In1955, the Congress of the United States directed that a comprehensive study be made of hurricanes on the Gulf and Atlantic coasts and of means for protecting coastal areas from their destructive effects. Under this authorization, the Corps of Engineers has made extensive studies of hurricane behavior and frequency and of means of preventing loss of human lives and damage to property. The Weather Bureau cooperated fully in the studies of hurricane characteristics and phenomena. This paper concerns the studies and the design of protecttive structures at Texas City on the upper Texas coast. The location of Texas City with respect to the Gulf of Mexico is shown on figure 1.

Texas City is located on the mainland shore of Galveston Bay, one of the large coastal lagoons that border Texas. Galveston Bay, as shown on figure 2, is separated from the Gulf of Mexico by the offshore bars of Galveston Island and Bolivar Peninsula and is connected with the Gulf by two natural passes: San Luis Pass, at the southwest end of Galveston Island; and Galveston entrance, at the northeast end of Galveston Island between the island and Bolivar Peninsula. The barrier islands are generally 1 to 3 miles in width with maximum elevations on old beach ridges of 8 to 10 feet above mean sea level. A massive sea wall (1) consisting of a concrete gravity section backed by sand fill extends along about nine and one half miles of the Gulf shore and protects the northeastern portion of Galveston Island, which is occupied by the city of Galveston. The seawall lies about 9 miles southeast of Texas City.

Galveston Bay, including its smaller connecting bays has a maximum length of about 30 miles in a north-northeast and south-southeast direction and extends about 17 miles in an east and west direction. Natural oyster shell reefs extend across the bay in two locations dividing it into two separate parts. Depths of 6 to 8 feet at mean sea level are available over most of the bay aheas. Two small bays on the north side of Texas City have a combined surface area in excess of 2,000 acres and average depths of 2 to 3 feet below mean sea level.

Texas City has a frontage of about 12 miles on Galveston Bay. The ground surface in the city slopes generally from maximum elevations of 20 to 25 feet along the west city limits to elevations of less than 5 feet above mean sea level along the east shore line. A ridge extends in an east to west direction through the central part of the city, from 15 feet above mean sea level on the west to about 5 feet on the east. The principal industrial development and business area is on this ridge, while the residential areas extend down the slope to lower elevations. The adjoining city of LaMarque is developed to elevations of 8 to 9 feet in its southerly portion. As shown on figure 2 a storm surge of 15 feet above mean sea level would inundate most of the developed areas of Texas City and LaMarque.

## DESIGN HURRICANE

The intial studies were to determine the design hurricane and the storm surge on the Texas coast that would be caused by the design hurricane. The U. S. Weather Bureau undertook intensive studies of the phenomena of all hurricanes on which it had records and the determination of frequencies of occurrence of given characteristics of hurricanes. In this study, as reported by Graham and Nunn (2), the coastal areas were divided into regions and a determination made of the characteristics of a hurricane with a recurrence interval of 100 years in each of these regions. The principal feature of this storm are selected as representative of a standard project hurricane. The results of this study are presented

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in a series of publications of the U. S. Weather Bureau of which the pamphlet referring to the region of the upper coast of Texas is entitled, "HUR 7-45"(3). These characteristics of the standard project hurricane in the gulf region off Galveston are as follows:

Maximum wind velocity (30 feet above water surface) - 101 miles an hour

Radius from center to region of maximum winds - 14 nautical miles

Forward speed of storm - 11 knots

Central barometric pressure - 27.52 inches of mercury

Asymptotic barometric pressure - 29.92 inches of mercury

These storm characteristisc are identified by the atmospheric pressure in the center of the storm which is referred to as the central pressure index (CPI). It was found by the Weather Bureau that the central pressure of a given hurricane is an index to its general magnitude of severity. However, the other characteristics, particularly the radius of the storm, are essential in the evaluation of of the magnitude of the storm and of the accompanying wind velocities, tide surge elevations and wave heights.

The frequency of recurrence of the standard project hurricane is estimated by the Weather Bureau as once in one hundred years in the region off the upper Texas Gulf coast; however, its occurrence on a path to give maximum surge in the Texas City area would be less frequent. The authorized project provides for hurricane tide protection at Texas City against a tide with a recurrence frequency of once in 100 years. A study of frequencies based on computed storm surges in the Gulf indicated that a hurricane surge elevation of 15 feet above mean sea level has a recurrence interval of once in 100 years. Accordingly, the characteristics of the standard project hurricane in the Gulf of Mexico at Galveston were modified too represent a design hurricane that would generate a storm surge of 15 feet at Galveston. The characteristics of the design hurricane are as follows, Maximum onshore component of wind velocity, 30 feet above water, 99 miles an hour; central pressure, 27.54 inches of mercury; asymptotic barometric pressure at periphery of the storm 29.92 inches of mercury; radius to region of maximum wind speed, 15 nautical miles; forward speed of the storm mass, 11 knots. The path of the design storm to result in the most severe tide surge elevation and wave heights in th vicinity of Texas City would be aligned normally to the coast and lie 15 miles southwest of Texas City, as shown on figure 1. The wind pattern of the design hurricane is given in Weather Bureau Memorandum HUR-7-47(4) and is shown on figure 3.

## DESIGN STORM SURGE

On the Gulf shore the total hurricane storm surge consists of a rise in water level caused by the wind stress and an increase in elevation from the reduction in atmospheric pressure in the storm center, all superimposed on the local astronomical tide.

The formula for dynamic storm tide on a constant sloping continental shelf, exclusive of the component caused by atmospheric pressure reduction, developed by Reid(5) was used in the studies at Texas City. This formula is as follows:

$$N_m = K \frac{T}{C_1} \left( \frac{d_1}{d_o} \right)^{0.25} W_m^2 S$$

where $N_m$ = maximum rise in water level caused by wind stress ( in feet).

$d_1$ = mean water depth at the seaward edge of the continental shelf just landward of the sharp increase in slope on the continental slope (in feet).

$d_o$ = mean water depth at shoreward edge of continental shelf just seaward of the sharp increase in slope in the near-shore zone (in feet).

$K$ = $3.0 \times 10^{-6}$, wind stress parameter

$C_o$ = $\sqrt{gd_o}$ speed of free wave at $d_o$ (in feet per second)

$C_1 = \sqrt{gd_1}$ speed of free wave at $d_1$ (in feet per second

$C = 1/2\ (C_o + C_1)$ average speed of free wave (in feet per second)

$B$ = breadth of continental shelf between the location of $d_1$ and $d_o$

$T = \frac{B}{C}$, period of travel of free wave over continental shelf (in seconds)

$W_m$ = maximum sustained wind speed in feet per second, 30 feet above the water surface

$S$ = Response factor depending on the ratio of fetch length to breadth of continental shelf and the ratio of forward speed of the hurricane to the propagational speed of the free wave C

The profile of the continental shelf off Galveston, parallel to the design storm path is shown on figure 4. The characteristics of the profile used in computing the storm surge at Galveston are as follows:

$$d_o = 36 \text{ feet};\ d_1 = 180 \text{ feet};\ \left(\frac{d_1}{d_o}\right)^{0.25} = 1.495$$

$$C_1 = \sqrt{g \times 180} = 76 \text{ ft/sec} = 51.7 \text{ miles/hr}$$

$$C = \frac{1}{2}\left(\sqrt{gd_o} + \sqrt{gd_1}\right)$$

$$= \frac{1}{2}(34 + 76) = 55 \text{ft/sec} = 37.5 \text{ miles/hr}$$

$B$ = 110 nautical miles = 127 miles

$T$ = 3.39 hours

Substitution of these characteristics of the shelf with factors for conversion to the proper units, in the general formula gives for the Galveston area

$$N_m = 1.55 \times 10^{-3}\, W_m^{\ 2} S, \text{ where } W_m \text{ is in miles per hour}$$

The response factor S for a hurricane is obtained from figure 13 "Response Digram: Isolines of S versus F/B and V/C" by Reid(5).

Data on characteristics of two hurricanes of 1900 and 1915 that crossed the coast near Galveston are given in additional U. S. Weather Bureau memoranda. Records of the storm surge caused by these storms are known and the constant in the formula was adjusted to reproduce the actual storm surges. The adjusted formula is:

$$N_m = 1.69 \times 10^{-3}\, W_m^2\, S$$

The adjusted formula was then used with the characteristics of the design storm to compute the maximum rise in water level that would be caused by the design storm wind stress. Using a maximum wind speed, $W_m$, of 99 miles an hour and a value of the response factor S of 0.82 from figure 13 of reference 5 for the characteristics of the design storm, the maximum wind setup is computed to be 13.5 feet.

The rise in water surface level from the reduced atmospheric pressure in the zone of maximum winds was computed from the following formula from Beach Erosion Board Technical Report No. 4(6).

$$N_p = 1.14 \quad P \times 0.63$$

where $N_p$ is rise in water surface level in feet

1.14 factor to convert inches of mercury to feet of water

$\triangle$P - difference between atmospheric pressure at center of storm and the asympotic pressure

0.63 - factor to reduce pressure difference to difference at zone of maximum wind

The difference in atmospheric pressure of the design storm is 29.92 - 27.54 = 2.38. Substitution of the P in the formula gives a rise in water surface level of 1.7 feet. The astronomical tide at Galveston has a range of only about 1.5 feet and is not included in the total design storm surge which is estimated at 15.2 feet above mean water level for a recurrence frequency of once in 100 years.

The propagation of the storm surge through the Galveston Harbor entrance and San Luis Pass and, as the tide rises above 6 feet, across the low areas of Galveston Island and Bolivar Peninsula into Galveston Bay is a most complex problem in tidal hydraulics, and one that cannot be accurately computed. The time sequence of the rising storm tide, the variation in storm winds, the irregular topography and the length of beach on the Gulf front add materially to the complexity of this problem. Undoubtedly there is a reduction in stage as the waters pour across barrier islands and the harbor entrance. However, the bay surface is also subject to the wind forces and further setup occurs against the bayshores. In the Galveston area, use was made of the records of the 1900 and 1915 storm surges. Based on these data, it has been estimated that the design storm surge at Texas City would be at the same height as the storm surge in front of Galveston or 15 feet. There would be a slight time lag in occurrence of the peak tide at Texas City, but it would be short.

The design storm hydrograph at Texas City, shown on figure 5 was developed from consideraton of actual hydrographs of storms of record. The peak of 15 feet m. s. l. for the design storm compares with 14.5 feet for the 1900 storm which crossed the Texas coast at Matagorda Bay 110 miles from Galveston, generated crest elevations of 9.0 in the Gulf at Galveston; 9.7 feet in Galveston Bay in front of Texas City and 11.7 feet in Texas City. The hurricane of September 11, 1961 was particularly sever because of the long duration of the extreme high tides. At Freeport a tide in excess of 10 feet was experienced for approximately 14 hours. This duration is much greater than that shown by the design storm hydrograph. The available records of hurricane tides on the Texas coast show no other instance of duration of maximum or near maximum storm tide that even approached the 14 hours of the September 1961 storm. The recurrence interval of this phenomena is believed to be greater than 100 years.

## WAVE CHARACTERISTICS

As shown on figure 2, the proposed protective structures will enclose the city of Texas City and part of the city of LaMarque. There are nine reaches of the structure that hav distinct differences in orientation and that are affected by waves from different directions and across different fetch lengths. Galveston Island and Bolivar Peninsula afford considerable protection to Texas City from large waves from the Gulf of Mexico and it is considered that the critical waves for design of the structures would be those generated in Galveston Bay during a design storm. The size and direction of approach of the Waves at Texas City depend upon the time position of the storm, the depth of water including natural depths and storm surge, the windspeed and the duraton and direction of approach of the storm.

For analysis of wind speed and water level conditions at Texas City the design hurricane wind field was moved in from the Gulf of Mexico on a path normal to the coast about 15 nautical miles southwest of Galveston. A time history of the wind and tide data was computed for the Texas City area. The results are shown in table 1.

**TABLE 1**
**TIME HISTORY - DESIGN HURRICANE AT TEXAS CITY**

| Time in hours (1) | Distance storm center from shore | Computed storm surge in feet | Average storm surge in feet | Wind direction and speed mph(2) | Average wind direction and speed mph(2) |
|---|---|---|---|---|---|
| 9.0 | 56 | 4.3 | 5.8 | 39 NE | 42 NE |
| 10.0 | 44 | 7.2 | 8.8 | 45 NE | 55 NE |
| 11.0 | 31 | 10.5 | 11.7 | 65 NE | 66 NE |
| 12.0 | 18 | 12.9 | 13.6 | 67 ENE | 76 E |
| 12.9 | 6 | 14.4 | 14.7 | 85 E | 90 ESE |
| 13.4 | 0 | 15.0 | 14.7 | 95 ESE | 97 ESE |
| 13.9 | 6 (3) | 14.4 | 13.6 | 99 ESE | 90 SE |
| 15.0 | 20 (3) | 12.8 | 11.4 | 80 S | 75 S |
| 16.0 | 33 (3) | 10.0 | 8.3 | 70 S | |
| 17.0 | 46 (3) | 6.6 | | | |

(1) Zero on time scale is start of water surface rise at shore in response to storm.
(2) Estimated maximum wind speeds at Texas City.
(3) Distance is inland from shore.

The data shown in table 1 are for a given storm moving on a given path. However, many variations can occur in the hurricane isovel pattern and in the path of the hurricane. The storm wind pattern was therefore rotated within the 150 degree limits shown in Weather Bureau Memorandum HUR 7-45A; that is 100 degrees counter-clockwise and 50 degrees clockwise. The rotations were made to obtain the most severe wind and tide conditions for each of the nine reaches of the protective structures. The isovel pattern of the design storm shown on figure 3 was used in the study.

Trial computations of wave heights along the several reaches of the protective levees at Texas City resulted in the conclusion that the maximum wave that could be generated in Galveston Bay during a severe hurricane would be limited by the water depth and that the fetch length would not be critical. The following criretia were used for wave computations:

a. The depth used was the average depth over a five-mile reach extending out from the structure.

b. The storm tide elevation was the average elevation during a period from 30 minutes before the peak tide to 30 minutes after the peak.

c. The wind speeds of the design storm were averaged along the fetch line for each reach and adjusted for the angle with the fetch line to determine the component normal to the structure.

The wave characteristics along each fetch line for the critical location of the storm tide and wind pattern were computed in accordance with the procedures set forth in Technical Report No. 4 of the Beach Erosion Board(6). The wave characteristics for fetch line A were determined as follows:

Wind velocity, $U = 82$ miles an hour or 120.50 feet per second.

Average depth, $d = 18$ feet

Wind fetch length, $f = 7$ miles

$H_s$, $T_s$, and $L_s$, are the height, period and length of the shallow water significant wave

$H_o$, $T_o$, and $L_o$ are the height, period and length of the equivalent deep water wave

$$\frac{gd}{U^2} = \frac{32.2 \times 18.0}{(120.5)^2} = 0.04$$

$$\frac{gf}{U^2} = \frac{32.2 \times 7.0 \times 5280}{(120.5)^2} = 82.0$$

With these two arguments, the graph on figure 15C of Technical Memorandum No. 4 (6) gives $\frac{gH_s}{U^2} = 1.48 \times 10^{-2}$

or

$H_s$, the significant wave height $= \frac{1.48 \times 10^{-2} \times 120.5^2}{32.2} = 6.7$ feet

$T_s$, the significant wave period $= 2.12 \quad 6.7 = 5.5$ seconds

$L_o$, significant wave length $= 5.12 \times (5.5)^2 = 155$ feet

$$d/L_o = \frac{18.0}{155} = 0.1160$$

With the argument $d/L_o$ the following relations are taken from table D-1 in Technical Report No. 4 (6).

$H_s/H_o = 0.9223$

$d/L_s = 0.1547$

$$H_o = H_s/0.9223 = \frac{6.7}{0.9223} = 7.3 \text{ feet}$$

$$L_s = d/0.1547 = \frac{18}{0.1547} = 116 \text{ feet}$$

$H_{max.}$, maximum wave height $= 1.87\ H_o = 13.7$ feet

In similar manner the characteristics of the waves generated by the hurricane rotated to critical positions on each fetch line, were computed. These data are given in table 2.

TABLE 2

WAVE CHARACTERISTICS

| Fetch line on plate 1 (1) | Average effective wind vel. (mph) (2) | Wind fetch length (miles) (3) | Average depth of water (feet) (4) | Significant waves in shallow water: $H_s$ (feet) (5) | $L_s$ (feet) (6) | Ratio: $H_s/L_s$ (7) | $T_s$ (secs.) (8) | Equivalent deepwater wave values: $H/H_o$ (feet) (9) | $H_o$ (feet) (10) | Ratio $L/L_o$ (11) | $L_o$ (feet) (12) | Ratio $H_o/L_o$ (13) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 82 | 7.0 | 18.0 | 6.7 | 116 | 0.058 | 5.5 | 0.92 | 7.3 | 0.750 | 155 | 0.047 |
| A[1] | 82 | 8.0 | 12.0 | 5.0 | 83 | 0.060 | 4.7 | 0.93 | 5.4 | 0.722 | 115 | 0.047 |
| B | 92 | 20.0 | 16.2 | 6.6 | 110 | 0.060 | 5.4 | 0.93 | 7.1 | 0.727 | 151 | 0.047 |
| C | 93 | 10.5 | 21.5 | 8.0 | 138 | 0.058 | 6.0 | 0.92 | 8.7 | 0.750 | 184 | 0.047 |
| D | 92 | 10.5 | 21.5 | 8.0 | 138 | 0.058 | 6.0 | 0.92 | 8.7 | 0.730 | 184 | 0.047 |
| E | 92 | 15.0 | 21.6 | 8.0 | 138 | 0.058 | 6.0 | 0.92 | 8.7 | 0.750 | 184 | 0.047 |
| F | 67 | 20.0 | 20.6 | 6.4 | 118 | 0.054 | 5.4 | 0.91 | 7.1 | 0.803 | 147 | 0.048 |
| G | 83 | 20.0 | 19.4 | 7.0 | 122 | 0.057 | 5.6 | 0.92 | 7.6 | 0.760 | 161 | 0.047 |
| H | 53 | 3.0 | 10.0 | 3.3 | 60 | 0.055 | 3.9 | 0.92 | 3.6 | 0.789 | 76 | 0.047 |

Protection against the design storm surge and waves would be provided by the earth levees and concrete sea walls. Determination of the levee grades and side slopes was based on considerations that the levee should be safe against destruction by design storm waves attacking its exposed face and that it should be of sufficient height to prevent excessive overtopping by storm waves that would endanger the inside slope and cause excessive interior drainage problems. Because of the low probability of occurrence of the design storm, it was considered that in the interest of economy in construction, appreciable damage to the levees during design storm occurrences could be accepted and repaired provided that the integrity of the structure was not endangered. To determine the combination of levee height and side slope that would best meet these conditions, estimates were made of the wave runup and wave overtopping of levees of various side slopes and crest elevations. Each reach of protective structure affected by different wave attacks was analyzed individually.

Runup factors developed by Saville, McClendon and Cochran (12) were used to determine wave runup on levees. Figure 9 in reference (12) is a graph of the runup factor ($R/H_c$) plotted against wave steepness ($H_o/L_o$) for embankment slopes varying from 1 on 1½ to 1 on 30. Factors are given for smooth earth embankments and riprap slopes. The factors are based on model tests made at the Waterways Experiment Station and at the Beach Erosion Board. Examples of the runup factors and runup are shown in the following table 3 which gives the runup and significant wave for each fetch line under design storm conditons on a smooth embankment with 1 on 6 slope.

**TABLE 3**

**WAVE RUNUP**
**BY SIGNIFICANT WAVE**

| Wave characteristics | | | Runup on smooth slope | | |
|---|---|---|---|---|---|
| Fetch line (1) | $H_o$ (feet) (1) | Ratio $H_o/L_o$ (1) | Runup factor $R/H_o$ (2) | Runup R (feet) | Maximum elevation (feet msl)(3) |
| A | 7.3 | 0.047 | 0.87 | 6.4 | 21.4 |
| A[1] | 5.4 | 0.047 | 0.87 | 4.7 | 19.7 |
| B | 7.1 | 0.047 | 0.87 | 6.2 | 21.2 |
| C | 8.7 | 0.047 | 0.87 | 7.6 | 22.6 |
| D | 8.7 | 0.047 | 0.87 | 7.6 | 22.6 |
| E | 8.7 | 0.047 | 0.87 | 7.6 | 22.6 |
| F | 7.1 | 0.048 | 0.87 | 6.2 | 21.2 |
| G | 7.6 | 0.047 | 0.87 | 6.6 | 21.6 |
| H | 3.6 | 0.047 | 0.87 | 3.1 | 18.1 |

(1) Wave data from table 2

(2) From figure 9 of reference (12).

(3) 15-foot storm tide surge plus wave runup

The rates and volume of overtopping of levees that would occur during a design hurricane were estimated using diagrams and graphs developed by A. L. Cochran for use in the design of storm protection at Texas City. The diagrams by Cochran are based on model tests of wave overtopping by Saville and reports of the Beach Erosion Board on model tests. The procedures used by Cochran are presented in an unpublished memorandum dated 15 January 1962. The rates and volumes of overtopping of levees of various slopes and grades for the design hurricane surge and waves at Texas City are shown in the following table 4.

## TABLE 4

### SUMMARY OF WAVE OVERTOPPING VOLUMES DURING ENTIRE DESIGN HURRICANE

| Levee slope (water side) | Volumes corresponding to various levee grsades (crests), elev. above MSL | | | |
|---|---|---|---|---|
| | Grade 24.6 | Grade 22.6 | Grade 20.6 | Grade 19.6 |
| Part (a) volumes in cubic feet per foot levee length | | | | |
| Vertical wall | 3,640 | 6,800 | 14,300 | 20,900 |
| Smooth 1:3 | 8,570 | 15,700 | 27,700 | 35,100 |
| Smooth 1:4 | 1,440 | 4,932 | 12,900 | 18,720 |
| Smooth 1:6 | 0 | 540 | 1,980 | 5,480 |
| Smooth 1:8 | 0 | 0 | 72 | 504 |
| Part (b) volumes in acre feet per mile levee length | | | | |
| Vertical wall | 441 | 824 | 1,730 | 2,530 |
| Smooth 1:3 | 1,040 | 1,900 | 3,370 | 4,250 |
| Smooth 1:4 | 174 | 597 | 1,560 | 2,270 |
| Smooth 1:6 | 0 | 65 | 240 | 664 |
| Smooth 1:8 | 0 | 0 | 9 | 61 |

Examination of the results of Cochran's study, shown in table 4, and the data on wave runup, shown in table 3, show that levee grades sufficiently high to prevent overtopping by the significant wave would prevent all but a comparatively small volume of of all overtopping. Since about 14 percent of waves in a wave spectrum exceed the significant wave in height, some overtopping of the levee would occur during the design hurricane. For example, table 3 shows that along fetch line D at the peak of the storm surge and wind, the significant wave would run up on a 1 on 6 slope to an elevation of 22.6 feet above mean sea level. As shown in table 4, waves greater than the significant wave during the passage of the design hurricane would produce about 540 feet of overtopping per foot of length of levee, or 65 acre-feet per mile on a levee of 22.6 feet grade with smooth 1 on 6 slope. The overtopping estimated by Cochran would occur over a period of about three hours and the peak rate at the height of the storm would be about 1 cubic foot per second, per foot of levee. This rate and duration of overtopping would not endanger the interior levee slope, and would not cause excessive interior ponding. Accordingly, levee grades and slopes were selected on the basis that the levees would not be overtopped by the significant wave. A comparison was made of the cost of levees of various side slopes to grades that would prevent overtopping by the significant wave. Estimates were made for levees with side slopes ranging from 1 on 3 to 1 on 10 with both smooth surfaces and riprap protected surfaces. From this analysis, it was found that a leveee with a slope of 1 on 6 on the waterside, 1 on 3 on the land side with a turfed face and 24-foot crown would be the most economical levee section. The grades of the different reaches, as shown in table 3, vary from 18.1 feet to 22.6 feet above mean sea level. The levee on higher ground elevations and not exposed to wave attack would have grades of 15 feet above mean sea level.

Divergence from the minimum section determined in the manner discussed above was found necessary in the reach along the bay side of Texas City and in the reach across the entrance to Moses Lake where the foundation conditions dictate a greater base width. The foundation conditions require a levee of 50 feet at an elevation of 15 feet above mean sea level. Where reaches of the levee extend in open water of Galveston Bay, the toe of the levee would be protected by riprap to an elevation of 5 feet above mean sea level to prevent erosion under normal tide wave conditions. The wave runup on the composite section was computed and it was found that the runup from the significant wave would be somewhat less than on the uniform slope section and that the crest elevation could be reduced. In two short reaches through the developed sections of Texas City it will be necessary to construct vertical concrete walls

## INTERIOR DAMAGE

The high tides accompaying a hurricane will block all gravity drainage from the area behind the protective structures. Measures must be provided to prevent undue damage from the ponding of the runoff from rainfall behind the protective structures and from the wave overtopping of the levees that would occur during the storm. The criteria tentatively considered as basis for design of the interior drainage system would provide the following drainage facilities:

a. Gravity drainage outlets adequate to discharge runoff from interior rainfall of 14 inches in 24 hours under normal tide conditions without ponding to damaging stages. This rainfall has an estimated all all season frequency of occurrence of once in about 50 years.

b. Pumping capacity adequate to remove the runoff from a rainfall of 9 inches in 24 hours plus the wave overtopping with all gravity outlets blocked by the storm tide. This rainfall has an estimated frequency of occurrence under all conditions of once in about 7 years, and a frequency coincident with tides of 2 feet or more, that would block gravity drainage, of once in 30 years.

The combined discharge capacity of gravity outlets and pumps would remove runoff from rainfall of 23 inches in 24 hours under normal tide conditions, which is equal to the rainfall of a standard project storm.

The area enclosed by the protection system drains to three separate outlets through the levee. Two small areas on the south side of the city, with contributing drainage areas of 4.52 and 4.64 square miles, drain southward into Galveston Bay; while all of the north portion of the city, with a contributing drainage area of 32.30 square miles, drains northward into Moses Lake. In the two smaller areas, pumping capacity of about 700,000 gallons a minute was found necessary in order to limit ponding to non-damaging stages from the runoff from rainfall of 9 inches in 24 hours plus wave overtopping, when high tide blocks gravity drainage.

In the Moses Lage ponding area, it was found that the interior runoff and wave overtopping could be ponded at low-damage levels and pumps would not be required. If the outlets were closed when the rising exterior tide reached 2 feet and opened as soon as the exterior tide fell below the interior water level, the runoff from a rainfall of 14 inches would pond to an elevation of 5.46 feet and the wave overtopping of about 500 acre feet would increase the ponding about one-fourth foot, to 5.71 feet above mean sea level. With the gravity outlets open, the runoff from a rainfall of 17 inches would pond to an elevation of 3.67 feet with an external tide of 0.0 mean sea level, and to 5.02 feet with an external tide 2.0 feet mean sea level. Ponding of these elevations would not cause excessive damages and would be permissible in the Moses Lake area.

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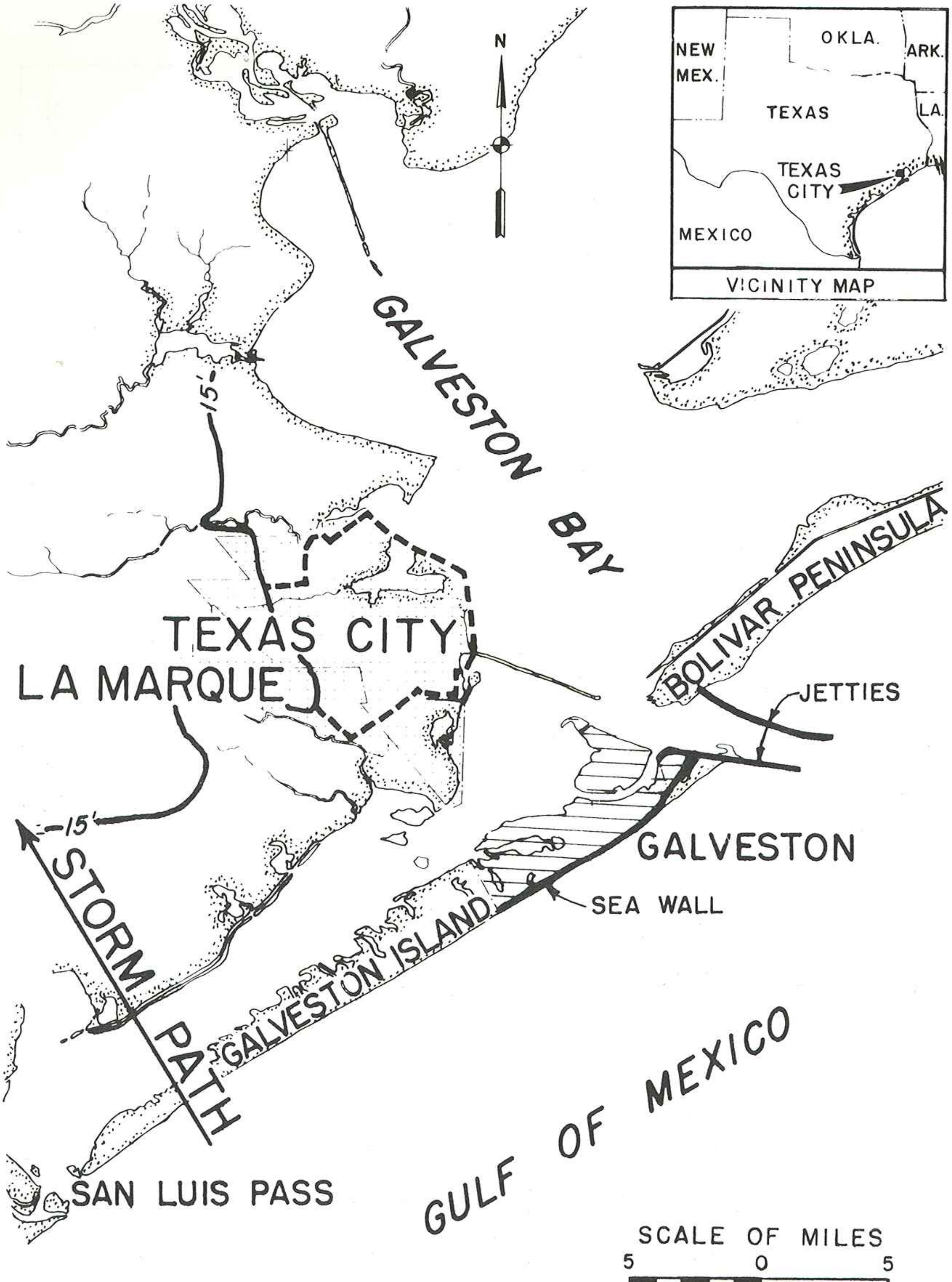
11. Beach Erosion Board, Technical Memorandum No. 108; Laboratory Data on Wave Run-Up on Roughened and Permeable Slopes (1959).
12. Saville, Thorndike, Jr.; McClendon, E. W. and Cochran, A. L. Freeboard Allowance for Waves in Inland Reservoirs, Proceedings of the American Society of Civil Engineers (1962).


LOCATION MAP, SHOWING LOCATION OF TEXAS CITY ON THE GULF OF MEXICO

FIGURE 1

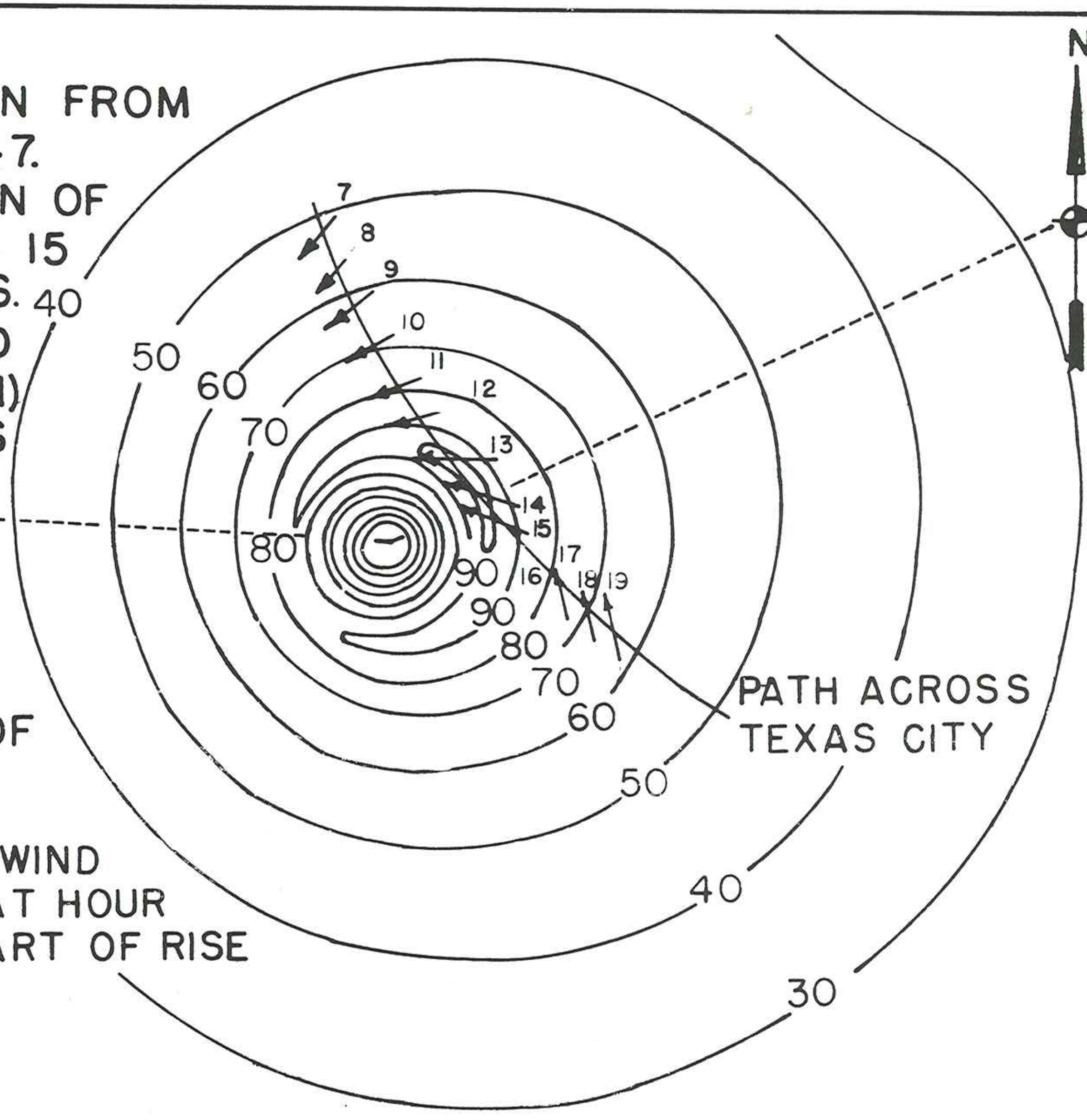



VICINITY OF TEXAS CITY

FIGURE 2

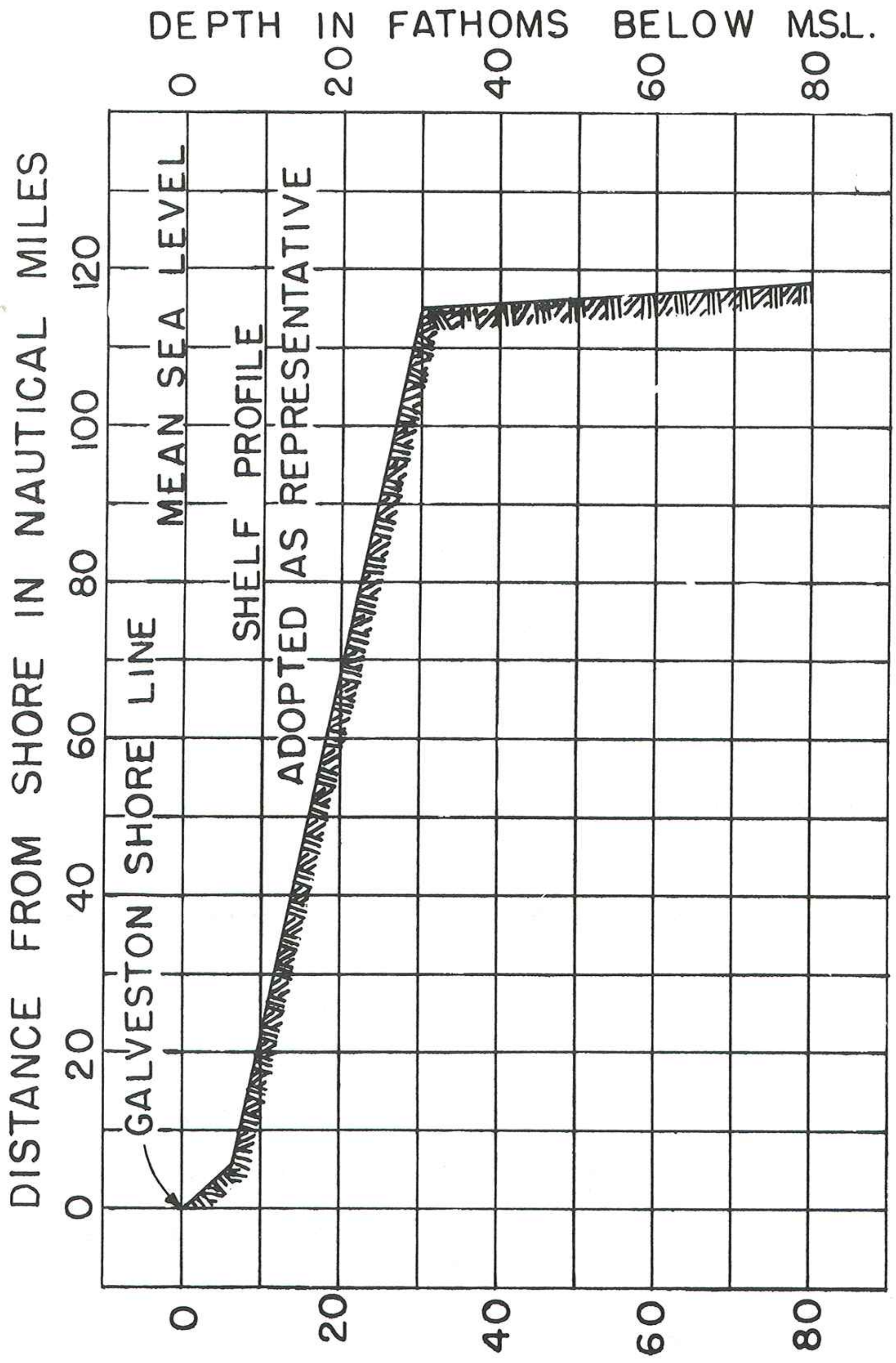
NOTES

1. ISOVEL PATTERN FROM HURRICANE 7-47.
2. RADIUS TO REGION OF MAXIMUM WINDS 15 NAUTICAL MILES.
3. FORWARD SPEED 11 KNOTS. (13 MPH)
4. WIND VELOCITES IN MPH SHOWN ON ISOVEL PATTERN.
5. ----- LIMIT OF ROTATION FOR DEVELOPMENT OF MOST CRITICAL CONDITIONS.
6. ↖13 DIRECTION OF WIND AT TEXAS CITY AT HOUR SHOWN FROM START OF RISE IN TIDE.




WIND PATTERN OF DESIGN STORM

FIGURE 3




PROFILE OF CONTINENTAL SHELF ALONG STORM PATH THROUGH GALVESTON

FIGURE 4

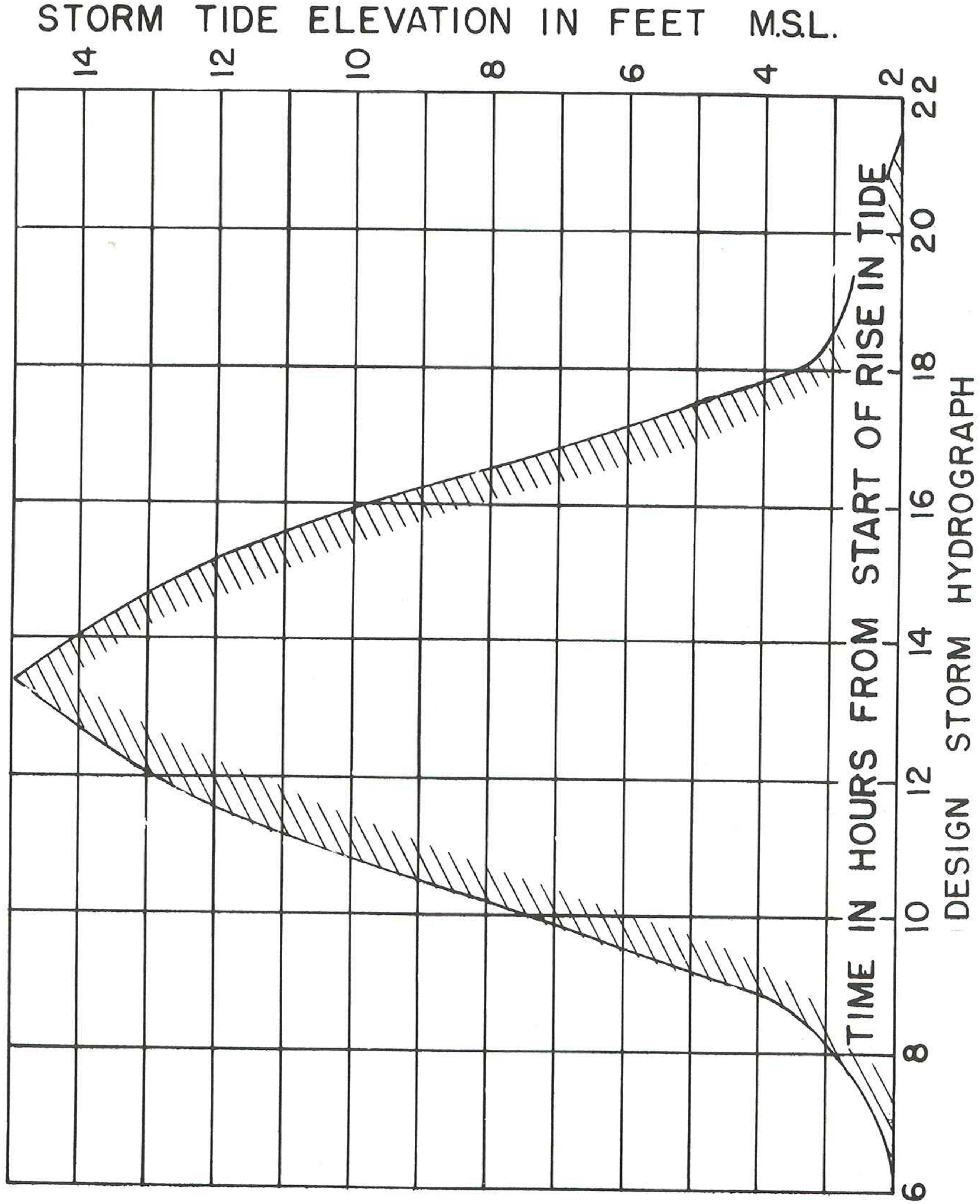
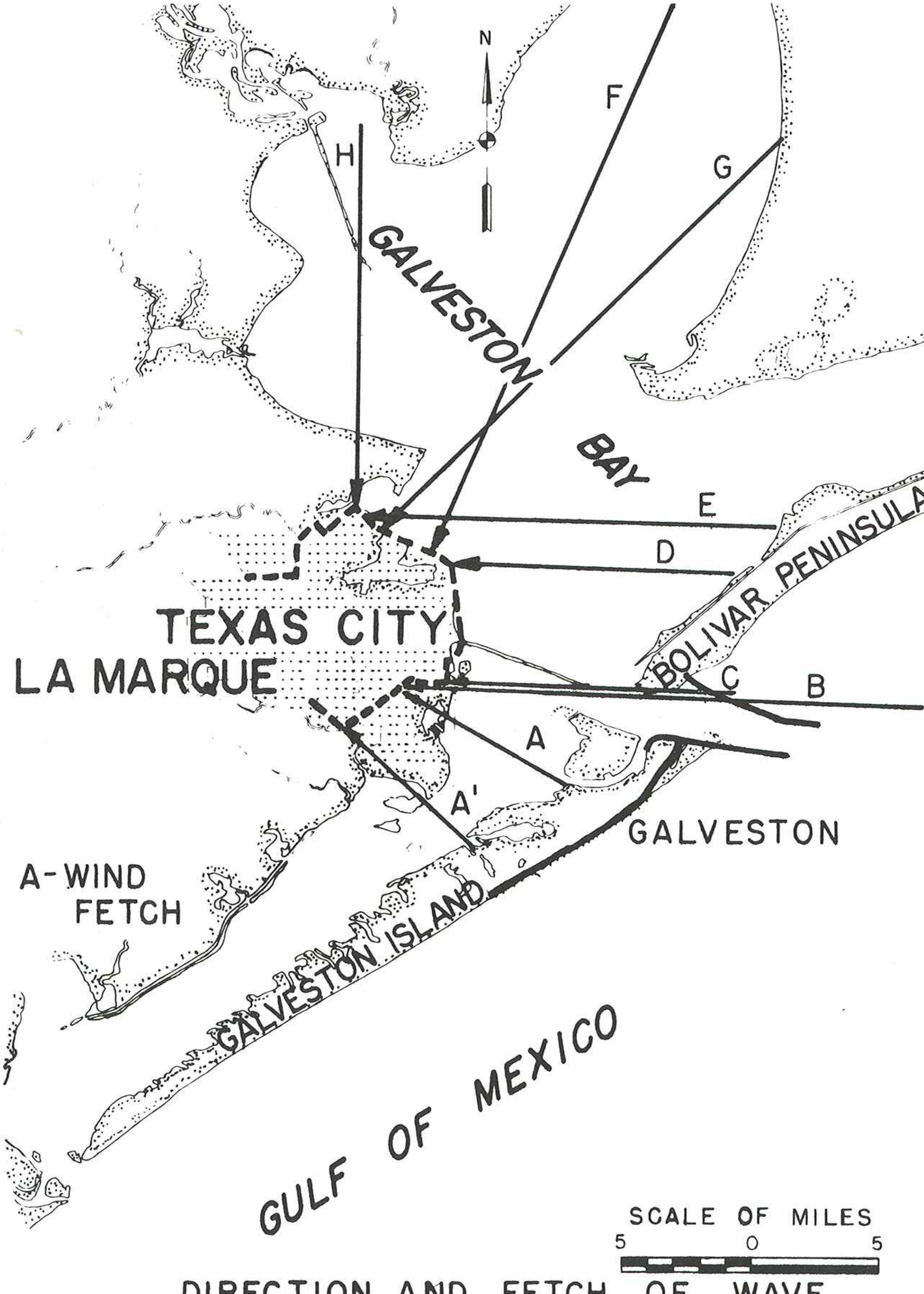

STORM TIDE ELEVATION IN FEET M.S.L.
14
12
10
8
6
4
2
TIME IN HOURS FROM START OF RISE IN TIDE
6
8
10
12
14
16
18
20
22
DESIGN STORM HYDROGRAPH

FIGURE 5




DIRECTION AND FETCH OF WAVE ATTACK BY REACHES OF PROTECTIVE STRUCTURE AT TEXAS CITY

FIGURE 6