CHAPTER 123

ANALYSIS OF HURRICANE TIDES AT PADRE ISLAND, TEXAS

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ABSTRACT

To establish design data, a study was undertaken to determine expected hurricane tide elevations, durations and frequencies of occurrence for events of various magnitudes in the vicinity of a proposed development at Padre Island, Texas A set of synthetic hurricanes with selected sizes, translation speeds, wind fields, and pressure patterns were generated corresponding to various frequencies of occurrence of the CPI Two numerical computer models were developed to determine the offshore surge hydrograph and to route the surge through the bay waters for each synthetic hurricane moving directly over the site

Results included storm tide hydrographs at selected locations near the development Synthetic storms were also routed across the coast at locations north and south of the site and storm hydrographs again computed

INTRODUCTION

This study was undertaken to investigate hurricane tides on the Laguna Madre and Corpus Christi Bay sides of Padre Island The location shown in Fig 1 represents an extensive property development on the northernmost end of Padre Island and is connected to the mainland near Corpus Christi, Texas, by the John F Kennedy Causeway Of particular concern at the site were hurricane tide elevations, durations, and frequencies of occurrence of storm events of various magnitudes

The specific objectives of this study are summarized as follows (1) Determine the offshore storm tide hydrographs near the site which result from hurricane events of various frequencies of occurrence, (2) Route these same hurricanes over the shallow waters of Corpus Christi Bay and the Laguna Madre and calculate the storm tide hydrographs generated on the bay side of the development site on both the Corpus Christi Bay and Laguna Madre sides

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of the causeway, and (3) Determine the effects of hurricanes moving across the coastline at distances north and south of the development site and calculate the storm tides generated on both sides of the causeway and at the development site

Because there are insufficient data to develop a reliable statistical representation of hurricane tides in Corpus Christi Bay and the Laguna Madre, two computer models based on the fundamental equations of motion were developed for computing offshore storm surge and for routing this surge through the shallow bay waters These models were first verified for measured astronomical and hurricane tides They then were used to develop synthetic offshore hydrographs for storms of various frequencies of occurrence and to compute the storm tides at selected points in Corpus Christi Bay and the Laguna Madre resulting from these hurricanes

For calculating hurricane tides, many of the hydrographic and physiographic features characteristic of the region needed to be described These features include shallow water depths in Corpus Christi Bay and Laguna Madre, small islands, spoil dumps and limited exchange of waters between the Gulf of Mexico and the bay and lagoon In the immediate vicinity of the development, other conditions exist that could affect the magnitudes of hurricane tides A step type seawall, Ref [1], is now in existence over a portion of the Gulf side of the development site and is proposed to be extended to eliminate the possibility of Packery Channel cutting open to the Gulf of Mexico during hurricanes

The John F Kennedy Causeway which connects Padre Island with the mainland is an earth-fill dike with openings for the Intracoastal Canal and the Humble Channel For hurricanes crossing the coast north of the development site, the causeway serves as a barrier and restricts the flow of water into the Laguna Madre until tides reach an elevation that produces overtopping of the causeway Similarly, the causeway restricts flow into Corpus Christi Bay for hurricanes moving up the coast from the south Islands formed by placement of dredge spoil from the construction of the Intracoastal Canal on the Laguna Madre side of the site also act as partial barriers to restrict somewhat the flow of water and consequently lower peak hurricane tide elevations slightly

PROBLEM ANALYSIS

To obtain answers to the stated objectives, the problem analysis was divided into the following three parts (1) Establishment of storm

characteristics for synthetic hurricanes with various frequencies of occurrence, (2) Determination of synthetic hurricane surges offshore of the site, and (3) Determination of storm hydrographs at the development site utilizing the hydrographic and physiographic features of Corpus Christi Bay and Laguna Madre, the synthetic hurricane characteristics and the corresponding offshore surges

Frequency Analysis After an extensive literature review, it was decided that within the scope and time frame available for this study, the most meaningful frequency analysis could be accomplished through the generation of a set of synthetic hurricanes The U S Weather Bureau, Ref [2], has divided hurricanes affecting the Gulf Coast into three zones of approximately 80,000 square nautical miles each, one of which covers the Texas Coast and a small portion of the coasts of Louisiana and Mexico Hurricanes within each zone have been analyzed for frequency of occurrence of the Central Pressure Index (CPI) and for size, translation speed, wind magnitudes, and other characteristics From these analyses, the frequency of occurrence of the CPI is determined for selected locations along the Gulf Coast, including Corpus Christi The CPI is the minimum estimated pressure in a storm and is a good indicator of storm intensity

Once the CPI has been determined for a specified frequency, Ref [2] presents a series of steps by which synthetic hurricanes or "standard project storms" can be constructed Utilizing the CPI as basic information, it is possible to determine the radius to maximum winds for various radii storms, the variations of this radius with longitude and latitude, the translation speed of the storm, probable azimuth, maximum cyclostrophic wind, maximum gradient wind and maximum wind speed 30 feet over water Table I is a summary of the principal characteristics of synthetic hurricanes developed at Corpus Christi with frequencies from 3 3 years to 100 years These characteristics were determined in part by the methods of Ref [2] and by adjustments based on judgment to more nearly reflect conditions near the Corpus Christi area

In reviewing the relation between CPI and the radius to maximum winds, it was noted that data for the Texas coastal zone and in particular that for the Corpus Christi area indicate that the local mean radius storm is smaller than the average mean radius storm for all events Similarly, the longitudinal correction to the radius to maximum winds shows a negative departure from the mean of about five nautical miles for a longitude near 96^{o} W Hence, the values of radius to maximum wind were adjusted to reflect these Corpus Christi characteristics Also in selecting the translation speed for the hurricane center, a modal value based on the cumulative percent of occurrences of all events was chosen From Ref [2], eleven knots is considered as a representative moderate speed and was taken as constant for all frequency hurricanes

TABLE 1 SUMMARY OF SYNTHETIC HURRICANE CHARACTERISTICS

S_o (ft)	T_r (yrs)	CPI (in)	R (n mi)	V_{cx} (mph)	V_{gx} (mph)	V_x (mph)
2 0	100	27 44	12	110	108 2	99 9
2 0	75	27 50	12 5	108	106 2	98 3
2 0	50	27 60	13	107	105 1	97 3
2 0	30	27 73	13 5	103	101 1	93 8
1 5	20	27 88	14	99	97 0	90 4
1 5	15	27 94	14 5	97	95 0	88.3
1 5	10	28 16	15	92	90 0	84 2
1 0	5	28 56	15 5	82	79 9	75 3
1 0	3 3	28 84	16	68	65 9	63 3

LIST OF SYMBOLS

S_o = Initial hurricane surge
T_r = Return period of storm
CPI = Central Pressure Index or the estimated minimum pressure for a particular hurricane
R = Distance from center of storm to region of maximum winds
V_{cx} = Maximum cyclostrophic wind
V_{gx} = Maximum gradient wind
V_x = Estimated maximum 30 foot over-water speed

Synthetic Storm Development Before the storm tide hydrographs could be determined at selected points in Corpus Christi Bay and Laguna Madre, it was necessary to know the hurricane surge hydrograph offshore in the vicinity of the development It is this storm surge that acts at the tidal inlets and, depending on magnitude, may overtop Padre Island As such, offshore tide represents one of the boundary conditions necessary to calculate tides within the bay and lagoon

In hydrograph form the offshore surge gives a complete picture of the effects of the hurricane Information required for the solution of this tide includes definition of the bottom profile offshore from the site to the edge of the continental shelf and knowledge of the wind's magnitude and direction across the entire width of the hurricane U S C G S Hydrographic Charts provided the required data for the bottom profile Wind patterns for the design storms could be taken either from actual historical hurricanes which have been documented or from synthetic storms such as illustrated in Ref [2]

Total storm surge offshore associated with a given hurricane is normally broken into several components for calculation The total hurricane surge above mean sea level consists of an initial surge, an astronomical tide, a pressure tide and the components of wind tide due to winds blowing perpendicular and parallel to the coast The initial surge is that associated with Gulf hurricanes and usually varies from one to two feet To be conservative, the astronomical high tide above mean sea level was selected to coincide with the peak of the storm tide The pressure tide was taken as 1 14 times the pressure differential expressed in inches of mercury Wind tides were computed from wind magnitude, wind direction, duration and from a consideration of bottom and water surface shear stress coefficients

In determining hurricane tide hydrographs there is the problem of appropriate values for the bottom friction and surface wind stress parameters used in the calculations The most direct way to evaluate such parameters is to compare actual measured hurricane tide hydrographs with computed hydrographs, determined as above but with actual data on the wind patterns, wind magnitudes, storm directions, CPI, etc It then becomes a matter of adjusting the bottom friction and wind stress coefficients until the computed hydrograph can be made to agree reasonably well with that actually measured

The final hydrographs at the coast for a series of synthetic storms were obtained by placing the hurricane wind patterns with their leading edge at the coast, calculating the wind tides shoreward from the edge of the continental shelf, and then moving the wind patterns shoreward a prescribed distance and again performing the wind tide calculations This process was repeated until the end of the hurricane passed over the coastline Synthetic surge hydrographs were computed for hurricanes with return periods of 3 3, 5, 10, 20, 30, 50 75 and 100 years, and those for 10, 30 and 100 year return periods are included in Fig 6 The isovel pattern used in the calculations is that of a mean radius moderate speed of translation standard project hurricane To reflect the lower winds in the more frequent hurricanes, the wind magnitudes at specified radii were scaled proportionally by the ratio of the maximum wind speeds of the lesser storms to that of the standard project storm

Storm Hydrographs at the Development Site The calculation of the storm tide hydrographs in Corpus Christi Bay and the Laguna Madre involved a numerical solution to the two-dimensional vertically integrated equations of motion and continuity These equations were solved for the boundary configurations of the bay and lagoon and included such significant features as spoil banks, causeway, barrier islands, tidal inlets, flow controls, and the Intracoastal Canal The boundary conditions for the equations included the storm surge hydrographs off-coast at Port Aransas, other tidal inlets and locations where Padre

Island was likely to be overtopped Wind was another external surface force applied to the water surface within Corpus Christi Bay and the Laguna Madre

The method utilized in the bay tide computations is based on work described in Ref [3] The first step was construction of an Eulerian type grid, one nautical mile square, which approximated the general physiographic and hydrographic features of the development area Figure 2 is a small scale map of Corpus Christi Bay, Laguna Madre and Baffin Bay with the computational grid superimposed Figure 3 illustrates the control features included within the computational model The dash lines correspond to reefs, spoil banks or other flow control situations The solid lines correspond to impermeable barriers such as islands and the causeway

In a manner similar to that used for the offshore hurricane surge hydrographs, it was also necessary to calibrate this computational model In a complicated configuration such as that represented by the combination of Corpus Christi Bay, Laguna Madre and Baffin Bay, this calibration was done in two steps The first involved calibrating the bay for normal astronomical tides without the influence of wind, or with wind effects minimized When the model was verified for astronomical tides, it was then operated using the offshore hurricane surge at tidal inlets and with varying wind on the water surface to compute the hurricane tide within the bay

Verification of the computational model for astronomical tide was obtained by comparing the computed tide with the actual tide measurements at the Naval Air Station in response to a known tide imposed at Aransas Pass The Naval Air Station is a location near the development site, Fig 2 , where normal astronomical tides were recorded by the Corps of Engineers Figure 4 illustrates an astronomical tide measured at Corpus Christi Naval Air Station compared with the computed tide from the numerical model The maximum departure of the computed curve from the measured tide is on the order of 0 1 feet For the purpose of this study, this agreement is considered adequate verification of the astronomical tides and bottom friction conditions in Corpus Christi Bay

Further hurricane tide verification was accomplished by introducing into the model, conditions associated with Hurricane Beulah The storm tide recorded at Port Aransas was introduced at the jetties, and utilizing the winds associated with Beulah, the hurricane storm tide was computed at the Corpus Christi Naval Air Station This hydrograph is illustrated in Fig 5 where it can be seen that the model reproduced the actual measured tide quite satisfactoril Tides were also computed at several other locations but are not included in this paper The major difficulty in this calibration process was the inclusion

of the high runoff resulting from the large rainfall which accompanied Beulah and the rainfall on the bay itself These conditions were approximated for this model from available data in Ref [4] Winds recorded at the Corpus Christi Airport during the passage of Hurricane Beulah were applied in the time-dependent fashion measured at the airport to duplicate the tides recorded at different stations within Corpus Christi Bay

To predict the tides on the Corpus Christi Bay and Laguna Madre side of the development and to simulate those conditions during which the Kennedy Causeway would be overtopped, the model had to be extended to include the Laguna Madre to a point south of Baffin Bay Another extensive data search was undertaken to acquire quantitative information on the hydrodynamic characteristics of the Laguna Madre-Baffin Bay area No tide data were available for this location and it was necessary to synthesize the behavior of tides south of the causeway Although it was not possible to verify the computed tides in the Laguna Madre or Baffin Bay area, it was possible to compare qualitatively the computed results with those obtained during Hurricanes Beulah and Carla, and to note that the same general trends and characteristics existed It was found that after allowing the Kennedy Causeway to be overtopped, very good verification of the Beulah hurricane tide at the Corpus Christi Naval Air Station was achieved For this reason, it is believed that the total model including Corpus Christi Bay, Laguna Madre and Baffin Bay was sufficiently verified for the analysis used in this study

ASSUMPTIONS AND MODEL LIMITATIONS

It is not difficult to envision a great number of combinations of hurricane events each of which may contribute to the storm hydrographs developed offshore and in the bays and lagoons Such factors as storm path, storm size, CPI, translation speed, winds, and storm azimuth are some of the variable hurricane characteristics Similarly, unpredictable factors such as the time during which the storm remains offshore and any unusual changes in storm course also control the formation of hurricane surge Once within a bay, such variables as the amount, intensity, distribution and duration of rainfall on the bay itself and the runoff from contiguous land areas are also factors which affect the height, shape, and duration of the storm tide hydrograph Obviously with so many variables very few of which are statistically predictable, caution must be used in attempts at generalizations of hurricane events at a given site

Although it was necessary to make assumptions on the distribution of rainfall during Hurricane Beulah for proper verification of storm tides at the Naval Air Station, the synthetic storms on which the results of this study are based do not include rainfall Since the storms themselves are synthetic and rainfall frequencies are not established relative to the hurricane frequencies,

attempts at introducing rainfall and rainfall distributions within the time frame available for this study would not be meaningful It also was noted in the offshore storm hydrographs that the surges rise and fall rapidly, even though a decay factor was included in the model Part of these rapid changes is due to the synthetic nature of the storms, but part is also due to the absence of rainfall which normally accompanies such storm events

The computational model used in this study does not allow for inundation of adjacent land mass The 10 and 15-foot contours lie very near the water line throughout most of the area in the vicinity of the development with the exception of the Laguna Madre side of Padre Island Actually the volume of water involved in land inundation in the area covered by the model is very small in relation to the volume of water in Corpus Christi Bay and the Laguna Madre, and omission of land inundation should not have a noticeable effect on the computed tides in this area Furthermore, this assumption is conservative, for if there is any effect at all, it would be to produce lower tides than those calculated

Although the results in the following section are based totally on synthetic storms, they provide an indication of the magnitude and duration of hurricane tides due to storms of specified frequencies The results are also conservative in that the lesser magnitude storms are based on the isovel patterns for a 100-year storm with a linear adjustment applied to the wind velocities for the less severe events Hence, the duration of the smaller events may be somewhat greater than would occur in an actual small storm On the other hand, these storms do not include rainfall and runoff and the computed tides could be of lower amplitude than those of a true storm with heavy precipitation

DISCUSSION OF RESULTS

The operation of the simulation model of Corpus Christi Bay, Laguna Madre, and Baffin Bay with synthetically generated offshore inputs at Port Aransas, Corpus Christi Pass, and Yarborough Pass has permitted the computation of tide hydrographs at selected points at the development site Synthetic hurricanes were routed across the shoreline with the eye crossing approximately 15 miles south of Port Aransas This produced maximum storm tides at the Port Aransas jetties, the major tidal inlet to the Corpus Christi Bay area Since the actual development site is protected on the Gulf side by a seawall and by proposed stabilization measures for Packery Channel and vicinity, it would appear that even though the maximum storm tides were allowed to exist immediately at the site, it would be unlikely that serious overtopping of Padre Island would occur at that point However, in the computational model, allowances have been made for flow and tide at Corpus Christi Pass, which presumably will be opened and maintained in the future Port Aransas also was

selected as the point for application of maximum storm tide since it was a location for which some surge data were available and was the input location for verification tides at the Naval Air Station during Hurricane Beulah Also, since frequencies are based on average conditions for the Texas Coast, the probabilities of an event crossing at a specific point are undoubtedly less Thus, the slight shift of the storm to permit tide computations at a point where some data were available is not considered significant

Development Site Tides Corresponding to the offshore hydrographs from the synthetic storms, tide hydrographs in the bay were computed near the development site at the points defined in Fig 1 The location of the two points considered most representative of the site were defined as Packery Channel and Padre Island Site West Three of the computed hydrographs for these two locations are shown in Fig 6 and are based on a causeway elevation of 4 5 feet which is near the present average elevation These hydrographs account for overtopping of the causeway when storm tides increase beyond an elevation of 4 5 feet For convenience, the input tides used in the calculations have also been included on these figures

The maximum storm tide elevations at Aransas Pass, Padre Island Site West, and at Packery Channel are summarized in Fig 10 where the maximum computed storm tide has been plotted against the probability of occurrence in any one year The input tide at Aransas Pass varies from 6 2 feet for a storm with 3 3-year return period to 11 7 feet for the 100-year storm The 30-year computed storm tide elevation is 11 2 feet although the curve indicates an elevation of about 10 8 feet Figure 10 also shows that the storm tides at Packery Channel, i e , on the Corpus Christi Bay side of the causeway, are always higher than tides on the Laguna Madre side of the development site The maximum storm tide at Packery Channel computed from the 100-year storm is 7 9 feet whereas at Padre Island Site West it is 7 feet The 30-year storm for the same sites produces tides of 7 4 and 6 7 feet respectively

It is also significant to note that for the less frequent storms there is less change in the magnitude of storm tide at all locations including Aransas Pass For example, it can be seen from Fig 10 that for the existing causeway elevation of 4 5 feet, the tides expected from a 30-year storm differ from a 100-year storm by less than 0 6 feet This small change in maximum tide is due to the small difference in maximum average wind speed between the less frequent storms This can be noted in Table I

As also illustrated in Fig 6, the Padre Island Site West tide always lags the Packery Channel tide indicating the delaying influence of the causeway Actually the storm tides on the Laguna Madre side of the development do not begin to increase appreciably until the tides on the Corpus Christi Bay side are of sufficient magnitude to overtop the causeway at elevation of 4 5

feet The Intracoastal Canal alone is not large enough to enable the exchange necessary for the tide to build up on the Laguna Madre side as rapidly as it does on the bay side This delay varies from about six to eight hours depending on storm magnitude It can also be noted that the Packery Channel tide reaches a peak shortly before the eye crosses the coastline and then falls rapidly as the eye crosses the coast and winds reverse direction This wind reversal also contributes to the rapid rise in the Padre Island Site West tide immediately after the storm passes the coast and winds begin to blow up Laguna Madre When the Padre Island Site West tide reaches its peak the eye has already crossed the coast and the Packery Channel tide has begun to fall Water from the Laguna Madre then flows back over the causeway into Corpus Christi Bay This, coupled with the fact that no sudden changes in wind direction occur after the eye has passed the site, produces a flatter peak on the Laguna Madre side The oscillation noted in the storm hydrographs after the passage of the peaks actually represents the astronomical component of the total tide

Further insight into the tide behavior on both sides of the causeway for different storm events can be obtained from Fig 7 These curves are computed for various frequency storms at points identified as Intracoastal Canal South, Intracoastal Canal North, Humble Channel South and Humble Channel North The locations of these points also are illustrated in Fig 1 These hydrographs give comparisons of the storm tide elevations for the three storm events of 10, 30 and 100 years at two points on each side of the causeway It is not possible to construct a duration of overtopping-frequency relationship because by the nature of the synthetic hurricanes the more severe events tend to be somewhat tighter storms in order to produce the lower CPI's This leads to the apparently anomalous condition in which the less frequent events produce shorter periods of overtopping once overtopping is significant The study of the isovel patterns for less severe storms requires analysis considerably in excess of that available to this study

It can also be noted from Fig 7 that the tides on the south side of the causeway are characterized initially by very low tides followed by a rapid rise in the water surface In fact, the tide at Humble Channel South becomes less than mean sea level meaning that water is blown out of the computational cell at that point No verification data of this condition are available, however, qualitative data obtained during Carla, Ref [5], indicates very low tides in this area Also an astronomical tide study south of the causeway, Ref [6], shows that tides change very rapidly with relatively small changes in wind velocity or direction In the case of the synthetic hurricanes, the winds are northerly to northeasterly until the eye crosses the coast As already noted, overtopping of the causeway occurs at about this same time This overtopping together with the sudden reversal to winds from the south and southwest lead to this very rapid rise in water surface elevation

Storms at Other Locations In order to obtain some insight into the tides generated from hurricanes crossing the coast at locations other than at the development site, two conditions were considered These included the 30-year storm crossing the coast at points 50 miles south and 50 miles north of the site The storm hydrographs computed for these conditions at Packery Channel and Padre Island Site West are shown in Fig 8 Also the corresponding tides on each side of the causeway are given in Fig 9 These computations have been carried out for a causeway elevation of 4 5 feet

Rather than re-rout the 30-year storm with its attendant adjustments into the coast over different offshore profiles, a linear adjustment based on observations made during Hurricane Carla, Ref [5] was applied to the input tide used in the previous computations It is well established that hurricane tides to the right of the eye when viewed in the direction of travel are larger than tides to the left of the eye This is because of the large component of tide resulting from onshore winds Thus, a hurricane crossing the Texas Coast south of the development site will produce a larger tide at the site than if the same storm moved inland north of the site Corresponding to the Carla results, the input tide at Aransas Pass was reduced to 90% for the storm south of the site and by 75% for the storm north of the site No adjustment was made to the storm duration

All the tides thus computed are lower than those produced by the 30-year storm at the site This can most easily be seen in Fig 11 which summarizes the maximum tides at Aransas Pass, Packery Channel and Padre Island Site West for the various storm locations One point of note is that for the storm south of the site, the Padre Island Site West tide is slightly higher than the Packery Channel tide Although the difference in actual magnitude may not be of numerical significane, the behavior of the tide in Laguna Madre relative to the Packery Channel tide is different than for a storm crossing at the site or to the north of the site It is possible that a slightly more severe storm or possibly one at some other location south of the site could produce a higher tide in the Laguna Madre than in Corpus Christi Bay This, of course, assumes that sufficient overtopping of Padre Island occurs so that a large enough volume of water is available for the tide buildup Although different storm paths were involved, a similar effect can be noted by comparing the computed tides with the spot tide elevations reported for Hurricane Carla and Beulah Carla which crossed the coast at Port O'Conner caused high tides at the Naval Air Station near the site and very low tides in the Laguna Madre Beulah, which affected the southern part of the coast, produced high tides in the Laguna Madre as well as Corpus Christi Bay

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[3] Masch, F D et al, (1969), "A Numerical Model for the Simulation of Tidal Hydrodynamics in Shallow Irregular Estuaries," Technical Report HYD 12-6901, The University of Texas at Austin

[4] U S Army Engineers District, Galveston, (1967), Report on Hurricane Beulah, U S Corps of Engineers, Galveston, Texas

[5] U S Army Engineers District, Galveston, (1962), Report on Hurricane Carla, U S Corps of Engineers, Galveston, Texas

[6] Copeland, B J and Thompson, Jr , J H , (1968), Effects of Wind on Water Levels in the Texas Laguna Madre, The Texas Journal of Science, Vol VV, No 2, December, 1968

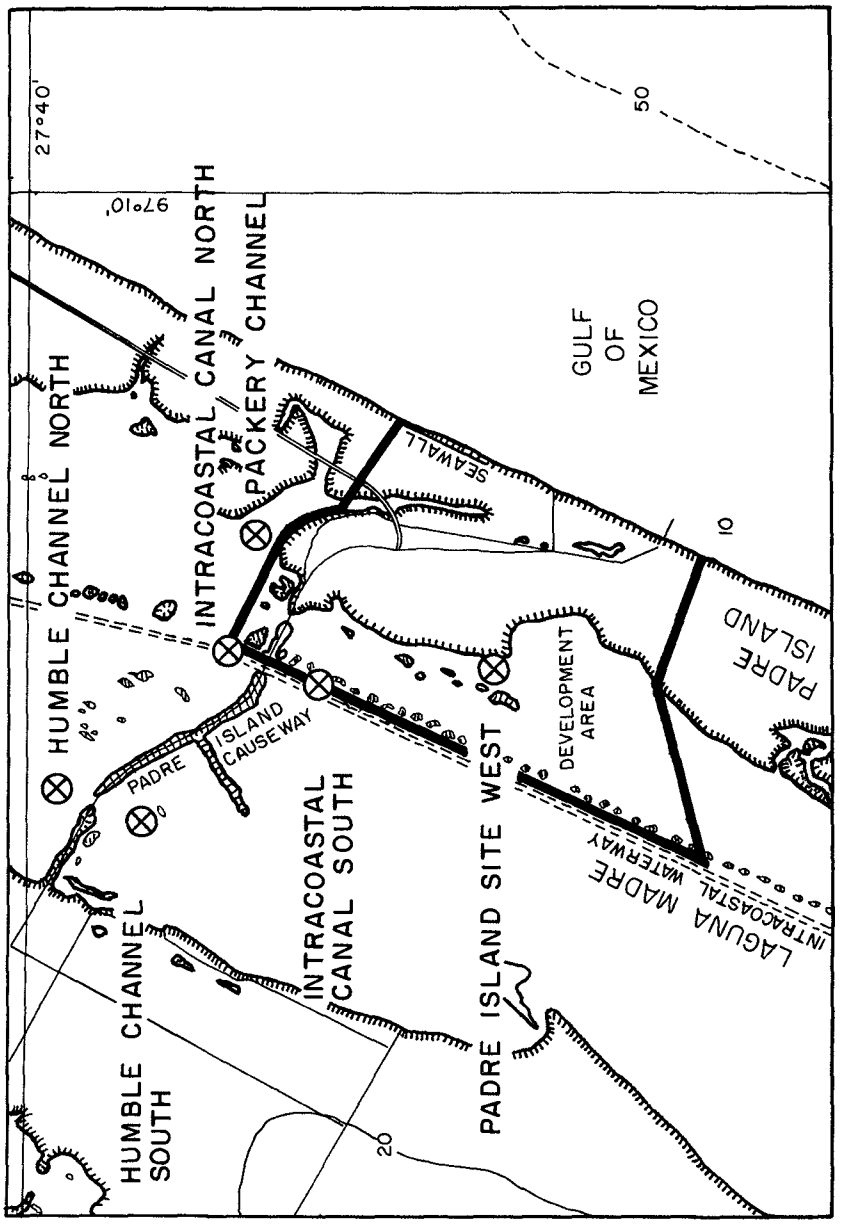


FIGURE I TIDE STATION LOCATIONS

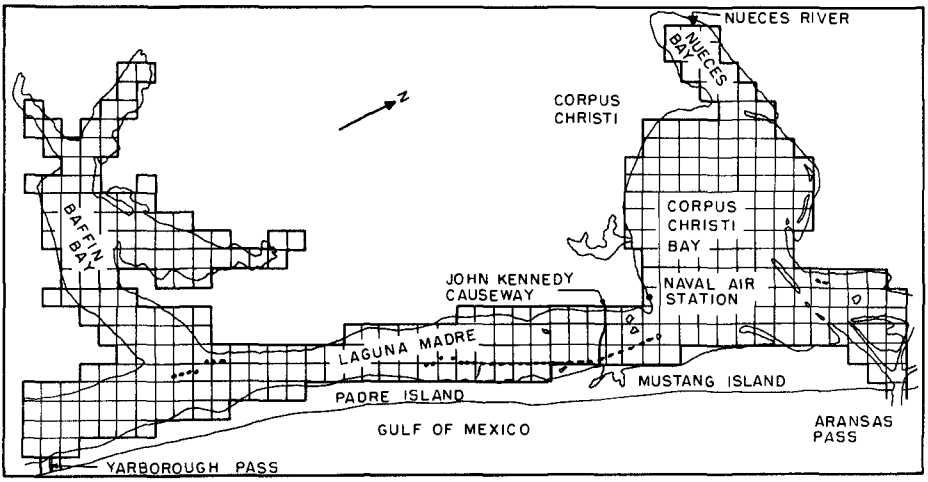


FIGURE 2 CORPUS CHRISTI AND BAFFIN BAY GRID LAYOUT

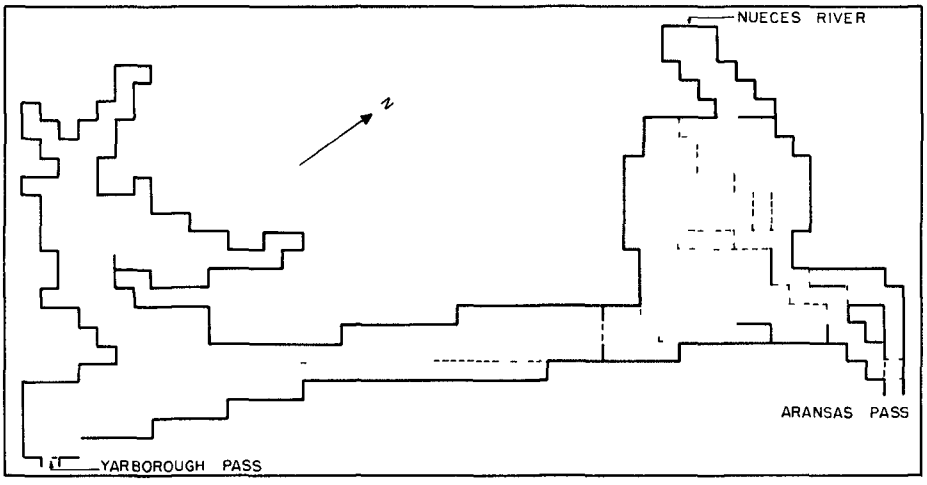


FIGURE 3 COMPUTATIONAL GRID SHOWING FLOW CONTROLS AND BARRIERS

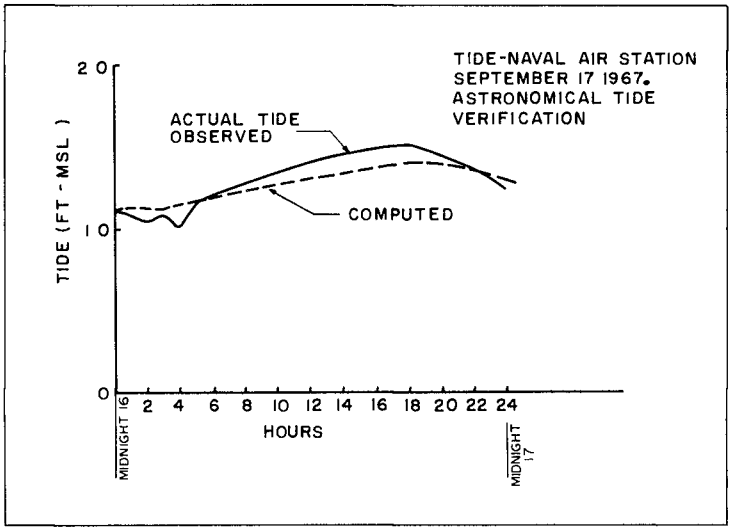


FIGURE 4 VERIFICATION OF ASTRONOMICAL TIDE - NAVAL AIR STATION

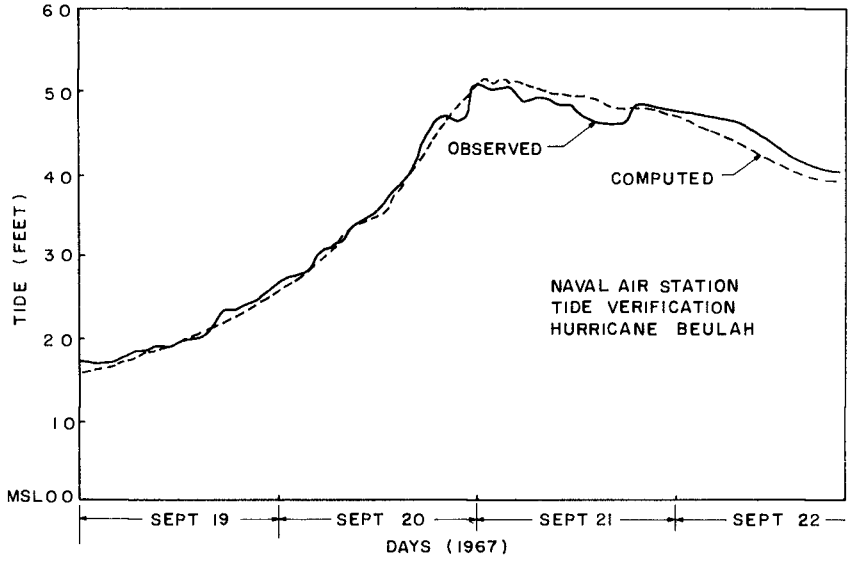
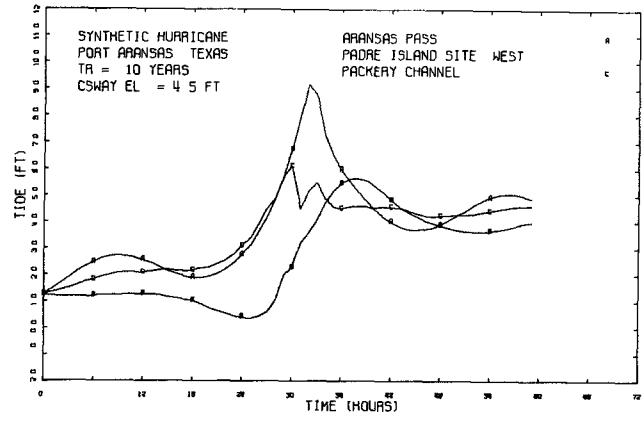
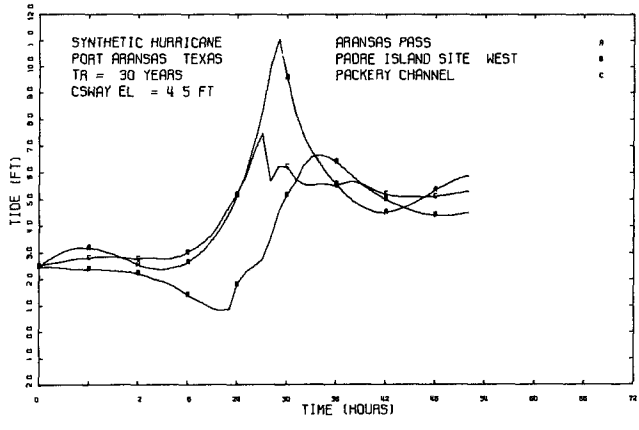


FIGURE 5 VERIFICATION OF HURRICANE TIDE-NAVAL AIR STATION


SYNTHETIC HURRICANE
PORT ARANSAS TEXAS
TR = 10 YEARS
CSWAY EL = 4 5 FT
ARANSAS PASS
PADRE ISLAND SITE WEST
PACKERY CHANNEL
TIDE (FT)
TIME (HOURS)


SYNTHETIC HURRICANE
PORT ARANSAS TEXAS
TR = 30 YEARS
CSWAY EL = 4 5 FT
ARANSAS PASS
PADRE ISLAND SITE WEST
PACKERY CHANNEL
TIDE (FT)
TIME (HOURS)

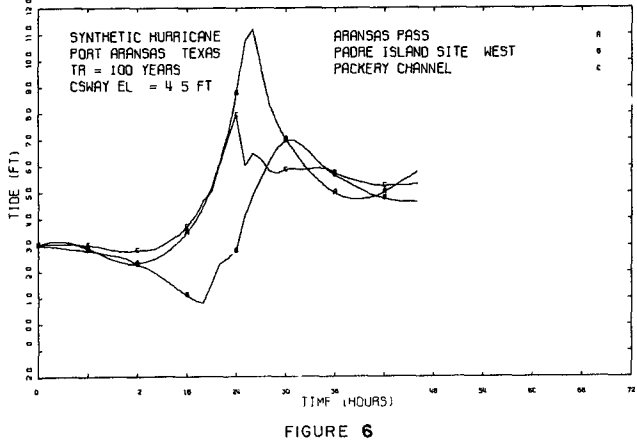
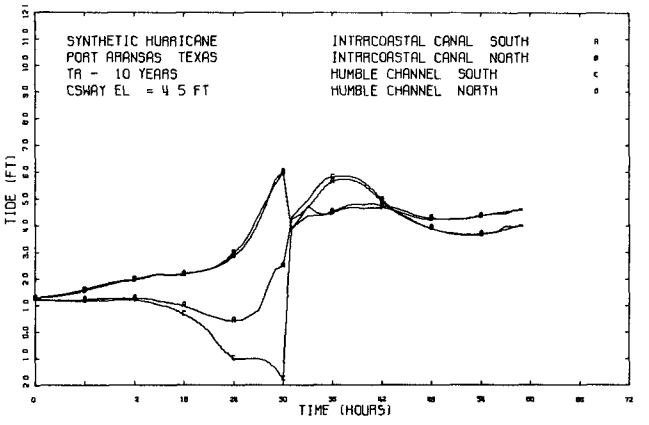
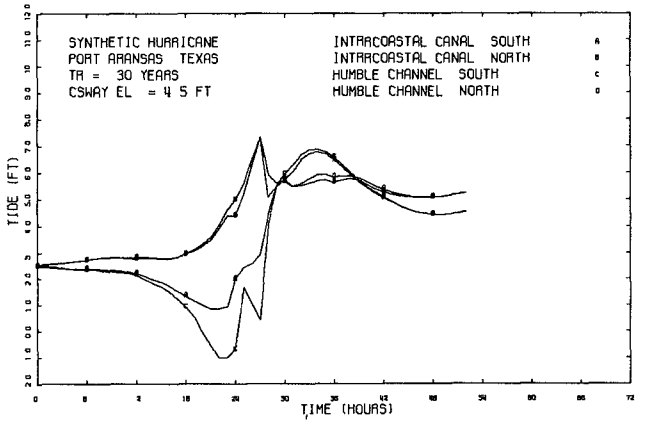

SYNTHETIC HURRICANE
PORT ARANSAS TEXAS
TR = 100 YEARS
CSWAY EL = 4 5 FT
ARANSAS PASS
PADRE ISLAND SITE WEST
PACKERY CHANNEL
TIDE (FT)
TIME (HOURS)

FIGURE 6


SYNTHETIC HURRICANE
PORT ARANSAS TEXAS
TR - 10 YEARS
CSWAY EL = 4 5 FT
INTRACOASTAL CANAL SOUTH
INTRACOASTAL CANAL NORTH
HUMBLE CHANNEL SOUTH
HUMBLE CHANNEL NORTH
TIDE (FT)
TIME (HOURS)


SYNTHETIC HURRICANE
PORT ARANSAS TEXAS
TR = 30 YEARS
CSWAY EL = 4 5 FT
INTRACOASTAL CANAL SOUTH
INTRACOASTAL CANAL NORTH
HUMBLE CHANNEL SOUTH
HUMBLE CHANNEL NORTH
TIDE (FT)
TIME (HOURS)

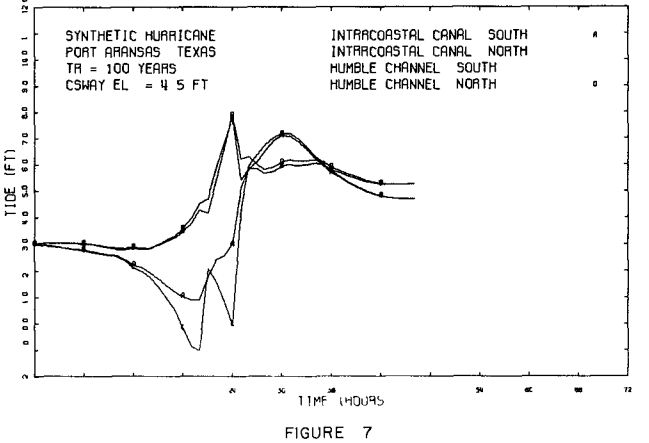
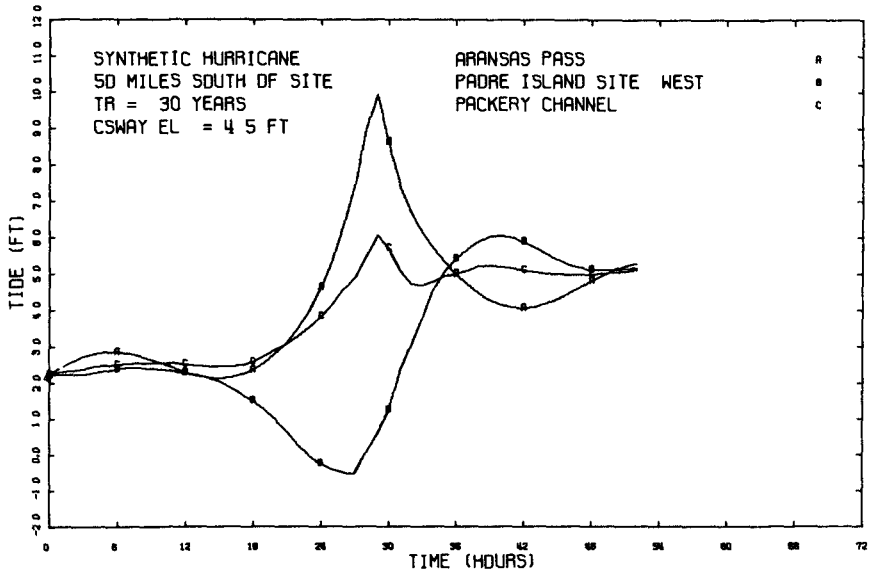

SYNTHETIC HURRICANE
PORT ARANSAS TEXAS
TR = 100 YEARS
CSWAY EL = 4 5 FT
INTRACOASTAL CANAL SOUTH
INTRACOASTAL CANAL NORTH
HUMBLE CHANNEL SOUTH
HUMBLE CHANNEL NORTH
TIDE (FT)
TIME (HOURS)

FIGURE 7


SYNTHETIC HURRICANE
50 MILES SOUTH OF SITE
TR = 30 YEARS
CSWAY EL = 4 5 FT
ARANSAS PASS
PADRE ISLAND SITE WEST
PACKERY CHANNEL
A
B
C
TIDE (FT)
TIME (HOURS)

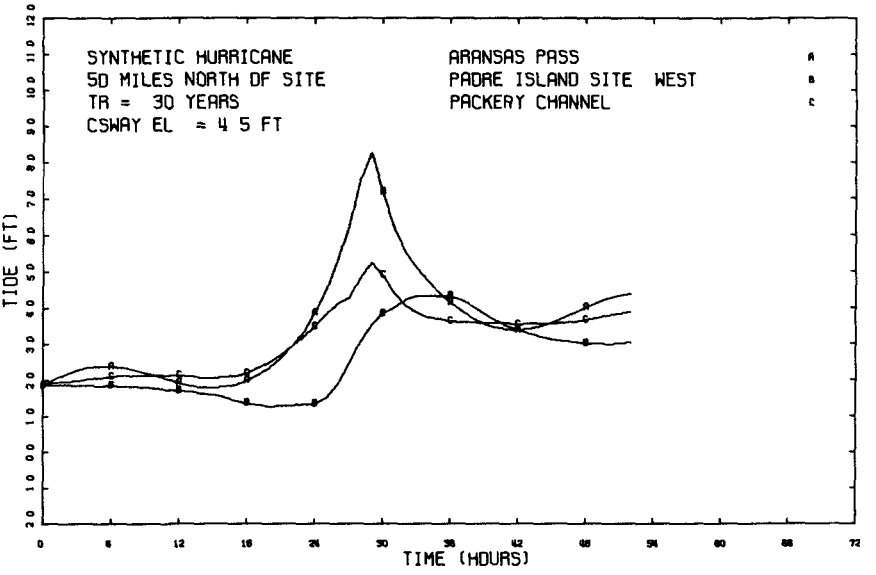
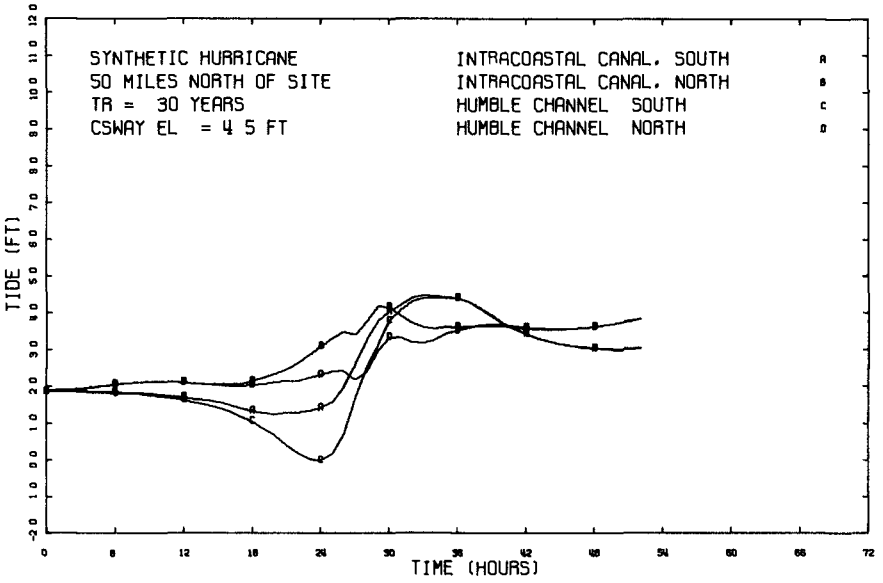

SYNTHETIC HURRICANE
50 MILES NORTH OF SITE
TR = 30 YEARS
CSWAY EL = 4 5 FT
ARANSAS PASS
PADRE ISLAND SITE WEST
PACKERY CHANNEL
A
B
C
TIDE (FT)
TIME (HOURS)

FIGURE 8


SYNTHETIC HURRICANE
50 MILES NORTH OF SITE
TR = 30 YEARS
CSWAY EL = 4 5 FT
INTRACOASTAL CANAL, SOUTH
INTRACOASTAL CANAL, NORTH
HUMBLE CHANNEL SOUTH
HUMBLE CHANNEL NORTH
TIDE (FT)
TIME (HOURS)

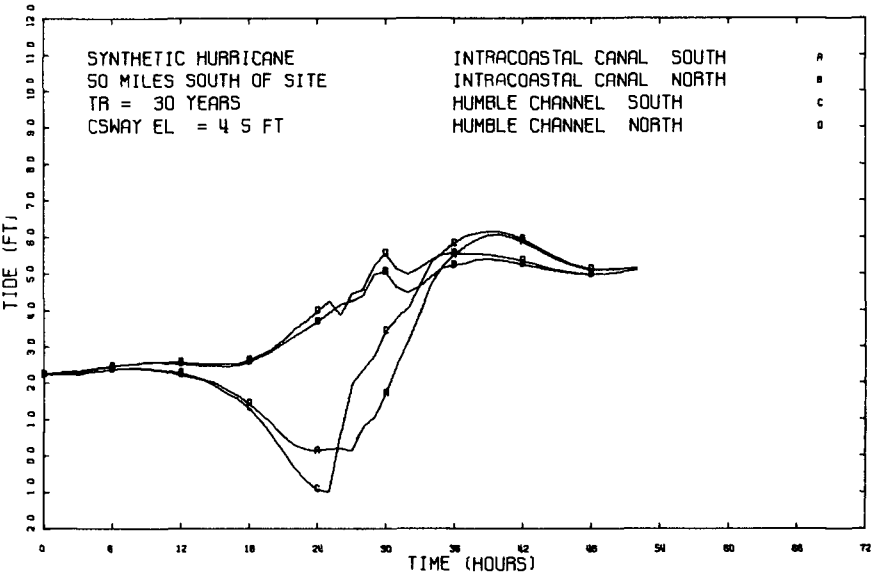

SYNTHETIC HURRICANE
50 MILES SOUTH OF SITE
TR = 30 YEARS
CSWAY EL = 4 5 FT
INTRACOASTAL CANAL SOUTH
INTRACOASTAL CANAL NORTH
HUMBLE CHANNEL SOUTH
HUMBLE CHANNEL NORTH
TIDE (FT)
TIME (HOURS)

FIGURE 9

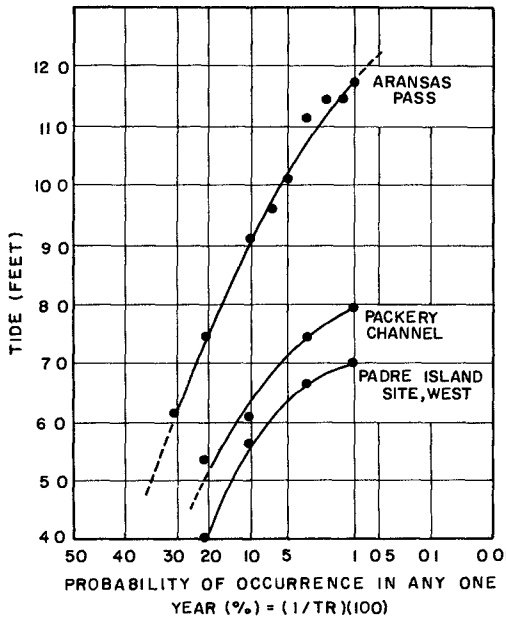


FIGURE 10 OFFSHORE AND DEVELOPMENT SITE TIDES AS COMPUTED FROM VARIOUS FREQUENCY SYNTHETIC STORMS

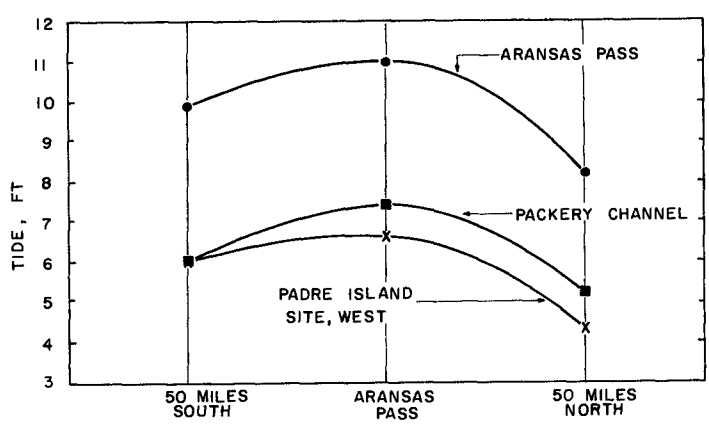


FIGURE 11 VARIATION OF MAXIMUM TIDE FOR STORMS CROSSING COASTLINE AT DIFFERENT LOCATIONS