

Box 6

GEOLOGY AND OCEANOGRAPHY

NORTH DEVELOPMENT SITE

PADRE ISLAND NATIONAL SEASHORE

NATIONAL PARK SERVICE

REPORT OF

W. Armstrong Price

Consulting Geologist and Oceanographer

1213 Ocean Drive

Corpus Christi, Texas

31 July 1965

To: Western Office
Design & Construction
San Francisco, Calif.

Contract No. 14-10-0434-1931

Mission 66 Project

10 June 1965

W. ARMSTRONG PRICE
CONSULTING GEOLOGIST AND OCEANOGRAPHER
CORPUS CHRISTI, TEXAS 78404

TU 4-4716 OFF.
TU 3-4890 RES.

1213 OCEAN DRIVE

July 31, 1965

Chief, Western Office, Design and Construction
National Park Service
P. O. Box 36025
San Francisco, California 94102

Dear Sir:

I enclose six (6) copies of my report:

GEOLOGY AND OCEANOGRAPHY, NORTH DEVELOPMENT SITE, PADRE
ISLAND NATIONAL SEASHORE, NATIONAL PARK SERVICE.

This report is furnished to you in conformity with
Contract No. 14-10-0434-1931, Mission 66 Project, 10 June
1965, Oceanographic Study, Padre Island National Seashore.

Very truly yours,

W. Armstrong Price
W. Armstrong Price

WAP:jmb

Encl.

~~PAIS Acc. 78~~

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SCOPE OF REPORT

Under Article I. Scope of Report, the consultant was to

conduct a comprehensive geological and oceanographic study to determine the past and projected wave energies, floods, winds and other natural phenomena in order to assure their significance as related to planned construction and planned use of the island by the National Park Service, and submit to the Contracting Officer the findings therein and recommendations for control thereof, together with recommendations for the protective design of planned construction facilities.

On June 27, 1965, Mr. Mike Malik, landscape architect, National Park Service, indicated in a memorandum entitled "Information Desired" that the report should cover specifically the following topics:

1. Required elevation for the development (wave and hurricane curves).
2. Type of site to select - where possible - where not possible.
3. Wave forces, Re: pile design, stabilized dune design, etc.
4. Curve to show energy loss as wave crosses beach.
5. Typical dune formations. How to build - How to prevent (BEB).
6. Wind velocity - mean - max. Directions.
7. Ideal construction time?
8. Road section.
9. Type stabilization required to protect the road from drifting sands, blowouts, and washouts (cured).

PART I -- SITES AND THEIR PROTECTION

A Site on Dunes Facing the Beach

As a result of the great flood disaster around the shoreline of the North Sea in February 1953, the commissions of engineers and geologists who studied the damages concluded that the best protection against storm waves and flood was a high, wide beach with a high, well-established and unbroken vegetated foredune back of it (C. A. M. King 1953). Even a footpath over the top of a dune allowed the flood to break through.

The 1953 disaster, as well as other experiences, shows that the dune-beach complex described above gives better protection to the land behind it and to structures overlooking a beach than seawalls would do.

For the more permanent types of development, therefore, a site overlooking and adjacent to a beach should be on top of a dune or a mound built on and among natural foredunes.

Because of the distribution in time of marine storms on the Texas Coast and the variability of the accompanying flood heights and wave activity, a design construction elevation based on flood-and-wave probabilities should be selected for the construction mound and for the floor of any structures built on piling out from the mound toward the beach.

Hurricanes are almost the only type of major onshore-moving storms of the Texas Coast. "Northers" (wind storms of advancing cold fronts) are the main offshore-moving storms.

Construction Mound Overlooking Beach

Such a mound should be developed on a large group of well-grassed high dunes as compactly grouped as can be found. If the dune summits rise above the design elevation, the dune group can be leveled and graded, Fig. I-1. Additional fill material, if needed, may be taken from small, unstable dunes of the inner border of the beach, or from borrow pits or channels dug back of the dunes. It is possible, but unlikely, that clay or clayey sand will be found on the northern part of the island near the beach. Clay occurs 3 to 8 feet down under some parts of the southern part of the island. Clay underlies an area of undetermined size south of and near Mansfield Cut. Clay at 8 feet below the surface was used in the extreme southern part of the island in the presently developed area south of the Seashore lands.

Construction of access roads and other facilities on the plain back of the foredunes, and back of a projected construction mound, must take into account the heights of flood waters that enter the lagoon from the Gulf or develop in the lagoon itself under northerly winds. Return floods may be destructive of roads and bridges built at or below flood levels.

Duneless Sites

Construction sites desired where there are no dunes will have to use piling or wholly artificially constructed mounds. A common way to obtain elevated construction sites on the sand islands of the coast is to use hydraulic fill in connection with marina channel development. Such developments are best suited to the rear parts of the island. In such areas the hydraulic fill material may contain a large percentage of shells, marl, or clay, any of which materials help to hold sand and keep it from blowing.

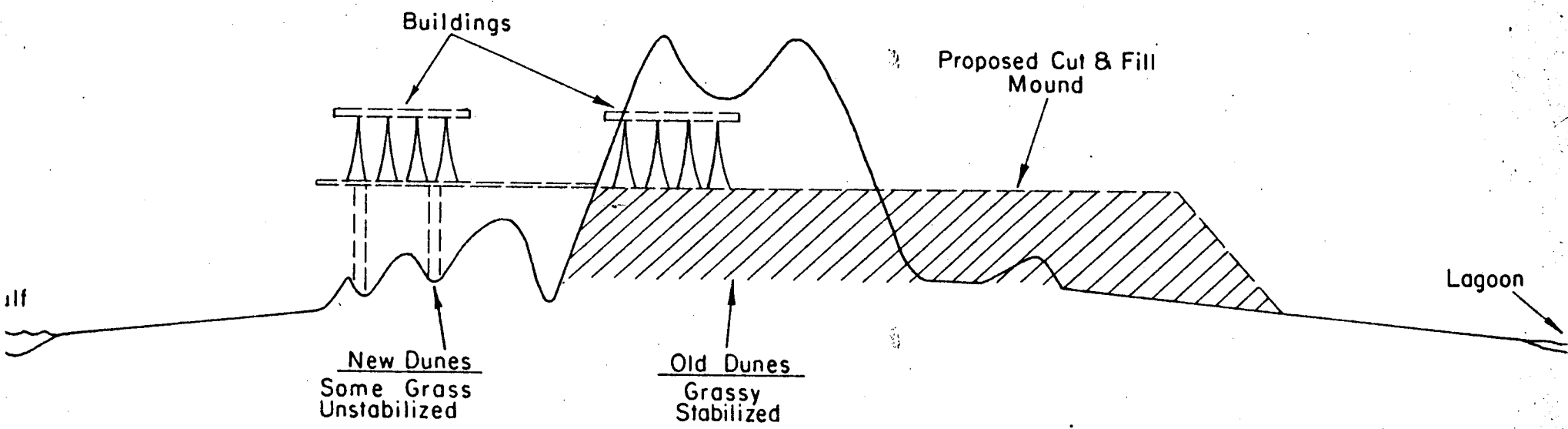


FIG. I-1

PLAN FOR RESIDENTIAL AREA

NORTH DEVELOPMENT SITE, PADRE ISLAND

Main Buildings on construction mound among old foredunes.

Bath houses on piling, inner part of beach.

Construction sites facing a beach where there are no dunes will also have to use piling or local fill. Borrow pits might be sunk below watertable (ground-water-level) and converted into lakes or ponds.

Foundation Strength in Sand

The writer is not competent to report on and has not been asked to solve foundation problems. Dry packed sand has great resistance to vertical pressure, but loose or wet sand has none until a sufficiently long pile has been sunk in it to develop "refusal" skin friction.

In moist, firm sand a 2-inch core barrel failed to penetrate more than a few inches when a pressure of 1,500 pounds was placed on it.

Stabilization of Bare Surfaces of Sand During and After Construction

Sand blows with great ease in anything but very light winds if it has no cover. A blowout (wind-erosion depression) once started may, if unchecked, destroy a dune and build a sheet of bare sand back of the beach-bordering foredunes. The blowout gap in the dune line may later become an overwash flood channel, with a fan of beach sand washed back of the foredune. These bare sand sheets in the rear then develop fields of bare migrating seif dunes. See Fig. IV-1j and IV-2c, 2d.

Dune Stabilization by Vegetation and Plantings

Fast-growing, thick-standing native dune grasses in any near-shore area are likely to be the best in the initial stabilization of bare areas because they have been naturally selected for their particular environmental niches under competition. It is difficult to learn the range of enemies -- climatic and organic -- which will attack exotics. Woody plants may grow in among the dunes after they have a thick grass cover.

If it is desired to try exotics, the best practice seems to be to stabilize at first with native grasses, meanwhile trying the exotics in experimental plots carefully selected as to micro-habitats.

The most successful thickly-growing dune grasses which were used by the writer in planning the initial sand stabilization in the Isla Blanca Park of Cameron County on the southern end of Padre Island have been the local forms of shoreline panicum (new, native species) and coastal Bermuda. These grasses are found growing over large areas in that part of the island. It is a semi-arid maritime climate exposed to wind and salt air.

Methods of vegetational stabilization are covered in a Beach Erosion Board publication (Davis 1957) but that publication does not list the native dune grasses of South Texas, having been written for humid climates, such as those from Florida to the Carolinas.

Mechanized planting buggies are poorly suited to use on hummocky dunes.

The native sea oats grass grows on high dune summits in fair profusion but has not been found to be a good, quick-growing, stabilizing plant for initial cover.

All the main stabilizing plants native to the Texas foredunes develop thick networks of roots that extend from the dune surface to and below the level of the inner surface of the beach. Such a root system allows dunes bluffed by floods to stand up with near-vertical surfaces. Where such dunes are removed or partly removed by wave-and-flood action, their former extent is revealed after the flood by the severed root ends. These root ends readily sprout again, if only lightly covered by sand, providing a stock for the initial grassing of new sand mounds.

Building of Sand Dunes

Sand dunes can be built by the well-known method of erecting snow fences or permeable hedges across the main direction of sand movement, which is the main dune-forming wind of the season. When the artificially formed dune has grown to the top of the fence or hedge, it must be covered either directly by grass planted ("sprigged in") or by a cover-sheet (such as shell, hay or a commercial mulch of oil or resinous materials) before or along with grass planting. To develop a high dune, additional fences are placed to the rear of the dune in increasing height and probably before grassing the first dune formed.

Use of Cane (*Arundo donax*) for Dune Stabilization

A means of stabilizing large areas of bare, migratory dunes successfully which has been used on a large ranch on the mainland sand-plain of South Texas (Armstrong Ranch, Kenedy County) is to plant dense hedges of cane (Georgia or riverbottom cane, *Arundo donax*) on the down-wind and flank areas of dunes that have about reached their maximum size and are only slowly migrating. The hedges are planted across the direction of sand movement, never parallel with it. The details of the process have not been analyzed in publication and are yet to be worked out in practice for the Padre Island operations. The cane has been grown successfully in sand of the island this summer, but, as yet, it has not been planted in a pattern adequate to halt a large blowout. The months of June and July have seen very active blowing of sand this year.

At present, the best use of Georgia cane on Padre Island would seem to be to plant in the cool months when the strong southerly and easterly winds are being replaced by the northerly winds of winter. These winds check the northward and westward movement of sand characteristic of

the warm months which tends to cut off or smother the cane before it can attain resistive height and toughness of stalk. If a substantial hedge can be grown in winter it should persist through the summer and stabilize the dune areas on which it is planted.

A cane hedge provides protection for the native grasses, whose seeds may be in the sand and are, in any event, blown about by the wind. The first such volunteer growth, in Kenedy County, is a "needle grass." After the terminal and flank areas are stabilized, hedges may be grown to progressively encroach on the main part of the dune.

In the Kenedy County dune stabilization, planted areas, and the entire blowout or migratory dune area, are fenced off from cattle. If the cattle are removed from the Seashore area, it is likely that the public will have to be restrained by fencing. Once a cane hedge is well established, it is highly resistant and the root system becomes so massive that the cane may be reaped annually. Only complete removal of the roots seems to kill such a hedge.

In planting, moist, mature (hard) stalks that have budded or sprouted are cut in maximum lengths and placed horizontally in the bottom of 6-inch to 12-inch furrows. The furrows are then filled in and compacted by tamping or driving a tractor wheel over the fill. Horse plowing may be better than tractor plowing.

The Davis (1957) report to the Beach Erosion Board indicates that a large migratory dune or growing blowout must be stabilized across its up-wind blowout origin before it can be planted down-wind. On Padre Island, only restoration and stabilization of the foredune will halt the addition of sand from the beach to a gap in the dune line.

It has not been determined how successfully a cane hedge can be developed facing the beach. Test plantings have been behind the foredune or in other somewhat protected areas.

North Development Site

The North Development Site, as now planned by the Seashore staff, lies among the foredunes between about 4.5 and 5.5 miles southwest of the northern boundary line of the National Seashore where it comes down to the beach.

Groups of well stabilized, thickly grassed foredunes range back of the beach with summits from 30-44 feet in elevation (U.S.G.S. msl). See the following section, "Conversion of Elevations," for explanation of this elevation datum. The groups are about 200 to 400 feet in width along this frontage, Fig. I-2.

Between the foredunes and the beach there is a narrow trough which separates the old foredunes from a belt of new ones developed since Hurricane Carla of September 11, 1961. The new foredunes have summits reaching from 20 to 26 feet (U.S.G.S. msl).

The beach along this frontage rises to about 5 feet (U.S.G.A. msl) at the feet of the new foredunes.

A gap 100 feet wide cuts through the foredune chain 800 feet north of Triangulation Station "Rush." The gap runs northwestwardly from Godley Monument 21. This gap is partly filled by bare sand and low bare dunes.

Sand from the new foredunes has blown extensively over the old foredunes in the northern part of the area, which is destined to be the camping ground. Extensive statilization will be needed in this area.

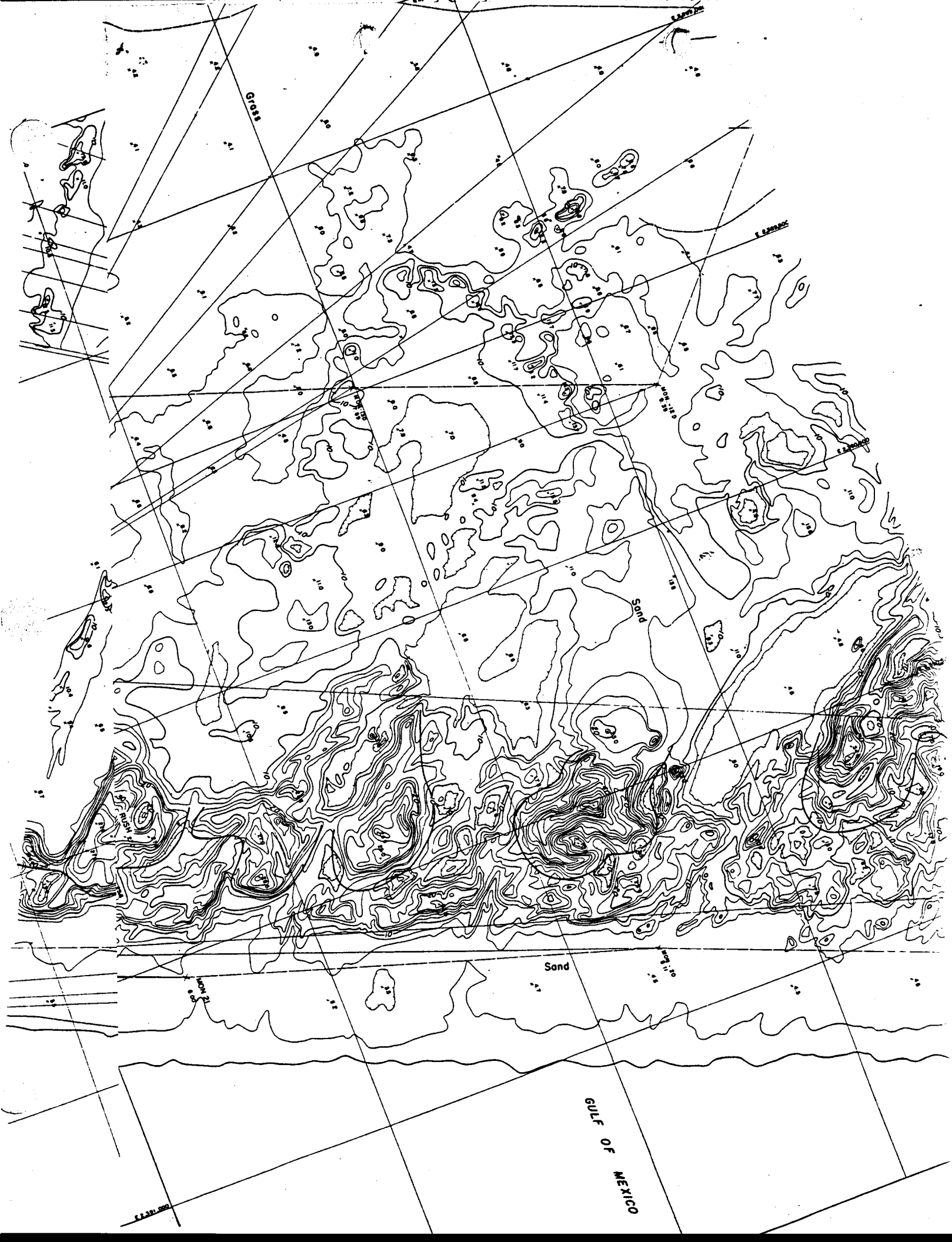


FIG. I-2

FRONT OF OLD, WELL-GRASSED FOREDUNE CHAIN

NORTH DEVELOPMENT SITE, PADRE ISLAND

Topographic base map from Godley Survey, 1965

Conversion of Elevations

Surveys in which a determination of stillwater level inside a perforated pipe in the water of the Gulf near the beach was made showed the water level to range from +0.8 to +1.1 feet, when tied in at the same hours to Godley Survey Monuments Nos. 16 and 21 on Padre Island, and to the tide gauge of the U. S. Coast & Geodetic Survey at the Horace Caldwell Pier, Port Aransas. The Godley and U. S. C. & G. S. datums seem to agree closely.

Because of progressive changes in the relative levels of land and sea during the last 30 years, the mean sealevel for the present 19-year cycle is not known here. A new figure will be obtained when the Port Aransas tide record for the past 17 years is inspected for a mean value.

If a true sealevel datum is required for the Seashore Area, the Port Aransas mean could be determined, or a tide gauge put in and operated for a series of years.

Most Favorable Season for Construction

Because of the near-tropical climate, outdoor work is done in any month.

Experience in the Cameron County Park at the southern end of Padre Island shows that grass will grow there in sand in any month.

Outdoor labor is done with difficulty during the 2 to 4 or 5 days of the duration of strong north winds associated with the advance of cold fronts of winter.

The period from June through September is the major season of hurricanes and tropical cyclones, with the greatest incidence of such storms in June and September. A few hurricanes have occurred here late in May and early in October.

Sand moves with the wind dominantly from easterly to southerly directions during the warm months and dominantly from the north in the colder months of November to February.

Protection of Buildings During Wind Storms

Measures to protect glass windows and doors against wind include criss-crossing the glass with tape or covering them with solid storm-shutters and doors. A further protection is to remove all loose boards and any other light objects which might be thrown against buildings by the wind. This includes signs, beach paraphernalia and possibly even storage piles of loose shell.

In the past, along the Texas coast, wind damage to substantial structures has not occurred under winds with sustained speeds of less than 90 miles an hour.

Experience in south Texas in the period 1930 - 1950 showed that, with construction materials then used, wooden shingles stood the wind better than composition shingles.

Management of Buildings During Hurricanes

A long-time practice of residents of the south Texas coast has been to remain in their buildings during hurricanes. Water forced in around windows and doors in large amounts should be mopped up. Chimneys from coal or wood fires should be strong enough not to burst if filled with rain water. Rain may be driven through the pores of unglazed brick.

Structural damage is said to be less likely to occur in very high wind storms (over 90 mph) if doors and windows are kept open on the side away from the wind at all times. This means closing rear openings and opening up front ones as the wind slowly shifts around the typical spiral path of the cyclonic storm.

PART II -- CLIMATE AND WIND

Semi-Arid Climate of Thornthwaite

According to the quantitative climatic system of C. W. Thornthwaite (1948), the northern end of Padre Island lies near the northern limit of the semi-arid zone at its contact with the dry sub-humid zone to the north. The semi-arid zone extends southward into Mexico, the southern end of the island being in the center of the coastal part of this zone at its area of maximum aridity along the coast. Further south in Mexico, the semi-arid zone passes again into the tropical sub-humid zone.

The semi-arid climates of the world are noted primarily for their variability. Thornthwaite's (1941) climatic atlas shows a high degree of variability for this coast, ranging from humid with 40 inches of rainfall to arid with 10 inches and with droughts of 3 to 7 years.

Freezes are likely to occur a few times in winter, but many years may lapse without a killing frost or freeze. The coldest year on record was 1880, with snow on the ground at Corpus Christi nearly all the time in November and December.

The maritime belt of the semi-arid zone along Padre Island has moist nights and morning mists, providing much moisture for plants in addition to the rainfall. This belt is also very windy. Corpus Christi lies in the center of the most windy zone of the eastern coast of North America (Dept. Agr. 1935).

Wind Regime

No weather stations are maintained on Padre Island, although some data are available from the Coast Guard stations at Port Aransas and Port Isabel. The weather data for the Corpus Christi Naval Air Station and the Corpus Christi Weather Bureau Station are used in the following discussion. The Air Station is on Flour Bluff. The Weather Bureau Station was on the western shore of Corpus Christi Bay from 1870 down to World War II, after which it was moved to the airport which is now about 25 miles west of Padre Island.

Curves of the annual distribution of temperature, rainfall and wind duration for Corpus Christi drawn by the writer from the Weather Bureau in 1931 (Price 1933), Fig. II-1, shows the monsoonal character of the wind. These curves are true in general for the region.

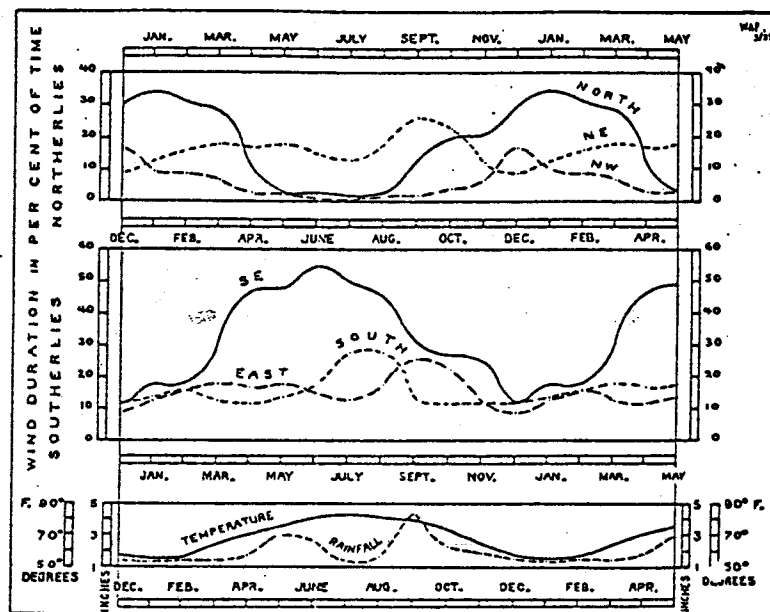
The coincidence of the peaks of temperature and rainfall with those of the onshore winds during the period from April to October illustrates the nature of the summer "monsoon." The relatively dry winter, with winds of cold fronts coming from northerly directions ("northers") define the winter "monsoon."

The almost entire absence of W and SW winds emphasizes the prominence, in duration, of winds from offshore.

The direction from which the wind blows longest each day is called the "prevailing" wind. Speed is not considered in this term. A graph of the "prevailing" winds for the Corpus Christi region prepared by Boker (1956, Fig. 2) is given here, Fig. II-2. Thus, the "prevailing" winds blow from SSE for 7 months of the year. Onshore winds "prevail" for a total of 11 months, according to this diagram.

FIG. II-1

METEOROLOGICAL DATA FOR CORPUS CHRISTI AREA, TEXAS



Above: Average wind duration for each month in per cent of time, for the northerly winds, 1923-1931.

Center: The same for the easterly and southerly winds.

Below: Average monthly temperatures in degrees F and average monthly rainfall in inches, 1887-1929.

From Price (1933), Fig. 5

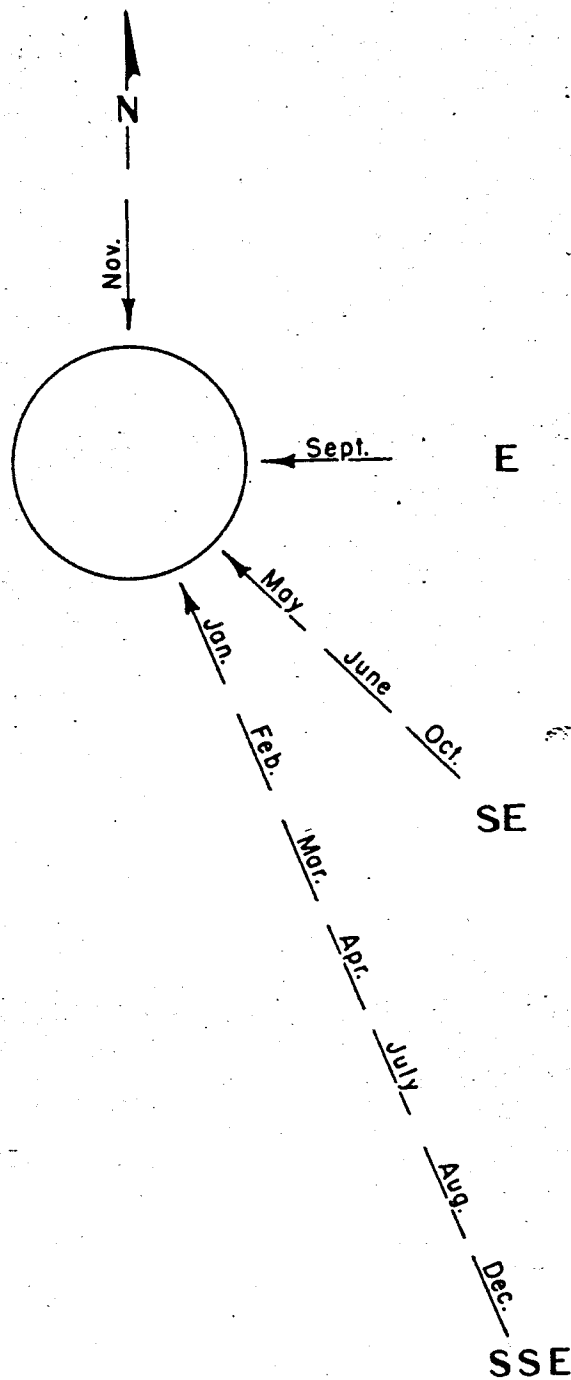
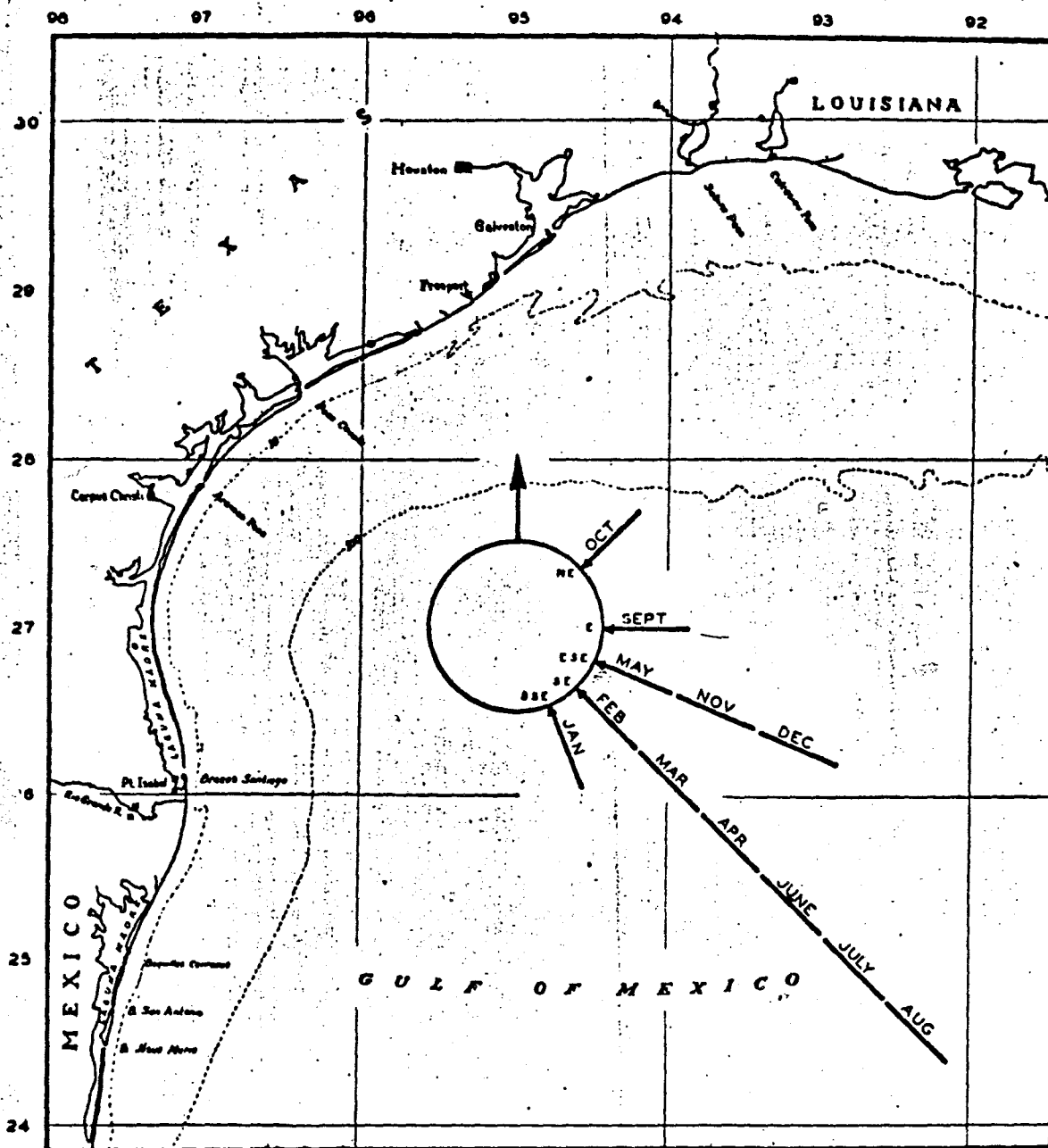


FIG. II - 2. Prevailing winds in the Corpus Christi,
Texas, region (after Boker 1956, fig. 2).

The term "prevailing" is somewhat misleading because it does not eliminate the winds of low speed; nor does either duration or velocity alone determine the effectiveness of wind on water, sand, or vegetation.

According to another viewpoint (Dept. Agr. 1938), onshore winds are "predominant" in the region in every month, considering NE winds as onshore. The NE wind is more nearly 'longshore than onshore in the northern part of Padre Island, but is directly onshore in the southern part, Fig. II-3. The graph is from Lohse (1952, Fig. 25).

In dune development, Bagnold (1941) indicates that the "dominant" (strong) winds are the dune-building ones, while the gentle winds are dune-modifying.



PREDOMINANT DIRECTION

IN NORTHWEST GULF OF MEXICO

PREDOMINANT WIND DIRECTION FOR EACH MONTH BASED UPON PERCENTAGE ANALYSES

The following discussion of the effectiveness of wind in building and modifying sand dunes is from Boker (1956, pp. 21-26, and figs. 3 and 4).

The relative transporting power, or strength, of winds observed hourly at the Corpus Christi Naval Air Station during the period March 1945-December 1951 was calculated by applying Bagnold's (1941, p. 69) formula expressing the relationship between wind velocity and rate of sand movement (Simonett, 1949, p. 7). This relationship is such that the quantity of sand capable of being moved by a wind varies as the cube of the excess of wind velocity over and above the constant threshold velocity at which the sand begins to move. A threshold velocity of 10 miles per hour was assumed for the sands in the area studied. The wind data used in this investigation had been compiled in such a manner that the wind velocities were grouped in the following categories: 3 to 8, 9 to 14, 15 to 23, 24 to 35, 36 to 46, and greater than 46, all expressed in miles per hour. A windrose (Fig. 3) was prepared from this data to illustrate the relationship of the winds analyzed in the following discussion. Determinations of the relative transporting powers of winds capable of moving sand were made using the average wind velocity within each category. Only those categories having an average wind velocity greater than 10 miles per hour were considered, since the sand-moving winds are those in excess of the threshold velocity. Knowing (1) the threshold velocity (v), (2) the measured wind velocity from a given direction (V), and (3) the number of observations (N) recorded for V ,

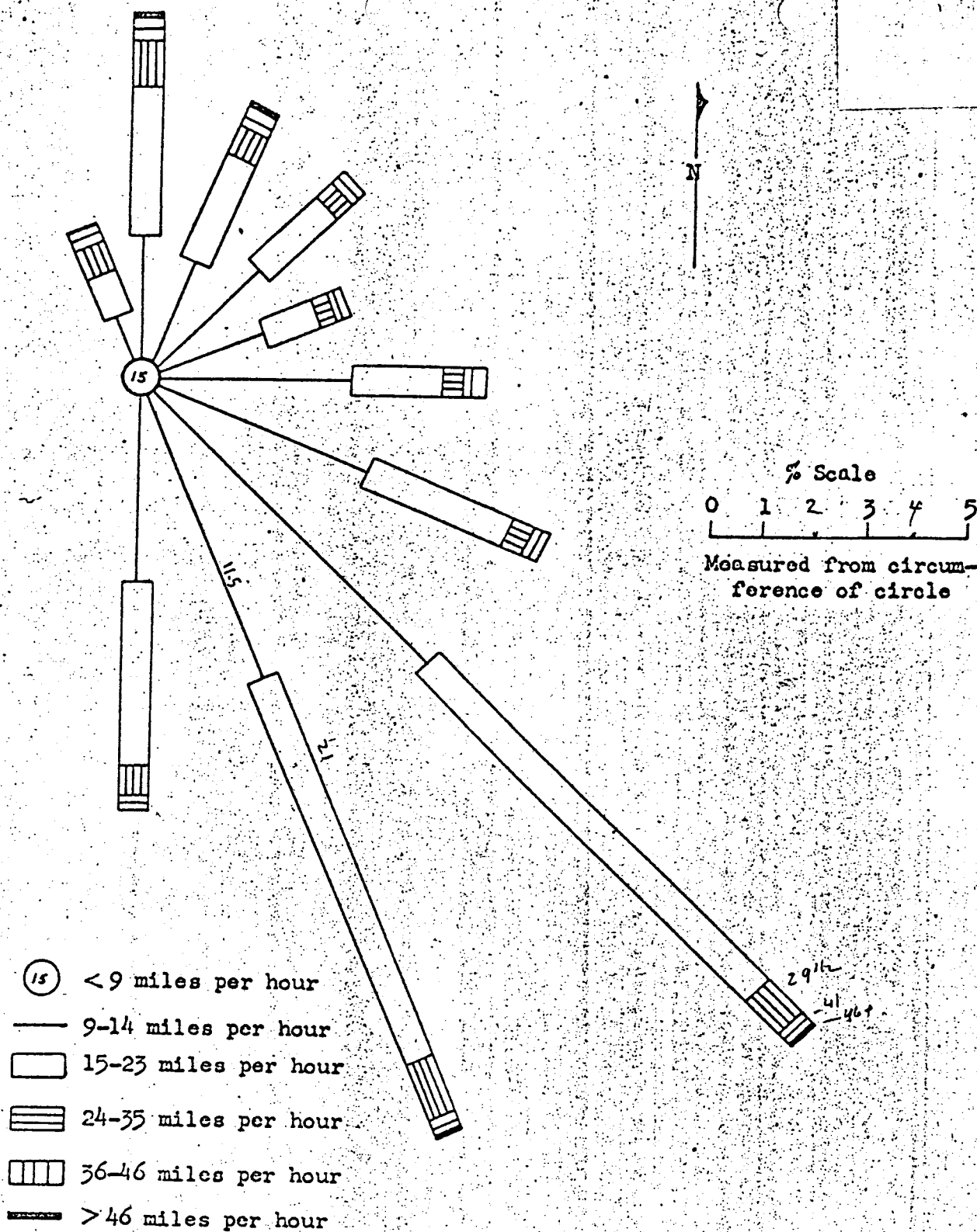


FIG. 3. Windrose prepared from data accumulated by Corpus Christi Naval Air Station for period March 1945 - December 1951. Wind directions comprising less than 3% of total winds observed during this period are omitted, since they are too small to plot on the above scale.

FIG. II-4

VELOCITIES OF SEMI-QUADRANT WINDS
Omitting Speeds Less Than 9 mph.

Description above is from Boker
1956, Fig. 3.

the transporting power (Q) of the sand-moving winds was calculated from the equation $Q = N(V-v)^3$. The total transporting power for each wind direction was obtained by adding the strengths of all winds observed from that direction. The results of all calculations were multiplied by 10^{-6} in order to simplify their tabulation. The dominant winds on the basis of relative transporting power, or strength, are the N-NNE and the SSE-SE winds (Table 1).

The vector diagram (Fig. 4), prepared by canceling strengths of opposite winds, shows the resultant direction of sand movement as determined by the predominant winds. This resultant has a direction of S 85°W. Field observations and measurements on aerial photographs of dune ridges show that the free-moving, non-vegetated dunes on the island are elongated approximately E-W, which agrees favorably with the direction of elongation as determined by the vector diagram. However, the analysis of the relative transporting powers of various winds only takes into account the differences in velocity between the winds studied, and the time of year that winds of a given velocity occur and the amount of moisture present at that time are not accounted for in the calculations.

The weather data used in this analysis also shows that during the winter months there is proportionately more moisture on the ground per day than during the remaining months. This does not imply that moist sand will not blow, for it does, but the actual amount of sand movement occurring with a wind of given velocity may be less when the sand is moist than when it is dry. In view of the fact that the actual

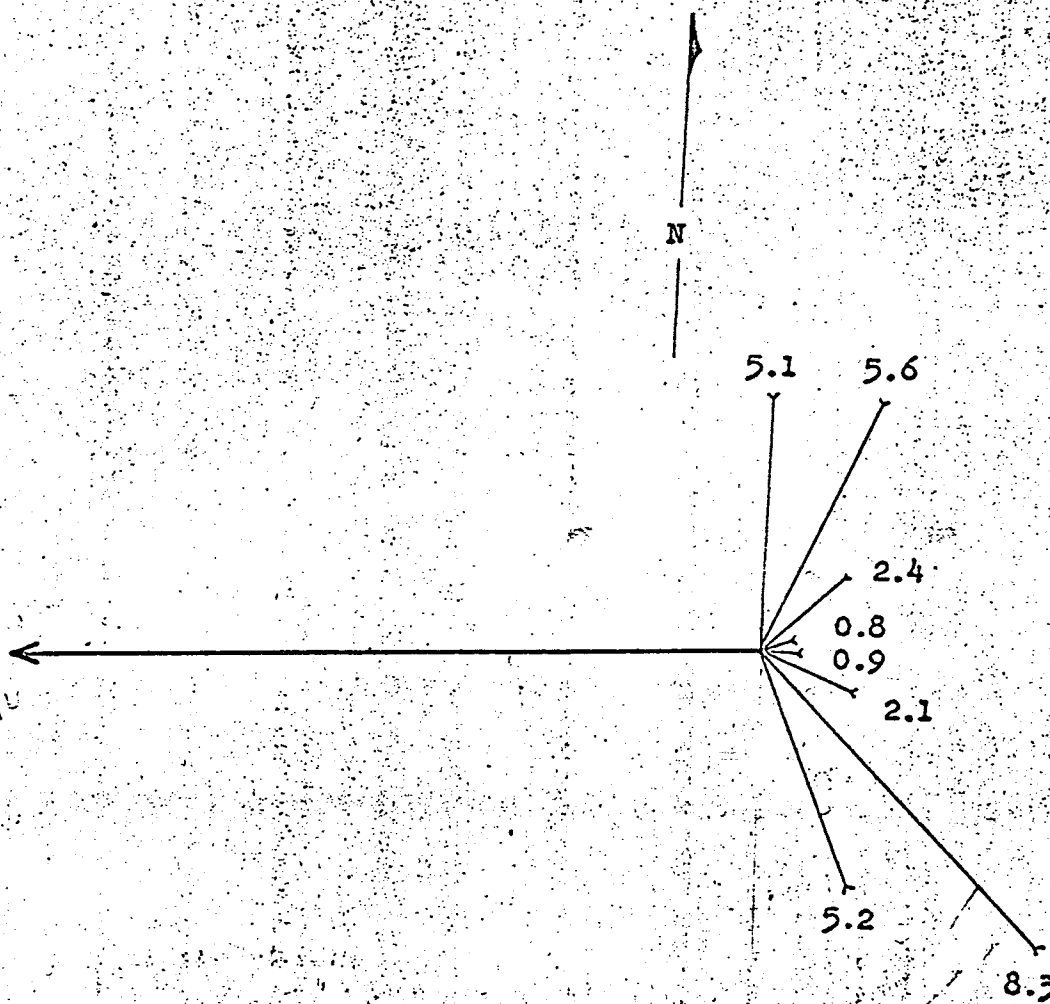


FIG. 4. Vector diagram indicating the resultant direction of sand movement as determined by all sand-moving winds. The relative transporting power of the winds was calculated from the following equation: $Q = N (V - v)^3$.

FIG. II-5.

RESULTANT OF RELATIVE TRANSPORTING POWERS
OF ALL WINDS WITH SPEEDS ABOVE 9 MPH.

Description above is from Boker 1956, Fig. 4.

TABLE 1. Relative transporting power of winds at Corpus Christi Naval Air Station during the period
March 1945-December 1951.

$$Q = N(V-v)^3$$

Direction

Wind force m.p.h.	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
9-14	.005	.005	.006	.004	.003	.009	.016	.013	.008	.001	.001	.001	.001	.001	.001	.002
15-23	1.42	1.14	.846	.542	.733	1.30	4.17	3.81	1.72	.238	.041	.015	.037	.041	.228	.515
24-35	5.44	3.68	1.43	.245	.207	1.02	4.81	5.86	2.59	.289	.007	.015	.052	.074	.156	2.85
36-46	2.11	.804	.149	.030	.030	.030	.089	.387	.030	—	—	—	.030	.179	.417	1.40
46	.512	.512	—	—	—	—	.064	.064	—	—	—	—	—	—	.064	.192
Total trans- port- ing power	9.49	6.14	2.43	.821	.978	2.35	9.14	10.13	4.34	.528	.049	.031	.120	.295	.866	4.95
Cancel- ing oppo- site winds	5.14 ⁵	5.61	2.38	.790	.858	2.06	8.27	5.18	—	—	—	—	—	—	—	—

Resultant ± 15.2 S 85° W

direction of dune orientation agrees quite favorably with that determined on the basis of strength of observed winds, it is possible that dune orientation on Padre Island is not markedly influenced by moisture associated with winds of any given direction.

Specific relationships between the wind regime and the different types of dunes represented on Padre Island will be discussed in detail when the various dune forms are analyzed.

Rain

The area in which Padre Island lies averages about 27 inches a year of rain; snow and hail being negligible in amounts and seldom occurring. There are two annual peaks of rainfall, in May and September, Fig. II-1. The May rains occur as the sun migrates northward over the equator and reflect in a lesser extent the heavy tropical May rains of the Gulf coast of Mexico in the Tampico-Veracruz region.

The September rain maximum depends on the occurrence of hurricanes and lesser tropical cyclones. This rainy peak is as variable as the incidence of hurricanes, Fig. III-1, and the tropical storms of less intensity which occur in both the "hurricane rich" and "hurricane poor" cycles (to be described).

Some rain is scattered through the fall-to-spring period, coming with the advance of cold fronts, although many "northers" are "dry."

Dune Moisture

The large amount of moisture available to Padre Island plants from night air and morning mists has not been measured.

In sand dunes on Padre Island, there is a zone of capillary moisture 6 inches below surfaces of sand which have been stable for a number of days. This zone does not yield wells. Such a capillary moisture zone supplies drinking water for Australian aborigines by sucking the water out of the ground. This moisture seems to be an internal precipitation on cool sand grains below the surficial zone of hot to warm sand. This is a phenomenon known in South American deserts. It is a feature of soil climate which seems not to have been discussed in dune literature. This moisture seems to be what permits the vegetation in porous sandy soils to thrive as well as it does in a semi-

arid climate under strong, dry, hot winds of daytime and a nearly vertical sun.

Ground Water

Ground water that will flow into wells occurs at depths of 5 to 6 feet under the surface of Padre Island back of the beach and east of the lagoonal tidal flats. The top of this water body is called the water table.

It is reported that there is only a thin layer of fresh to relatively fresh water resting on more brackish waters, but the writer has no specific data on this subject.

On some sand islands, such ground water may descend many feet below surface, limited by lenses of marly or clayey sediments.

PART III -- PERIODICITY OF TEXAS HURRICANES

Records Used

The records used include those of the following sources in the order of dependence: Price 1956; Tannehill 1956; Ludlum 1963; Corpus Christi Weather Bureau Records for 1956-1964.

Only those tropical cyclones are included in the data which crossed the Texas shoreline with wind speeds greater than 74 mph or otherwise caused hurricane conditions on some part of the Texas coast.

The lesser tropical cyclones are not included because, in nearly all cases, their winds, waves and floods should not create conditions critical for the Padre Island Seashore and its operations, except as rain and the threat of intensification of the storm may do so.

Period Considered

In the 136 years from 1829 to 1964, 59 hurricanes are listed reliably as having visited the coast of Texas in the sense defined above. The overall incidence was one hurricane every 2.3 years along some 400 miles of coast. The records for this period are adequate for the purpose of making curves of incidence and probability.

Common Width of Hurricane Front

One-fourth of the shoreline of Texas, or roughly 100 miles, is taken here as the characteristic hurricane front for statistical purposes. Both wider and narrower hurricane fronts have developed here. For a front of 100 miles a factor of 4 is used, so that the overall incidence given above becomes one hurricane every 9.2 years.

Cyclic Periodicity

The data assembled show that the hurricanes which affected the Texas coast as here restricted have had a marked cyclic fluctuation in numbers per cycle. The cycle is 17 years with a range of from 8 to 28 years. Others, viewing weather on a larger scale, find weather cycles of 20 years average, and some have found a relationship between hurricane cycles and the sunspot cycles of 11 years. The cycles defined here occur within cycles based on data of wider scope.

Analysis of Hurricane Periodicity

The writer has previously designated the Texas cycles (Price 1956) as alternately "rich" and "poor" in hurricanes. Table III-1 gives the basic data which are plotted on curves a and b of Fig. III-1.

TABLE III-1

CYCLES OF HURRICANE OCCURRENCE, TEXAS COAST, 1829-1964

Y, years; H, hurricanes; y/h, average inter-hurricane period.

<u>Hurricane Poor</u>	<u>Y</u>	<u>H</u>	<u>y/h</u>	<u>Hurricane Rich</u>	<u>Y</u>	<u>H</u>	<u>y/h</u>
1850-1865	16	2	8.0	1829-1849	21	12	1.7
1892-1907	16	3	5.3	1866-1891	26	21	1.2
1920-1928	9	0	-	1908-1919	12	10	1.2
✓ 1937-1964*	28	5	5.6	1929-1936	8	6	1.3
Average:	17	2.5	4.7	Average:	17	12	1.3

* Cycle may not be ended.

FIG. III-1

CYCLIC OCCURRENCE OF TEXAS HURRICANES, 1829-1964

Graph A (Above). Average numbers of years between hurricanes.

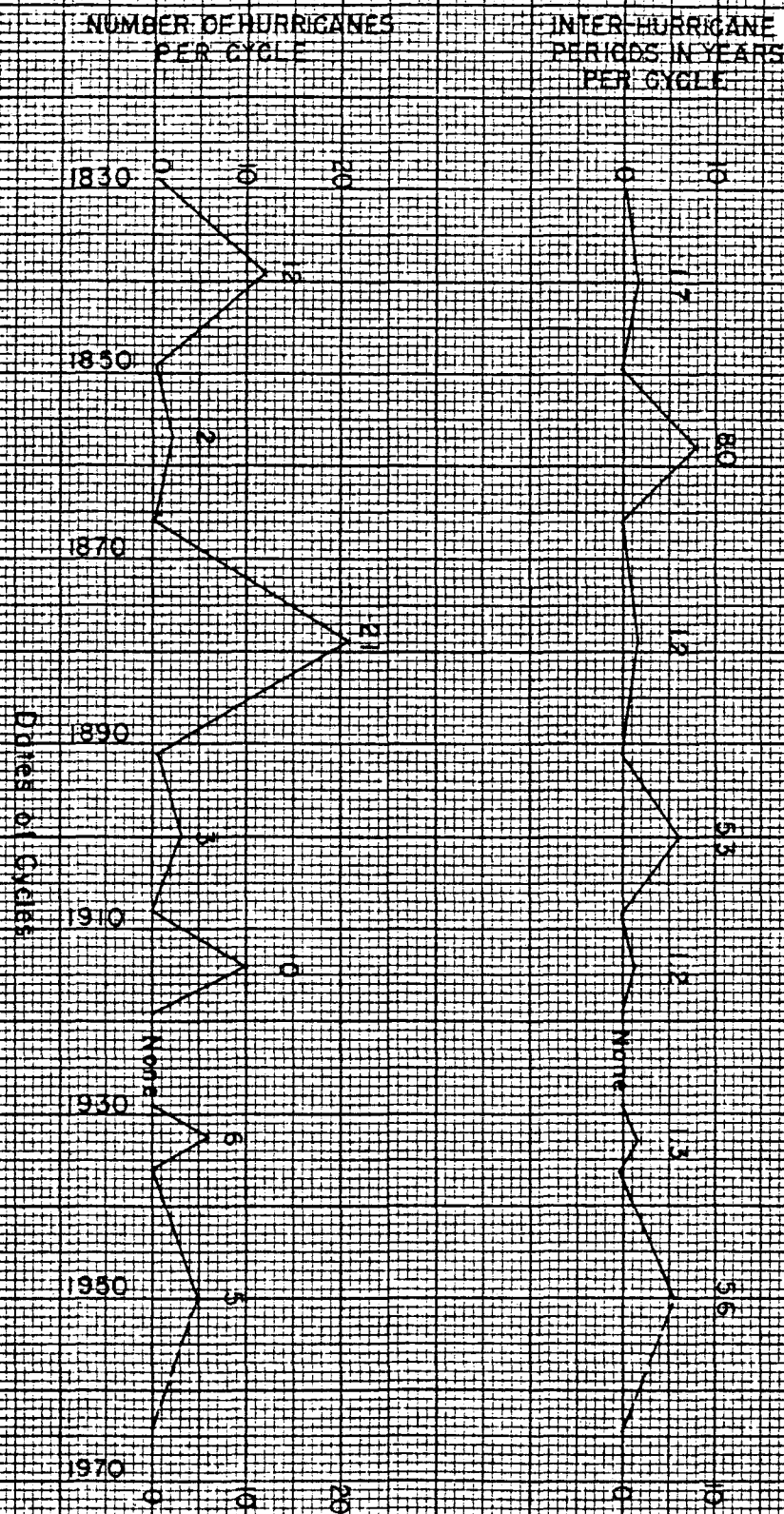
4 "Hurricane rich" cycles, 0-1.7 year intervals (ave. 1.35 yrs.).

4 "Hurricane poor" cycles (last incomplete), 5.3-8.0 year intervals (ave. of 2, 6.6 yrs.).

Graph B (Below). Total numbers of hurricanes per cycle.

4 "Hurricane rich" cycles, 8-26 yrs. long (ave. 17 yrs.)
had 6-21 storms (ave. 12.25 each).

4 "Hurricane poor" cycles (last incomplete), 9-28 yrs. long
(ave. 17 yrs.), had 0-5 storms, 3 (including incomplete
cycle) had ave. of 3.3 each.



Seven completed cycles (1829-1936) spanned 108 years and had 57 hurricanes. The cycles ranged from 8 to 28 years, averaging 17 years. Hurricane occurrence ranged from 0 to 21 per cycle. The total number of hurricanes was 59, in that period, averaging 3.4 per cycle.

The present incomplete cycle (as of July 26, 1965) has extended from 1937 through 1964 and a part of 1965, or 28 and a fraction years. Although the number of hurricanes since 1936 is within the range of "rich" occurrence, the hurricanes per period were few. A number of other hurricanes entered the Gulf of Mexico, especially in the period 1954 and 1961, so that the Gulf itself had a "rich" period.

The averages of Table III-1 show that a "hurricane rich" period is characterized by 12 hurricanes per cycle occurring at a rate of one every 1.3 years; and that a "hurricane poor" cycle is characterized by 2.5 hurricanes per cycle occurring at a rate of one every 4.7 years.

The variability is too great for predictions to be made successfully for any one year or small number of years. However, on a statistical basis, the cycles average out remarkably evenly.

Three Hurricane Aspects

There are three aspects of the occurrence of hurricanes: (a) wind velocity, (b) threat as to point of landfall and amount of damage, and (c) flooding. These will be discussed below.

Wind Damage

Wind damage to buildings, except for weak structures, has been restricted here to storms with wind speeds over 90 mph. Some vegetation is damaged and leaves dehydrated and "burned" by hurricane winds, especially above 90 mph. Roofs should be smooth and simple; ornate projections

and false fronts extending above the roof line are especially vulnerable. How well overhanging eaves and new types of roof design and support will stand up in very high winds has not been well tested here.

The worst wind damage in previous Gulf hurricanes has been from tornadoes. These have occurred with hurricanes at Galveston, Palacios and Harlingen. The winds of a hurricane blow in a spiral path about the eye, blowing counter clockwise in the northern hemisphere.

Threat to the Coast Line, and Hurricane Paths

The path of a hurricane is controlled by the larger air masses and pressure cells of the areas to the north and west of the initial paths. The path is commonly northwesterly to westerly.

Hurricanes originating in the Caribbean and entering the Gulf follow in general two types of path: a path curving to the NW and N, and one passing straight through the Gulf to the W or WNW with local departures back and forth. A minor percentage of these Caribbean storms recurve to the SW to strike southern Texas or northeastern Mexico (Price 1956). A few hurricanes originate in the Gulf, but are seldom severe.

Hurricanes of exceptional paths -- reversals of direction, looped paths, and persistence over land -- are discussed by Tannehill (1956).

Aids to Hurricane Path Prediction for Isolated Observers

If, during the hurricane season, the surface of the Gulf rises more rapidly than the normal tide or rises when the normal tide would be falling, it indicates that a hurricane may be approaching. The hurricane surge (flood) may run ahead of the eye by 3 or 4 days. This surge moves out from the eye in the direction of its progress and mainly to the right of the path. Low water may develop on the coast at some distance

to the left of the path. The strongest winds and greatest damage occur to the right of the path.

The hurricane surge may rise quite rapidly, in some cases 5 feet in an hour or two. Persons on low land may wade through 2 or 3 feet of water but cannot do so effectively in 5 feet.

To aid in locating the general direction of the eye from a point of observation, the observer faces the wind and extends his right arm out sideways along the line of his shoulders. The hand will then point in the direction of the eye.

A "hurricane top" is a transparency on which a counter-clockwise spiral has been drawn. As a hurricane approaches a coast this "top" may be placed on a map with its center in the approximate position of the hurricane eye and the spiral adjusted so that the existing wind direction agrees with the spiral path. If the "top" is then moved inland across the map, the spiral arms will indicate the probable changes in direction of the wind. With a little practice, quite good results may be obtained, and a change in the curvature of the path detected soon after it occurs. Tannehill (1956, Fig. 50) shows the distribution of winds in a typical hurricane. This circulation diagram is a form of "hurricane top."

History of Flooding Across Padre Island

In 1956 the writer (Price 1956) compiled data on reports of flooding across Padre Island adding floods that probably passed over the island, judging from the nature of the storm and its path. These data have been reviewed and others added to produce Table III-2. Many of the elevations given are estimates and some others are of somewhat uncertain sealevel datum.

TABLE III-2. SUMMARY OF FLOOD DATA FOR 400 MILES OF TEXAS COAST

NORTH DEVELOPMENT SITE 1900-1964

PADRE ISLAND

Gulf Shore Flood MSL		Date & Storm (Hurricane or Tropical Cyclone)	
Feet	Feet	Year	Landfall and Remarks (All figs. are for stillwater level)
Rept. or Est.	Group Avg.		
15	15	1900	Galveston disaster storm (only one with Gulf Flood at 15 ft. Others with 15 ft. are in bays, with lower flood elevations at Gulf shoreline).
(1 storm)			
12+		1915	Landfall at Freeport, est. 12+ (Galveston reported 12 ft.)
11.5		1919	Landfall south of Corpus Christi. Port Aransas. 11.5
(4 storms)			Corpus Christi disaster storm.*
11.5		1949	Freeport, landfall.
12.2	12	1961	Port O'Connor, HURRICANE CARLA, landfall.
10+		1909	Velasco (Freeport) (Galveston reported 10 ft.)
10+		1916	Padre Island, Northern (driftwood logs at 12 ft. on western shore, central Laguna Madre).
(4 storms)			
10+		1933	Sept. 5 Padre Island, Northern (est.)
9+	10+	1945	Padre Island, Northern (est.)
6-7+	6.5+	1902, 1908, 1910, 1912, 1913	Padre Island (est.);
(6 storms)		1934	Rockport.
3.5 - 5.0	4.2+	1933, Aug. 5; 1950; 1951; 1955; 1957; 1933, June 6.	
(7 storms)			Elevations are estimates for Padre Island.

* Tannehill's report of 16 feet at Corpus Christi was from a news report of the height of trash washed up on a clock on a bank building.

Flood Probability Curve

Table III-3 uses the data of Table III-2 to obtain probability estimates.

TABLE III-3 -- HURRICANE FLOOD PROBABILITY DATA

400-MILE COASTLINE, TEXAS, 1900-1964, FLOOD MAXIMA

Elevations are for stillwater level and are conservative.

In error, deleted per memo ltr 8/4/65

FLOOD HEIGHTS		NUMBER OF STORMS For Each Height 400 Mile Coast	NUMBER OF STORMS Per 100 Mile Sector			NUMBER OF YEARS For One Oc- currence	
Mean	Range	65 Years	65 Years	1 Year	100 Yrs.	Calc'd	Used
15	15	1	0.25	0.385	0.385	250	125
12	11.5 12.2	4	1.0	1.539	1.539	66	33
10	9+ 10+	4	1.0	1.539	1.539	66	33
6.5	6.0 7±	6	1.5	2.308	2.308	45	22
4.2	3.5 5.0	<u>6</u> 21	1.5	5.385	2.308	45	22
Column Nos.							
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)

The storms of Table III-3 either actually crossed the shoreline of Texas or affected the Texas coast with hurricane conditions, as in the case of the hurricane incidence data of Tables III-1 and III-2. The choice of storms used accounts in part for differences in estimates and histories of other writers and from this writer's 1956 estimates.

In Table III-3, the data of Columns 4, 5 and 6 have been reduced by the factor of 4 to apply to 100 miles of coast, only. The number of

years for an occurrence of a flood at a given elevation shown in Column 7 is reduced by a factor of 2, to give the figures of Column 8. This reduction is made because of the imprecise nature of many flood reports and estimates.

The data of Table III-3 are used to draw a probability curve, Fig. III-2. The time curve is a solid line representing years from date. The broken lines are vertical or height uncertainty curves. A vertical uncertainty of 1.5 feet is added for the 125-year, 15-foot flood, to indicate the daily tidal range. A seasonal range of ± 0.5 foot could be considered here also. The seasonal tide is low in February and in July and August. It is high in May and November.

For the less frequent flood heights of from 10 to 12 feet, a greater range height uncertainty is shown because many reports of flood heights are not precise. Some such uncertainties come from flood data in which the height is given in feet above the predicted tide without the predicted figure having been ascertained.

Tornadoes and Harmless (?) Twisters

Destructive tornadoes occur in southern Texas in two ways: (1) associated with advancing cold fronts from the north and with "line storms," and (2) during some hurricanes and close to the eye or, at times, somewhat removed from it. Narrow, vertical, seemingly non-destructive cyclonic circulation pipes form in the air in large numbers on some hot days over the so-called Sand Plain of the mainland west of Corpus Christi, but have not been reported over Padre Island. As many as 8 or 10 may be seen in the sky at once on some days. They extend a thousand or more feet above ground. The writer has learned of no

FIG. III-2

HURRICANE FLOOD PROBABILITY CURVE

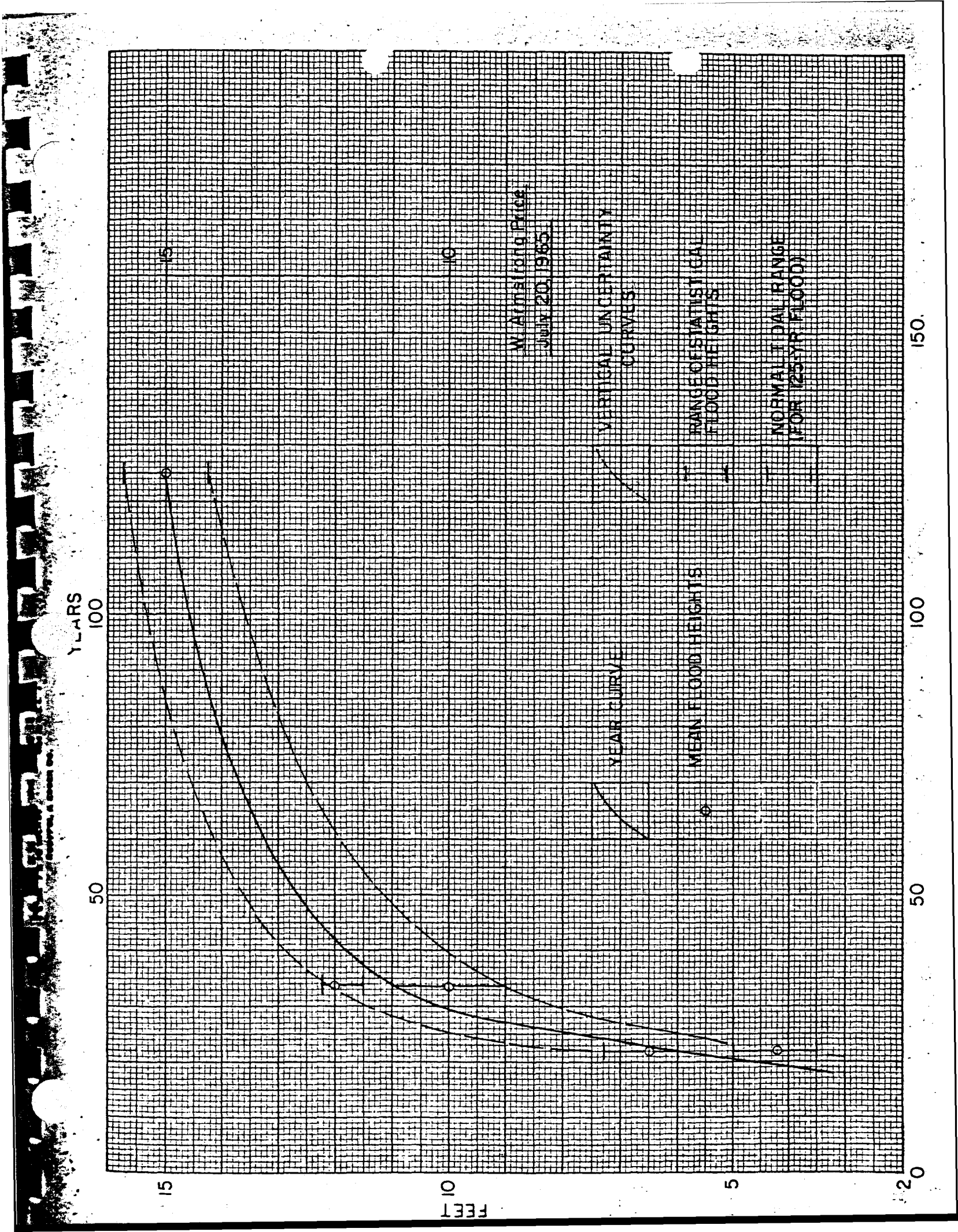
PER 100-MILE SECTOR, TEXAS COAST

Year Curve. Solid line, probability of floods (stillwater levels) of indicated heights above mean sealevel, if data used are accepted at face value.

Vertical Uncertainty Curve. At 125 years and 15 feet, a flood will have the normal tidal range of 1.5 feet imposed on it as an oscillation during 24 hours.

At 33 to 35 years, a total vertical uncertainty range of 3 feet is shown for the storms with stillwater elevations of 10 to 12 feet, the uncertainty range being from 9.0 to 12.25 feet.

This precaution is indicated because some flood reports are not clear as to the elevation, and elevation datums are at present in some confusion along world coasts.



damage from these narrow "twisters." They occasionally touch ground and instantly become black from top to bottom. They cause some of the stronger "dust devils."

The coast of south Texas lies in the area of fewest tornadoes for the state. There seems to be no record of a destructive tornado as far southeast as Corpus Christi, except during hurricanes of the Rio Grande delta area in the 1930-40 decade. A few minor tornadoes in the last few years have done a small amount of damage to barns and light buildings about 10 to 15 miles west of the Corpus Christi waterfront and north of Highway 44.

PART IV -- FORMS OF DUNES AND DRIFTS OF SAND

Dune Classification

Moving, wind-driven sand accumulates in unstable, partly stable and stable forms.

The most stable dunes develop in the presence of vegetation and are held in place by a vegetative cover. The density of the vegetative cover and the development of a dense network of roots extending to and below the base of the dune enable it to resist erosion by wind and water. The foredune, Fig. IV-1a, is the initial form of the stabilized dunes of Padre Island. A foredune is a linear succession of hummocks and saddles some of which may be blowout gaps. Foredunes have been called "source-bordering" lee dunes. They will form along the lee side of any large disturbed area or belt of sand if given time. Erosion of foredunes may leave scattered remnants as isolated vegetated mounds.

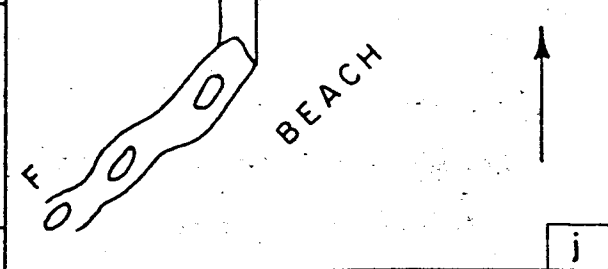
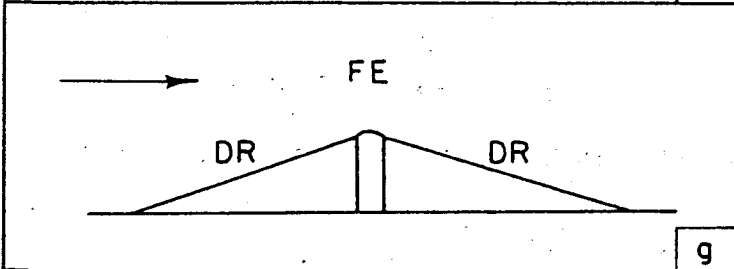
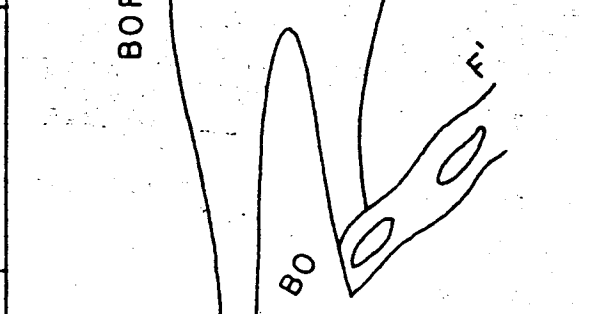
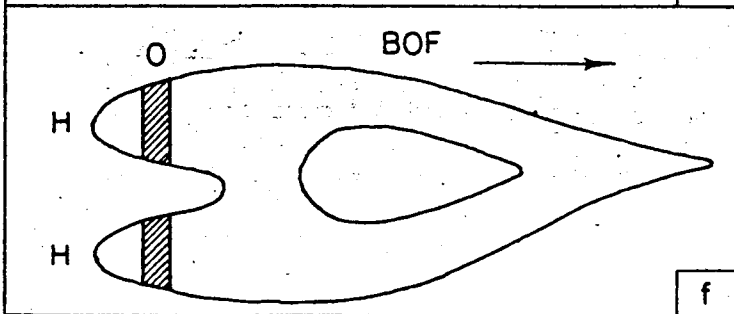
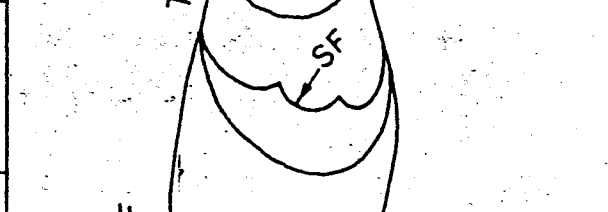
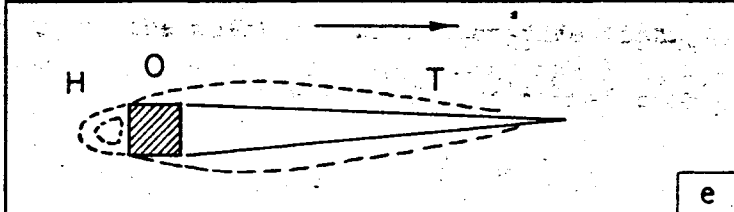
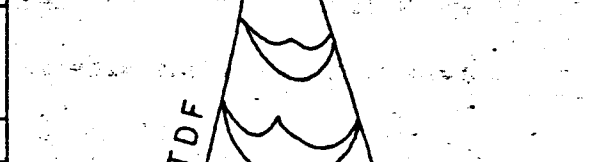
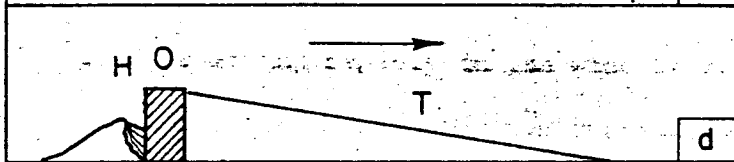
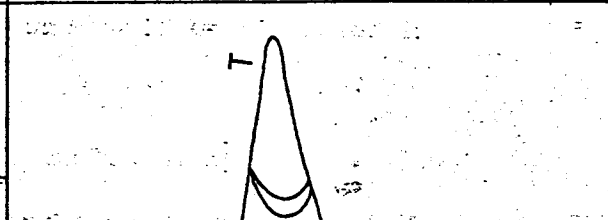
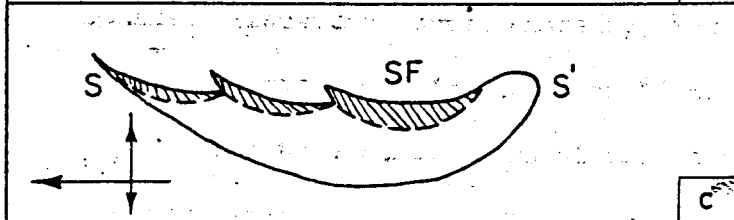
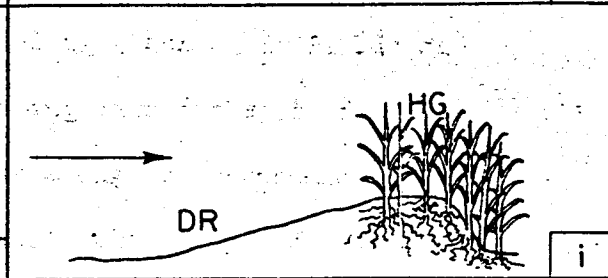
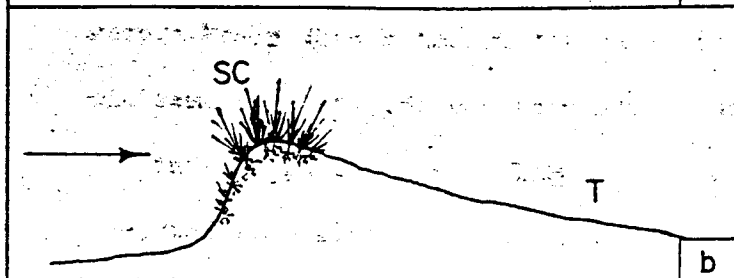
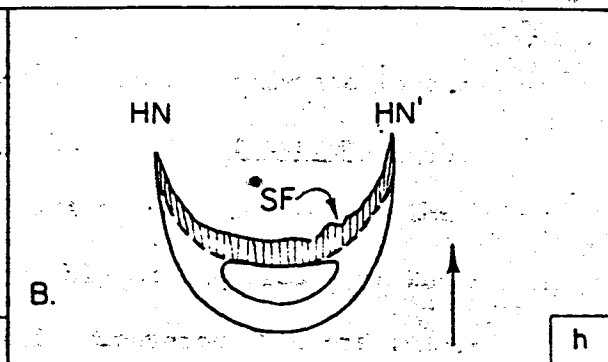
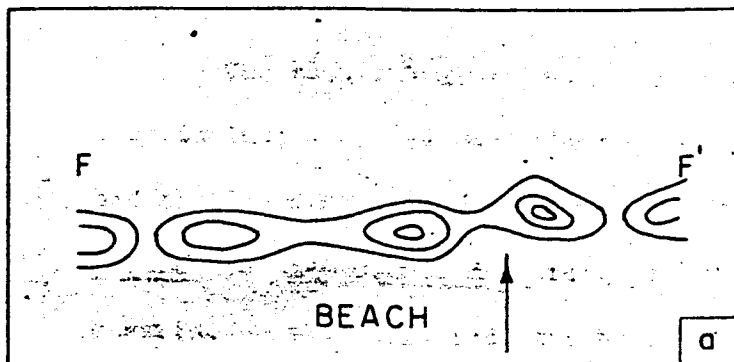
The more temporary, mutable forms of dunes are the free migratory dunes. These accumulate because sand grains are moved for relatively short distances at a time, some grains settling on the ground from the air and rolling grains coming to rest on the first. Such bare accumulations are vulnerable to the winds that built them and may either blow away entirely or slowly migrate with the wind. Individual grains pass on down-wind, but the form remains, like an oscillatory water wave.

Under the climate and sand-supply conditions of a region, its sand dunes have characteristic maximum dimensions.

FIG. IV-1. FORMS OF DUNES AND DRIFTS OF SAND, PADRE ISLAND.

Arrows show directions of movement of winds.

- a. Foredune chain. FF', map. Vegetated, stabilized or partly so, a succession of knobs and saddles, often with gaps.
- b. Shrub-coppice dune, SC, profile. A drift loosely held by bunch vegetation, subject to very slow migration in direction of tail, T.
- c. Seif (longitudinal) dune, SS', map. Pointed down-wind; blunt up-wind; slip face, SF, on side away from seasonal flank wind. Migrates in summer to N, and returns (to S) in winter. Net migration down-wind.
- d, e. Solid-obstacle drifts, d, profile; e, map. O, obstacle; H, hood-shaped drift with slip face; T, tail. Hood in e has closed summit contour. Non-migratory.
- f. Drift to leeward of gap between obstacles, map. O, twin obstacles; BOF, blowout fan with tail. Non-migratory.
- g. Drift with openwork fence or hedge, FE; profile. DR, drifts. Non-migratory.
- h. Barchan (crescent) dune, B, map. SF, slip face; HN, HN', horns. Migrates.
- i. Dense cane hedge arresting migratory dune, profile. DR, drift.
- j. Blowout fan developed to leeward of foredune gap, map. FF', foredune chain; BO, blowout in gap; BOF, blowout fan; TDF, transverse or seif dune field on fan; SF, slip face. BOF on Padre commonly shorter and broader in proportion to foredunes.



The bare migratory dunes of Padre Island are moderate in size. They include the crescentic barchan, Fig. IV-1b, the transverse dune and the longitudinal or seif dune. The latter is common here. The barchan and transverse dune ridge occur mainly on the flanks of the deserts. On Padre Island, the barchan and transverse dune are temporary. Newly formed transverse dunes standing alone or in fields of the same type are low and temporary, passing into the seif if they remain through the year. They are ridges elongated perpendicular to the wind and, like the seif, have slip faces along their down-wind flanks. Transverse dunes crossing seif dunes will be discussed in connection with seif fields, Page IV-6.

Lesser accumulations of bare sand include long, narrow, low stripes formed on bare surfaces in the direction of wind travel where sand is moving rapidly in the wind in relatively small amounts. Such stripes extend down-wind from the ends of seif ridges or stand alone on the moist lagoon-border tide-flats. Their directions indicate the direction of the wind that formed them. They are temporary, being destroyed by wind and tide.

Drifts

The term "drift" is given to accumulations of sand caused by and held in place by the protection of obstacles. The forms will be described below, Figs. IV-1, d-g, i.

Dunes of the Inner Border of the Beach

The inner parts of the beach above the inter-tidal and swash-and-run-up zone become covered with loose, dry, bare sand that accumulates into drifts, mounds and low dunes on its way to form the stabilized,

non-migrating foredune chain, Fig. IV-1a. The latter is the line or belt of high, grassy dunes that overlook the beach.

The drifts, mounds and low dunes are migratory but become loosely held by specialized "loose-sand" plants, including vines and grasses. As these mounds grow in height and bulk, the tall sea oats and shorter grasses of the high dunes gradually stabilize them. This final stabilization takes place during periods when an excess of sand is not blown against and smothering the plants.

Formation of a Foredune Chain, a Vegetated, Non-Migratory Dune Ridge

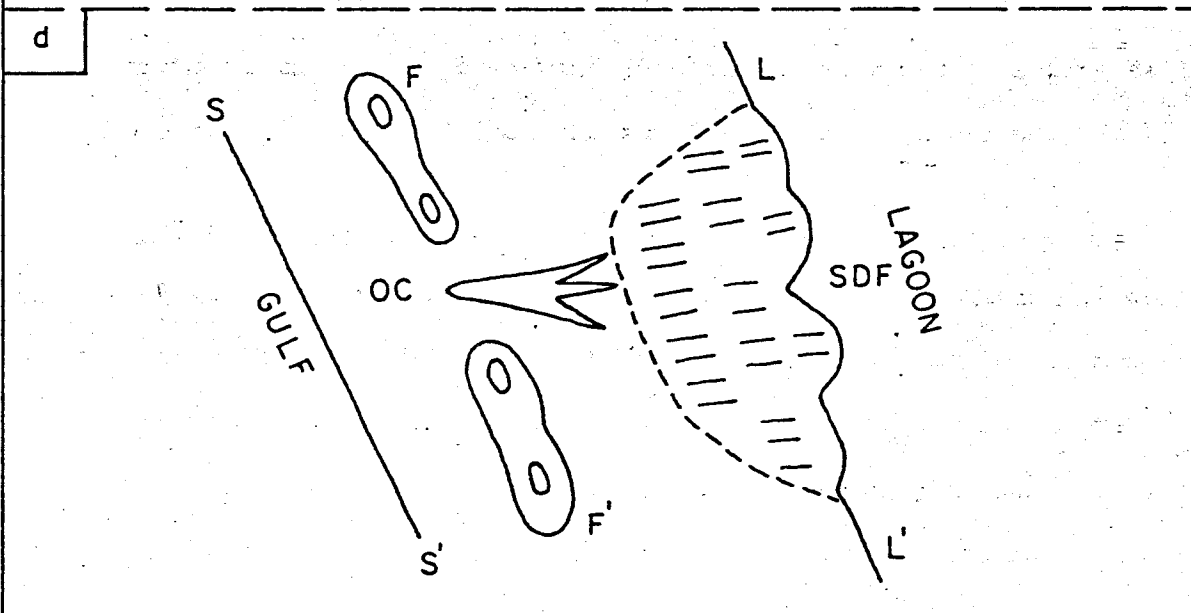
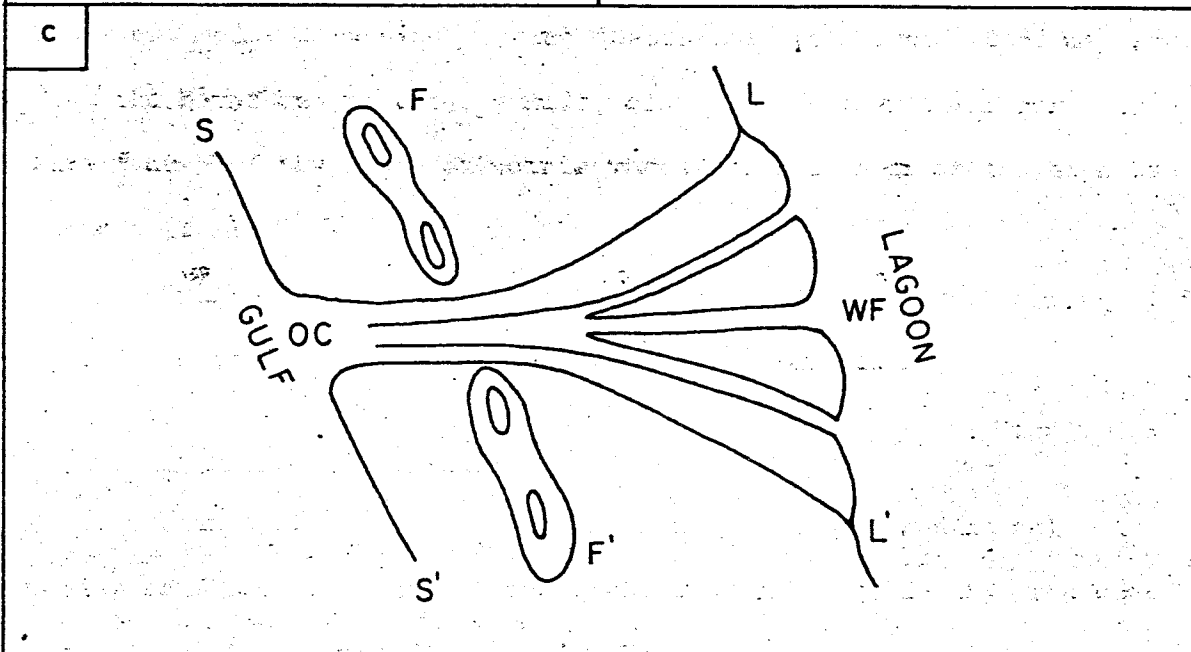
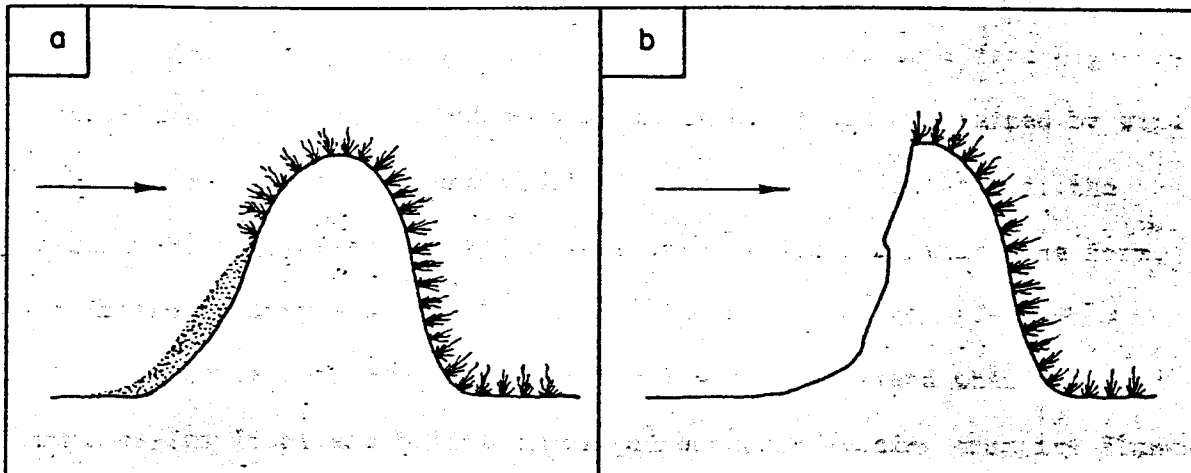
On Padre Island, the growth of a foredune seems to have begun with a storm-built beach ridge of bare sand raised by the waves along the inner border of the beach. It develops to an elevation slightly less than that of the stillwater level of the flood. Sand from the beach blows up on this beach ridge and may remain loosely held for many years. This process was observed by the writer in the weeks immediately following the erosion of the beach zone and foredunes by Hurricane Carla of September, 1961. Old beach ridges containing shells have been exposed beneath the old foredunes of Padre Island when a drought permitted the wind to destroy sections of it (Fisk 1959, Fig. 5c).

The beach ridge of Hurricane Carla was nearly 9 feet high. In a few weeks it had been raised by windblown sand in places to 12 feet. The summits now reach 15 to 20 feet above the inner border of the beach but are not yet stabilized. The older well-grassed foredune was bluffed by the 1961 storm. Its grassy summits now rise 20 to 37 feet above the beach. Its eastern foot is outlined in the North Development Area on the map, Fig. I-2.

FIG. IV-2. SOME ADDITIONAL DUNE EVOLUTIONS

Arrows show directions of movement of winds.

- a. Foredune, profile. Rapid addition of wind-blown sand on flank kills vegetation
- b. Same, later. Wind eroding bare flank is destined to remove entire dune, making gap in foredune chain.
- c. Overwash of Gulf flow through gap forms washover fan of sand in rear of island toward lagoon, map, SS'. Gulf shoreline. OC, overwash channel in gap in foredune, FF'; WF, washover fan with channel network (cross channels occur, but not shown); LL', lagoon shoreline, scalloped.
- d. Same area later, map. OC shortened by sand fillings, leaving ponds; SDF, seif-dune field developed on washover fan, three ranks of seifs being shown; dune field migrates into lagoon. Seifs are usually crossed diagonally by transverse dunes perpendicular to SE winds.



Barchan Dune

This crescentic dune, Fig. IV-1h, is low--2 to 3 feet high--and short-lived on Padre Island because it is built and maintained by wind which does not vary in general direction. As the wind shifts, the barchan becomes asymmetrical, passes into or joins another dune form, or is eroded away.

The barchan develops from any low mound of sand when the wind smooths its front and builds a pair of horns projecting from its flanks. The horns point down-wind, moving faster than the mound. Sand may stream from the horns and over the summit, also sliding down the inner face -- slip face -- of the mound at points where the latter grows too high to support itself.

Small barchans migrate relatively rapidly and here commonly join a larger dune, including the foredune or the seif dune.

Shrub-Coppice Mound or Dune

Clumps of grass that grow on a drift, mound or dune collect moving sand and hold it in loose stabilization, Fig. IV-1b. The dune slowly migrates downwind as erosion kills the plants up-wind, and new grass grows on the summit down-wind from the first growth. A long tail of sand streams to leeward from the summit of the coppice-mound.

Seif (Longitudinal) Dune

Fig. IV-1c shows the seif (Arabian, sword) or longitudinal dune as a ridge which is broad and blunt down-wind and narrowly pointed up-wind. On Padre Island the seif ridges attain lengths of 0.75 mile and point westwardly in the direction of the resultant of the dune-building winds of the year, Fig. II-5. The direction of seif elongation varies by 5° to 10° from due west.

For a dune ridge to become elongated in the direction of the annual resultant wind, it must receive sand from a wide spread of directions, as in Figs. II-2, II-5. The flank longshore winds nurture the seif and the onshore components of these and the east wind determine its elongation. Movement under a flank wind results in the development of slip faces on the opposite, leeward, side. Summits develop here and there along the ridge and sand from each summit slumps down to form a slip face. Each slip face ends toward the west in a small barb, each such element being like a barchan. Asymmetrical small barchans on Padre Island take the form of the seif.

In winter, northerly winds smooth over the slip faces of summer and develop small slip faces along the upper part of the southern flank. Because the total duration of the northerly winds is shorter than that of the winds of the warm months, the south-flank slip faces are commonly smaller than the north-flank ones.

A seif migrates slowly down-wind at an average rate -- for the past 30 years -- of about 88 feet a year. The flanks move back and forth by about 25 to 30 feet from a summer to the winter and to the next summer. The amounts of this north-and-south movement are shown by beveled flank laminae of the dune base, the more resistant ridges standing up a fraction of a centimeter above the ground across which the dune has retreated. The westward migration is shown by comparing successive aerial photographs and by the retreat of the blunt east ends relative to roads and other landmarks.

The free play of the yearly winds is needed to develop the seif dune. It does not seem to form close behind the foredunes, but further out on the plain to the west.

Seif Dune Fields

A seif ridge does not stand alone. Like other bare, migratory dunes of broad surfaces of sand, the seif forms in multiple. The individual ridges here point westward, and are separated by swales parallel with the dune ridges and of about the same width as the dunes, from bottom of swale to summit or ridge. The development of seif fields is shown in Figs. IV-1j and IV-2.

Because the seif is the product of all the sand-moving winds of the year, its form is mutable in detail. Most vertical aerial photographs of Padre Island show that the southeast wind, the main wind of the long period of warm weather, has imposed transverse dunes on the longitudinal seif dunes. This has formed a lacy, diagonal network of major seifs and minor, but prominent, transverse dunes. Here, the transverse dunes are not perpendicular to the all-year resultant wind, but only to the warm-period resultant, Fig. II-4. The details of the network vary with the seasons of active sand movement, but the general pattern seems to have remained for many years on most parts of the island.

Northward from about $26^{\circ} 50'$ N. Lat. along Padre Island, seif fields develop mainly in a single rank. Southward from this parallel, the seif fields may form in double or triple ranks. Fig. IV-2d shows a triple-rank field in diagram. The ranks are separated by N-S clear lanes (gassis of the Sahara) about 1,000 to 1,500 feet wide in typical examples. The clear lanes are shallow troughs.

North of $26^{\circ} 50'$, the trend of the island is such that after 0.3 to 0.9 mile an established clear lane threatens to intersect the seifs to the north, but is unable to do so. A second length of clear lane then develops to the east about 0.3 to 0.4 mile and runs again north.

This offsetting makes the eastern front of the seif field jagged. The troughs along the east side of the seif dune fields run dominantly North 10° West. A few go North 5° East. North of N. 26° $50'$ W. the island trends NE. South of this line the island trends SE. Thus, in the southern part of the island the troughs trend parallel to the island, whereas in the northern part the troughs trend at an angle with the island. This latter condition makes the troughs run diagonally across the island while the east front of the dune field runs parallel to the island. This conflict in direction seems to explain the offsetting of the east front of the seif dune field in the northern part of the island. In the same way, in the southern part of the island the troughs run parallel with the shoreline and, consequently, parallel with the fronts of the seif dune fields. Thus, in the southern part of the island there are no appreciable offsets in the fronts of the dune fields. These statements are based on the dune fields lying at approximately the same distances from the shoreline all along the island.

Along the east flank of the seif field, there is nearly everywhere one of the shallow, bare-bottomed erosional troughs discussed, which are about 200 to 500 feet wide. It seems to develop because the blunt east ends of the seif deflect the wind to the north. These troughs hold water after rains and in some places long, narrow and shallow oval basins, somewhat wider than 500 feet, have developed along them.

The eastern sides of the troughs of the seif field receive sand from the north and northwest in winter. This sand accumulates in the east-side marginal vegetation of the trough to form a low, loosely stabilized ridge. This is a miniature source-bordering lee ridge, but not high enough or hummocky enough to be called a dune.

Dune Evolutions

As sand is blown inland from the dry part of the beach, it accumulates in different forms, including dunes, drifts, sheets and stripes. A grain may pass through or over each of several of these forms before being stabilized by vegetation or being blown or washed into the lagoon.

The complex "corduroy pattern" of sand ridges left by a migrating seif dune field will be discussed.

It has been noted that barchans are among the first free, migratory dunes formed and that they join other dunes, losing their identities. Fig. IV-1a and 1b show how a blowout on the face of a foredune may destroy the dune and, with Fig. IV-1j and IV-2, how a succession of erosional and depositional forms may develop in and back of the gap formed in the foredune by the blowout.

An Intact Foredune Chain As a Conservation Structure

Studies of Padre Island over a number of years, with the aid of successive aerial photographs, show that foredune gaps permit the spreading out of bare sand on the grassy plain of the island, the destruction of the grass, and the development of large seif dune fields which move slowly off into the lagoon.

As a part of the migration of the dune-forms into the lagoon, much sand passes over the dunes and adds to the filling of the water body.

If the foredune is kept intact and its gaps closed, the inner and rear parts of the island should eventually regain their grass cover and prevent further filling of the lagoon with wind-blown sand and washover fan deposits.

The scarcity of dune fields in some southern sectors of the island seems to be due to the stabilizing influence of the large content of shells and shell fragments in the sand of the beach in those areas.

Corduroy Sand-Ridge-and-Trough Pattern of Seif Migration on Padre Island

The seif fields of northern Padre Island migrated a half-mile to the west between the aerial photographs of 1934 and 1964. Where the seif fields have migrated to the west across the interior plain of Padre Island, they have left a succession of N-S, former east-margin troughs with their lightly stabilized east-side sand ridges. This alternation produces a pattern of low ridges and depressions which may be called a corduroy pattern.

Where the east-flank troughs of the seif fields were offset, the projecting angles of the blunt ends of the seif have in some obscure manner left mounds of sand behind. The growth of the offset pattern while the field of dunes migrated, left behind E-W cross ridges which interrupt the corduroy ridging. These cross-ridges have become hummocky stabilized dune ridges. They tend to connect the foredune chain with the seif fields of the rear of the island.

Drifts Formed by Sand-Stream Obstacles

Sand accumulates against and in the lee of obstacles. Solid obstacles, as a post or building, tend to cause sand grains to bounce back and accumulate on the up-wind side in a crescentic form, with a slip face immediately in front of the obstacle, Fig. IV-1d, 1e. This crescentic drift is here called a "hood." Wind forms eddies between the slip face and obstacle, keeping the depression open. The hood develops in both small and large examples. To the rear of the obstacle, there is a sand "tail" pointing down wind.

With two solid obstacles separated by a moderately wide gap, two hoods and an oval sand sheet, shown in Fig. IV-1f, develop. On a large scale, the drift sheet takes the form shown diagrammatically in Fig. IV-1j, the drift forming to leeward of a gap in a foredune.

An openwork obstacle, as a fence or openwork hedge, develops a sizeable drift on each side across the path of the wind, as in Fig. IV-1g. A dense hedge, such as a hedge of cane (Arundo donax species), may stop drifting sand, if the dimensions of hedge and drift are in scale, and the hedge is planted transverse to the direction of summer-time sand migration.

Bare, Migratory Sand Dunes Stabilized by Cane Hedge and Volunteer Grasses

Georgia cane (riverbottom cane, Arundo donax) has been used on south Texas sandy land to stabilize large bare, migratory dunes on the Armstrong Ranch, Kenedy County.

This cane has joints at short intervals of an inch or two to several inches. It develops dense hedges 10 to 15 feet tall. A hedge was restored from the roots (after having been cut down) to a height of 5 to 6 feet in 6 months of fall, winter and spring. This hedge grows at Staples Street and Lexington Avenue, Corpus Christi.

Where the cane hedge is dense, it seems to stop the sand entirely if the hedge is planted at a sufficient distance from the blowout area, the source of sand supply, Fig. IV-1j.

This cane can be used to stabilize the terminal and lateral parts of a large dune, if the sand does not move too rapidly into the hedge before it attains maximum height and density. Native grasses sprout in the protection of the hedge. The use of this cane on Padre Island is in the experimental stage.

PART V -- BEACH PROFILE AND WAVE ENERGY DATA

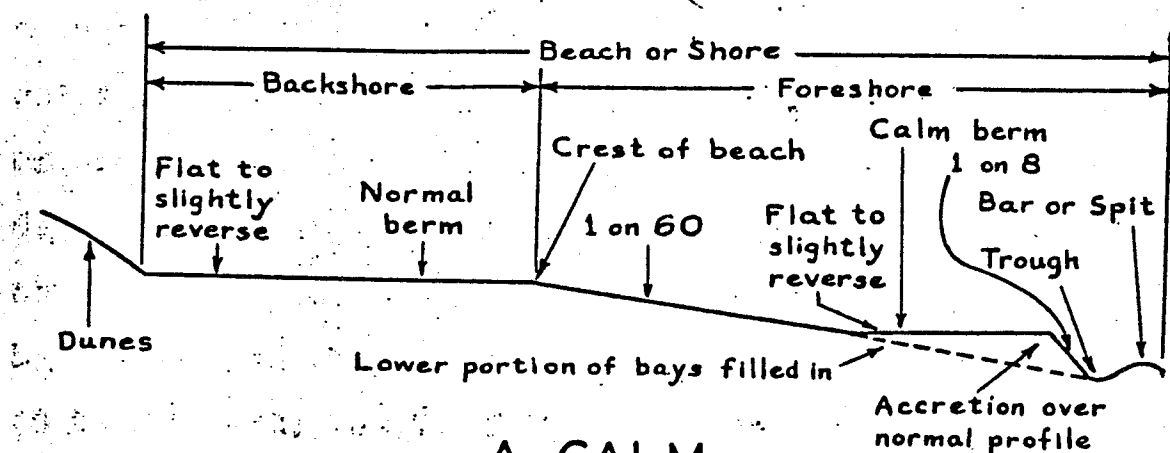
Beach Profiles

Blankenship (1952) studied changes in beach profiles on northern Padre Island at intervals throughout a year. His diagram, Fig. V-1, shows (a) the calm condition, "with light to gentle, southerly or easterly winds"; (b) the normal condition, "with gentle to fresh southeast winds"; and (c) the storm condition, "with fresh to strong, southerly and easterly winds," but no hurricanes or gales were experienced.

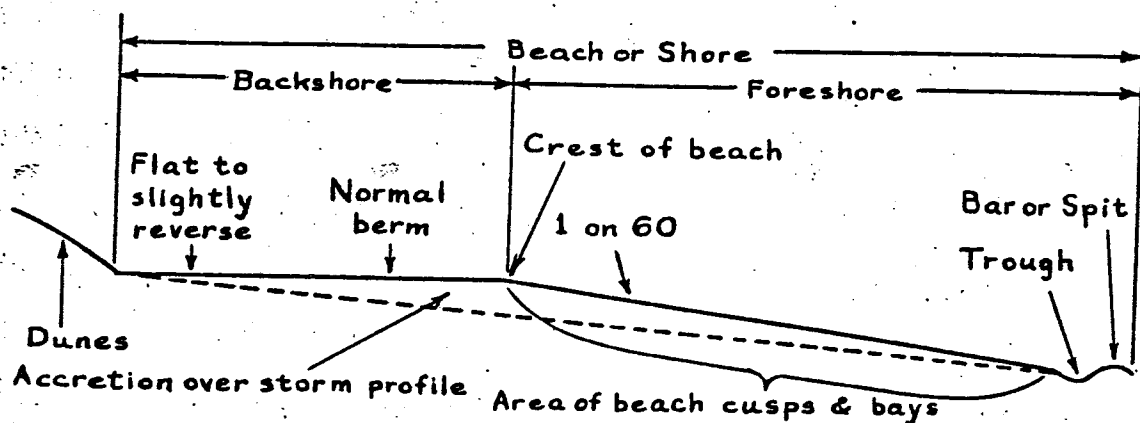
The changes in the beach illustrated by Blankenship occurred with changes in the forms of accretionary additions and their loss, or the smoothing of the breaks in slope known as "berms."

The writer made observations of the beaches of Mustang and Padre Islands from the air on September 18, a week after Hurricane Carla of September 11, 1961, had crossed the shoreline over Matagorda and Lavaca Bays, Texas, 75 miles north of Padre Island. Ground observations with profiles measured by foot-pacing and hand-leveling were made on Padre Island on October 22, a month and ten days after the hurricane.

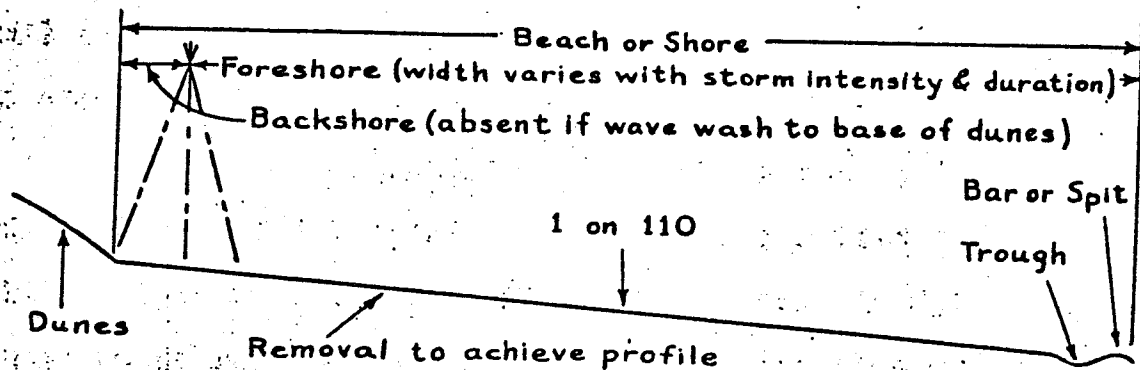
Measurements from vertical aerial photographs of September 16, 1961, made for the Coast and Geodetic Survey have been compared with landmarks which are still recognizable and which were mapped in July 1965 with precision. Statements of responsible landowners as to the relation of the flood elevation to beach and dune losses on their properties have also been used. These data, along with elevations obtained in the instrumental survey, have been used to compile the data of Table V-1. The stillwater level of the flood at Port Aransas was 9.2 feet msl and seems to have been as high or nearly as high on northern Padre Island (U. S. Engineers 1961).



A. CALM



B. NORMAL



C. STORM

FIG. V-1

BEACH PROFILES, NOT INCLUDING HURRICANES, PADRE ISLAND
(Vertical scale exaggerated 20X)

From Blankenship (1952, Fig. 7)

TABLE V-1 -- DATA ON BEACH GRADIENTS DEVELOPED BY HURRICANE
CARLA OF SEPTEMBER 11, 1961

NORTHERN PADRE ISLAND, TEXAS

Measurements in Feet

HORIZONTAL RECESSION OF FRONT OF OLD FOREDUNE	INNER BORDER OF BEACH	MEAN SEA LEVEL	BEACH WIDTH		BEACH GRADIENT
			Before Carla *	After Carla	
Not including gaps	Height Above Msl Ø	Datum is from U.S.C. & G.S. Bench Mark, Port Aransas			
125	7.6		360	150	1 : 16
to	to		to	to	to
150	8.6		530	250	1 : 29
	Some at 9.0 ?				

* Including young post-Carla foredunes.
These data are for July, 1965, assumed to be of the order
of magnitude of pre-Carla beaches.

Ø These heights are from the beach ridge built by the breakers
of the storm.

The data of the 1961 and 1965 surveys and of Table V-1 are used in the dimensionless profile diagram Fig. V-2.

The shelly beaches of Padre Island, which begin about 18 miles south of the Nueces-Kleberg Counties boundary line, are commonly steeper than those further north. Wave erosion cuts a nip or low bluff 3 to 6 feet high in the front of the beach. Back of the nip, the surface may support a steeper profile than that of the corresponding parts of the beaches further north. No surveyed profiles are at hand for the shelly beaches.

Wave Energy Data

The accompanying report of William A. Price, C. E., a civilian engineer with the Corps of Engineers, Galveston Office (Appendix) combines the data of the Corps with the oceanographic data of the Department of Oceanography and Meteorology, Texas A & M University,

The wave energy report gives data computed by him for use in planning construction on the beach and dunes of Padre Island.

These data may be used in conjunction with the hurricane-flood probability and hurricane-cycle data of Fig. III-1 and Fig. III-2 to select design elevations for structures to be erected on piling on or overlooking the beach.

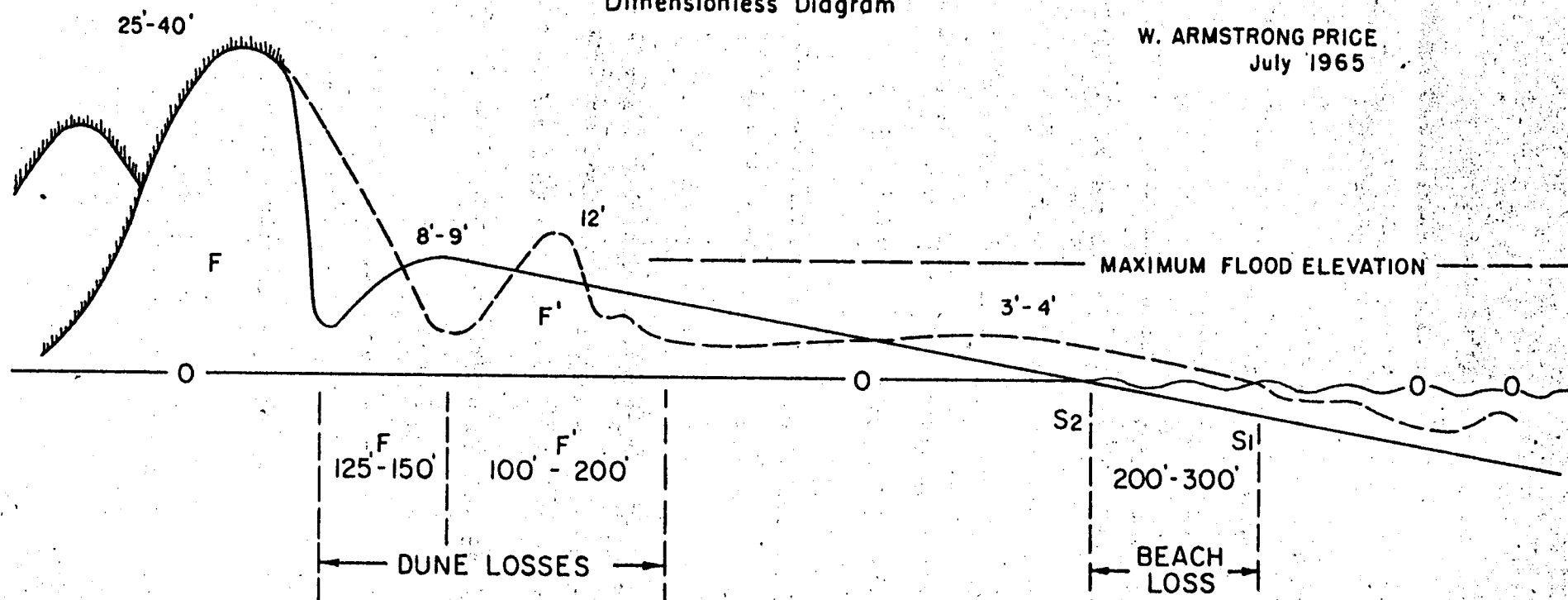
Front of Old Foredunes and of Proposed Construction Mound

Fig. V-2 shows by a solid line, with gaps, the present eroded front of the old well-grassed foredunes within the area of the North Development Site where it was left by the flood of Hurricane Carla. This conclusion is based on the recency of the lower, lightly stabilized foredunes which form a belt 100 to 200 feet wide in front of the old

CHANGES IN FOREDUNES AND BEACH PADRE ISLAND, IN HURRICANE CARLA, SEPT. 11, 1961

Dimensionless Diagram

W. ARMSTRONG PRICE
July 1965



FOREDUNES: F, old, grassy, stable; F', young, unstable.

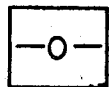
BEACH LOSS: Shoreline S1 to S2.



After Storm Profile



Pre-Storm Profile



Mean Sealevel Datum



Gulf Surface, contemporary normal MSL

foredunes. The writer has had sufficient contact with the beaches and dunes of Padre and Mustang Islands since 1961 to recognize the contact surface between the old and new foredunes.

It is believed that the present front of the old foredunes as shown on Fig. V-2 is a safe front for the proposed construction mound now planned for the North Development Area.

It cannot be stated with any degree of assurance whether the new foredunes, if grassed and well stabilized at their present positions and in their present heights and degree of compactness, would stand the attack of another hurricane as severe as Hurricane Carla. However, if these dunes are stabilized they should check the invading beach profile within their mass, thus helping to conserve the construction mound.

Degree of Reliability of the Mapped Front of the Old Foredunes

The time limits of the contract, with its extension to July 31, did not permit the mapping of the entire lengths of the foredune front on foot.

The foredune front was identified on the Godley topographic map by the steep slopes of the high dune mass, the succession of unfilled troughs along its front, and the lower elevations of the summits of the young foredunes in front of the trough.

The map determination was supported by ground reconnaissance and precise profiles measured across the contact in two places.

During the construction period, National Seashore staff members familiar with the contrast in vegetation-stabilization along the contact line will be able to assist in identifying it on the ground.

The importance of the contact line is two-fold: (1) it is the best assumption afforded by the data for a safe front line for the construction mound, and (2) the advanced state of stabilization of the old foredunes makes it highly desirable to avoid as much as possible damaging this protective growth during construction.

Alignment of Beach Face of Mound

A straight, smooth front for the construction front would seem to lessen the chance of the funneling of wind-blown sand up the face of the mound. An irregular front might also provide headlands for erosion by waves. The present deep gaps should be closed along the alignment of the mound front.

STRUCTURAL INVESTIGATION
of
PADRE ISLAND DEVELOPMENT
for
W. Armstrong Price, Oceanographer
by
William A. Price, Civil Engineer

July 5, 1965

Scope:

This investigation is of a preliminary nature, based on general assumptions. These assumptions may be modified as final structural design progresses. It presents wave forces and recommendations for the guidance of the architect and structural engineer engaged in final design of the proposed structures.

Basic Assumptions:

Generalized offshore profile slope of twenty-five feet per mile offshore of elev. 0.0 MSL. This slope is not critical.

Maximum surge tide elevation corresponding to a storm frequency of 125 years is elev. + 15.0 MSL. Lesser tides occur more often.

The beach elevation before a storm varies from elev. 0.0 MSL at the front to elev. + 5.0 MSL at the rear of the beach.

Beach slope is sufficient (1:100+), slopes of 1:100 or steeper, to cause waves to be breaking at critical depth breaking wave index.

General Conclusions:

Forces expected to occur at a water depth of ten feet, corresponding to a 125-year storm at the rear of the beach, are of such a magnitude that it is recommended that the main building fill and any permanent structures be kept above elev. + 22.0 MSL unless overall economy makes it desirable to consider them expendable in a storm of this magnitude. A fill elev. of + 15.0 MSL would be feasible with a seven-foot high floodwall along the front. The extreme wave force for this storm and location is concentrated below elev. + 19.0 MSL. Water above this elevation is wave run-up and can cause flooding but no structural damage.

It is essential that the actual floor of a structure not on fill be above the wave crest elevation corresponding to the water depth of the design storm tide and beach elevation. Waves passing under a floor set below the crest generate very high uplift pressures. Structural framing members may be below this elevation and above the top of dynamic force elevation

shown in Figure 1 if they are designed for a hydrostatic force of 64 pounds per cubic foot. Below the top of dynamic force elevation structural framing members should be designed to withstand the dynamic wave force shown in Table I. This force is given in pounds per lineal foot of width along the beach. An 18-inch diameter pile, for example, should be designed for 1.5 times the value shown.

Above the wave crest elevation shown, structures should be designed for a wind speed of 100 miles per hour.

Structures, including their piling substructures, should be designed for lesser tides as well as the maximum for the design storm frequency. This is because varying tide elevations result in the point of wave force concentration moving with the tide.

Wind speed and beach geometry are such that design should be for breaking waves.

Experience shows that unpaved shell and sand roadway areas and roadway shoulders will be severely damaged by storm waves when the roadway is covered by the tide. To reduce damage, roadways must be paved and shoulders must be paved or stabilized with cement or asphalt. A growth of grass, such as Bermuda, with a good root system has been effective in resisting wave attack. This stabilization must extend out to at least the bottom of any side ditches.

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Shore Protection Planning and Design, Beach Erosion Board of the Chief of Engineers, U. S. Army, 1961.

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Wave Forces:

Wave forces for varying water depths are shown in Table I. The use of these values is illustrated in Figure 1.

Explanation of Terms:

The following discussion is concerned with the structure as a whole, It deals with any one tide elevation. In actual use for structural design, the tide elevation will have to be selected to produce the maximum loading on any specific structural member being considered.

The loading diagrams can be considered as graphs of unit pressure per square foot plotted horizontally, and vertical position on the structure plotted vertically. This diagram is effective anywhere along the width of the structure; values are for a one-foot wide strip.

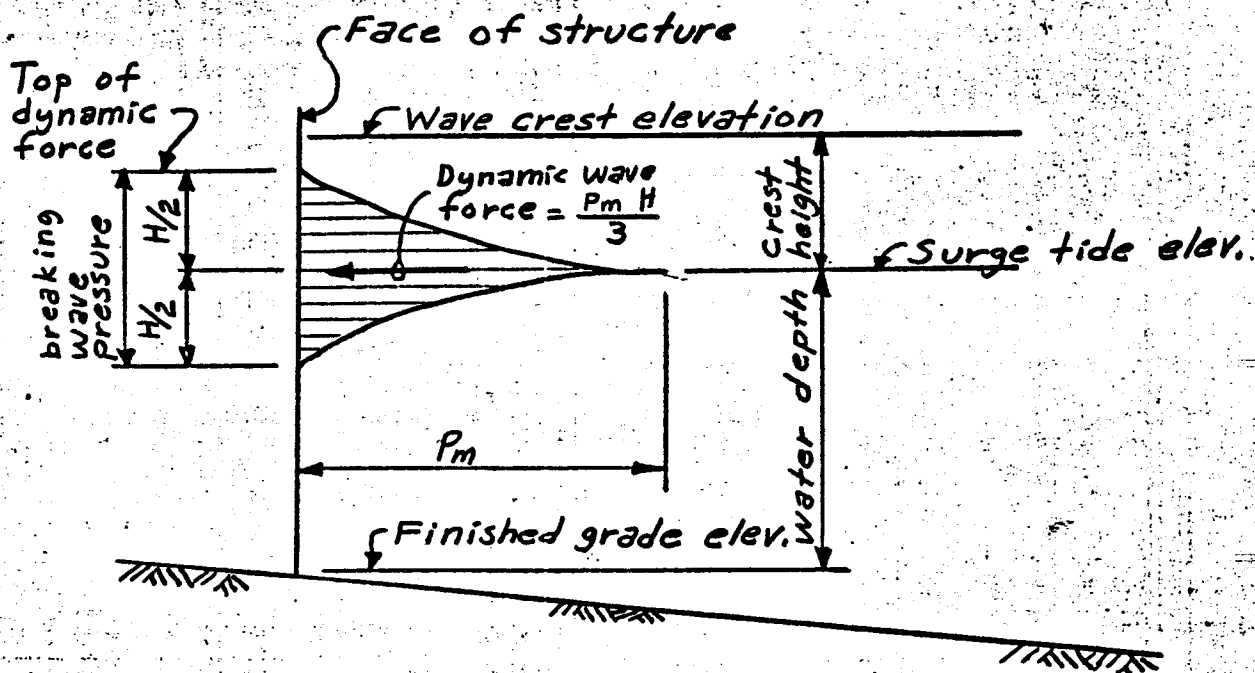


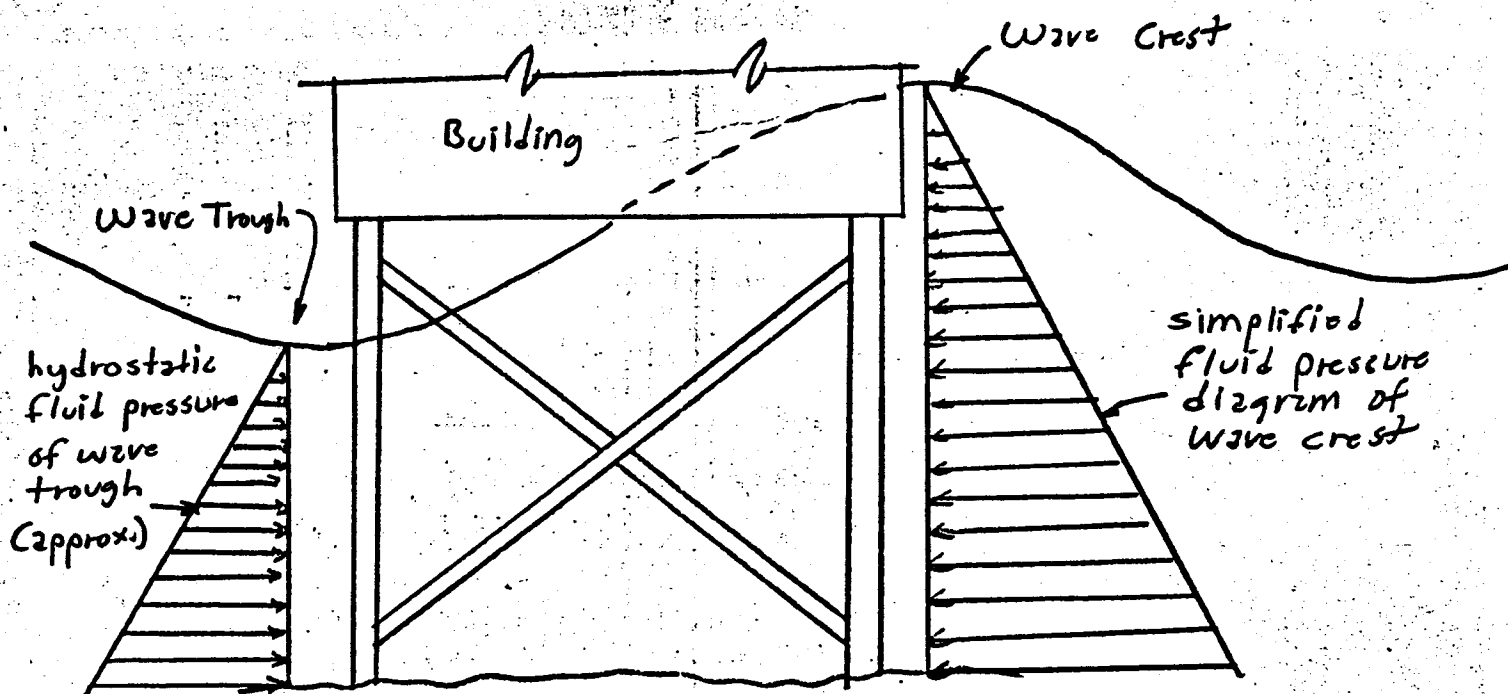
FIGURE 1

TABLE I:

Water Depth, feet	Crest Height, feet	H, feet	Dynamic Wave Force, lb./ft.	P_m , psf
5	3.3	3.9	3,770	2,900
6	4.0	4.7	5,390	3,460
7	4.7	5.5	7,350	4,040
8	5.3	6.3	9,580	4,610
9	6.0	7.0	12,190	5,200
10	6.6	7.8	14,900	5,730
11	7.3	8.6	17,500	6,120
12	8.0	9.4	21,500	6,900
13	8.6	10.1	25,300	7,490
14	9.3	10.9	29,300	8,060
15	9.9	11.7	33,800	8,650

Definition of terms: "Wave crest elevation" is self-explanatory. For maximum overturning of the entire building (maximum pile penetration determination), use this on the Gulf side of the building and assume a wave trough on the other side. The trough elevation is obtained by subtracting the wave height "H" from the wave crest elevation. This hydrostatic loading is illustrated in Figure 2a. "Pm" is the maximum value of the dynamic force of the breaking wave. It occurs at the tide elevation and drops to zero over a vertical distance of $H/2$ up or down. This dynamic pressure acts in combination with the hydrostatic pressure shown in Figure 2a. The combined pressure is shown in Figure 2b.

William A. Price, C. E.



note = this diagram is schematic, not to scale

a. Simplified Hydrostatic Loading

b. Combined Pressure

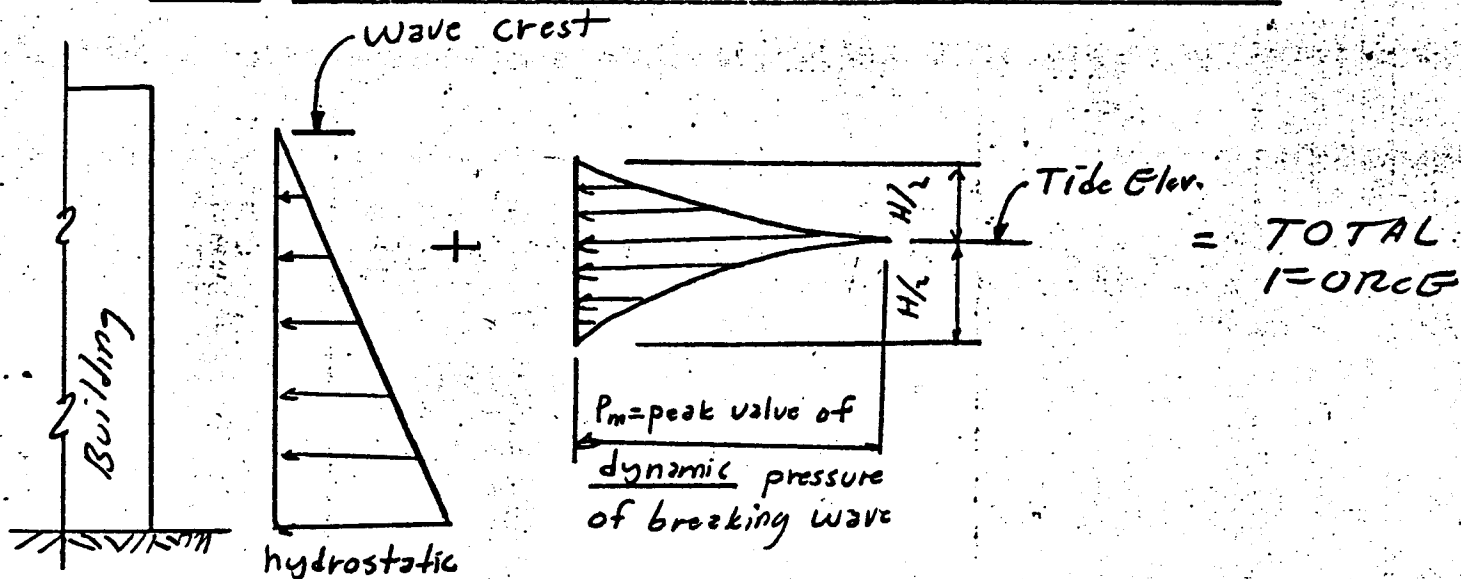


FIGURE 2

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