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Major Environmental Variables Affecting Grain Size Distribution in the Shoaling-Wave Zone Under Storm Conditions at Virginia Beach, Virginia

Dunnie Richard Tuck
College of William and Mary - Virginia Institute of Marine Science

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PUEBLO OCEANOGRAPHER—Dunnie Richard Tuck, one of two oceanographers aboard the U.S. Navy intelligence ship Pueblo captured last week by North Korea, is shown during 1965 when he was a graduate student at Virginia Institute of Marine Science. His research included work on erosion problems at Virginia Beach. Tuck, 30, is a native of South Boston. His parents, Mr. and Mrs. D. R. Tuck Sr., live in Richmond.

Civilian No Spy, Mother Declares

RICHMOND, Va., Jan. 27 (AP)—The mother of Dunnie Richard Tuck, one of two civilians aboard the captured Navy intelligence ship Pueblo, said today he is not a spy, as claimed by the North Koreans.

"I know he is not a spy. He's an oceanographer," said Mrs. Dunnie R. Tuck of Richmond.

The North Koreans earlier this week cited an alleged statement by the Pueblo's captain, Cmdr. Lloyd M. Bucher, as identifying Tuck and the other civilian aboard, Harry Iredale, as "espionage agents."

Mrs. Tuck said her son was employed two years by the Naval Oceanographic Laboratory in Washington before going to the Pueblo as a civilian oceanographer. He is a graduate of Virginia Military Institute and of the Virginia Institute of Marine Science.

MAJOR ENVIRONMENTAL VARIABLES AFFECTING GRAIN SIZE DISTRIBUTION IN THE SHOALING-WAVE ZONE UNDER STORM CONDITIONS AT VIRGINIA BEACH, VIRGINIA

A Thesis

Presented to

Virginia Institute of Marine Science

The College of William and Mary in Virginia

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of the
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of
MARINE SCIENCE

In Partial Fulfillment

Of the Requirements for the Degree of

Master of Arts in Marine Science

By

D. Richard Tuck, Jr.

1969

APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirements for the degree of
Master of Arts in Marine Science

D. Richard Tuck, Jr.
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ABSTRACT

Temporal variations of ten major environmental variables occurring during a storm were studied in relation to mean grain size distribution in the shoaling-wave zone of an oceanic beach. A similar study had been conducted earlier on the same beach by Harrison and Krumbein (1964) during relatively calm to moderate weather conditions. By augmenting their data with the "storm-condition" data and performing the same type of multiregression analysis, an evaluation could be made of the influence that storm conditions exerted upon the mean grain size distribution on this beach. Environmental variables studied included those related to beach geometry, local water properties, local wind conditions, tidal fluctuations and wave characteristics. The effect of these variables on the beach response was investigated by sequential linear multiregression analysis utilizing high speed computers.

The most influential sets of four-variable combinations, in a least squares sense, were found to suffice in "explaining" the observed variability in mean grain size distribution. Analysis of the effects of combined storm and non-storm values indicated that the "average" mean grain size (referring to the average of several sediment samples collected simultaneously in the study zone) was most dependent upon the variables manifested 4-8 hours prior to measurement of the beach response. The most influential four-variable combination consisted of: sigma-t, still-water depth, tidal-current speed and wind speed offshore. Sigma-t was found to be the most influential single variable when examined in four-variable combinations. The influence of mean bottom slope angle, which was the major influential variable during calm to moderate conditions (Harrison and Krumbein, 1964), became less prominent in the analysis of the combined non-storm and storm data. The recent study suggested that a reversal in the bottom-slope-grain size relationship occurred under the storm conditions. (Generally, mean bottom slope and average mean grain size are inversely related in the shoaling-wave zone.) With the decreased effect of bottom slope angle, wave-drift currents and tidal currents became more influential on average mean grain size distribution, according to the multiregression analysis.

MAJOR ENVIRONMENTAL VARIABLES AFFECTING GRAIN SIZE DISTRIBUTION IN THE SHOALING-WAVE ZONE UNDER STORM CONDITIONS AT VIRGINIA BEACH, VIRGINIA

INTRODUCTION

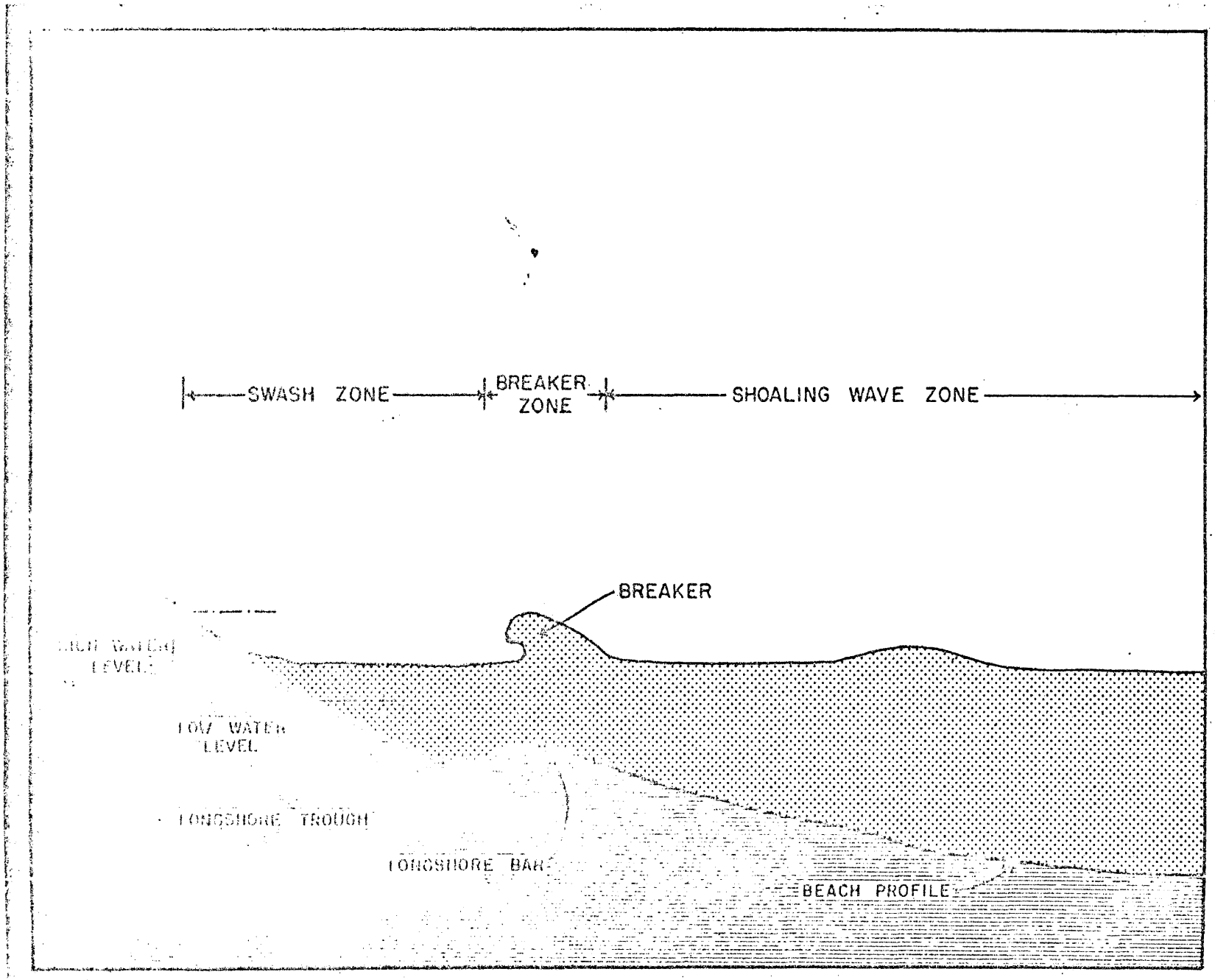
On a natural oceanic beach mean grain size varies significantly from one of the several beach zones to another (Fig. 1) and periodically within each of the given zones. This study was concerned with determining what environmental variables, acting during a storm period, are significant in affecting the distribution of average mean grain size (referring to the average of several sediment samples) with respect to time in the shoaling-wave zone of an oceanic beach.

Many variables of the beach-ocean-atmosphere system participate in affecting mean grain size. To elide unnecessary complications in the analysis, ten of the major environmental variables (Table 1) were selected for observation of their effects upon average mean grain size distribution.

An approach to the defined problem of average mean grain size distribution entailed three sequential phases. First, field measurements of selected "causal" elements in conjunction with measurements of the related "effect" element had to be obtained during storm conditions. Second, correlations between the environmental causal factors and distribution of average mean grain size were determined by sequential linear multiregression, a least squares search procedure, which will be discussed later. The final phase involved the evaluation of the correlations.

Harrison and Krumbein (1964) conducted a similar study on the

Figure 1.--Schematic diagram showing boundaries of the various beach zones.


SWASH ZONE
BREAKER ZONE
SHOALING WAVE ZONE
BREAKER
LOW WATER LEVEL
LONGSHORE TROUGH
LONGSHORE BAR
BEACH PROFILE

same oceanic beach under calm to moderate weather conditions. Some comparisons between related results of the two projects have been included in this study.

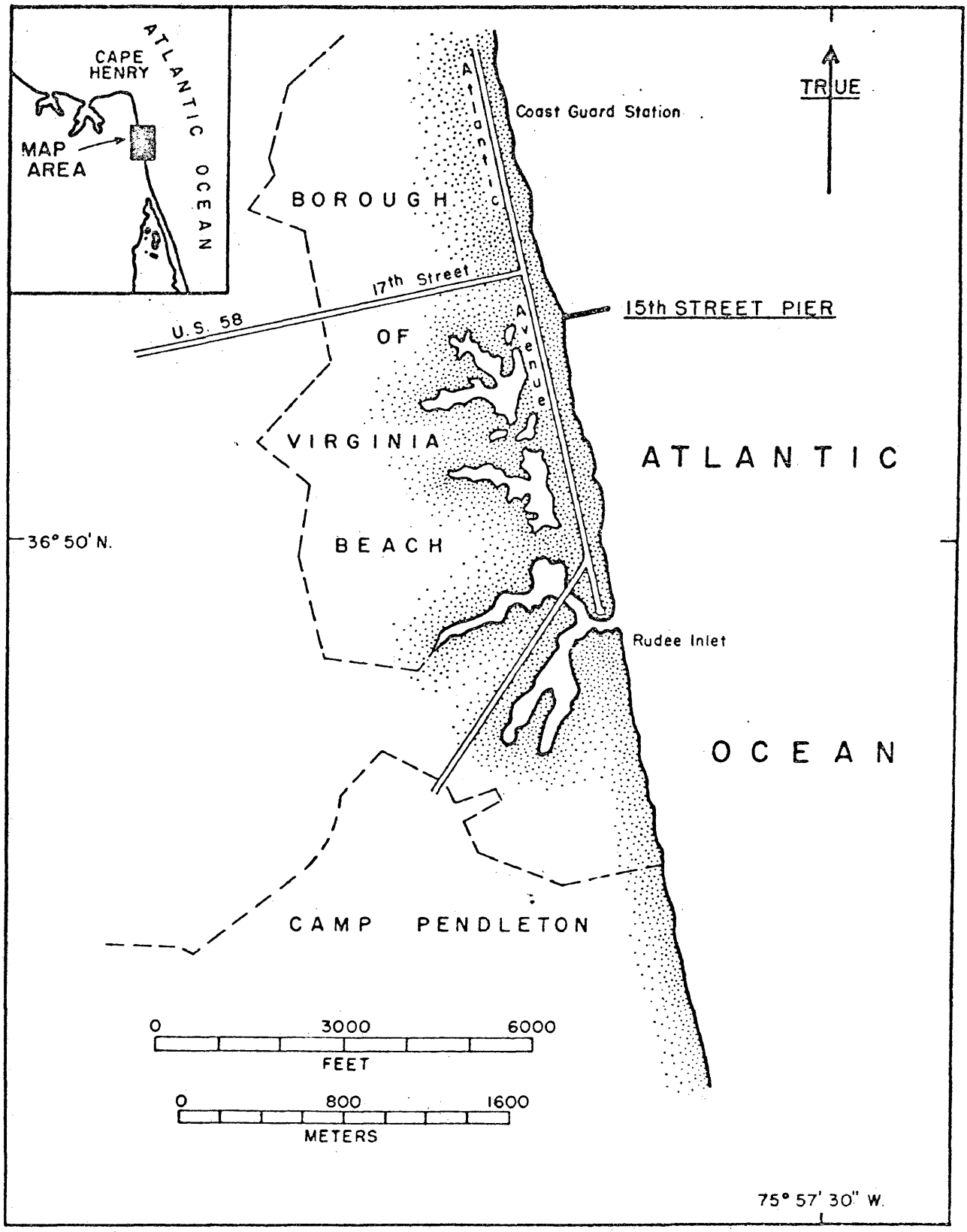
AREA OF INVESTIGATION

The beach selected for this study is located at Virginia Beach, Virginia, an oceanic beach situated immediately south of the entrance to Chesapeake Bay (Fig. 2). The area of the shoaling-wave zone examined was centered along the north side of the 15th Street pier (Fig. 3) which is about 10 km south of Cape Henry. The 15th Street pier, from which certain measurements were taken, extends seaward for a distance of 260 m from the shoreline and terminates at approximately the 6-m contour.

The site of investigation in the nearshore shoaling-wave zone was limited to a 30.5 x 4.6 m area roughly between 61.0 and 91.5 m seaward of the normal breaker zone under calm conditions. Generally, the area of investigation had an average water depth ranging between 3.3 and 4.3 m. In surveys conducted by the U. S. Army Corps of Engineers (U. S. Congress, 1953, p. 13), it was found that the beach slopes, beyond the breaker zone to the 6-m contour, ranged between 1:50 and 1:60. In the same survey studies, the Corps of Engineers found that the beach face was experiencing a long-term net erosion, while a slight accretion of beach material was occurring in the region seaward of the breaker zone and extending to the 6-m contour.

The beach material throughout the area is composed of quartz sand particles that exhibit an average Corey Shape Factor of 0.7 (Harrison and Morales-Alamo, 1964). The Corey Shape Factor for

Figure 2.--Maps showing general area of investigation.


CAPE HENRY
ATLANTIC OCEAN
MAP AREA
Atlantic Avenue
Coast Guard Station
TRUE
BOROUGH OF VIRGINIA BEACH
17th Street
U.S. 58
15th STREET PIER
ATLANTIC OCEAN
36° 50' N.
Rudee Inlet
CAMP PENDLETON
0 3000 6000
FEET
0 800 1600
METERS
75° 57' 30" W.

a sand particle is defined by:

$$S.\ F. = \frac{c}{\sqrt{a.b}}$$

where a, b, and c are the orthogonal long, intermediate, and short axes, respectively. Observations suggested that the average mean grain sizes in the study area generally range from 0.250 to 0.400 mm. In the shoaling-wave zone, there is a gradual decrease in mean grain size with increasing water depth.

A review of wind and swell records (U. S. Congress, 1953, plates 5 and 6) indicates that the higher wind velocities and total wind movements are greater from the northern quadrants and the dominant medium and high swells are from the northeastern quadrant. These high swells and wind velocities occur normally in the fall and winter and tend to erode the beach slightly, regardless of artificial nourishment. During the summer, the low swells approach from the southeast and the prevailing winds are from the southwest. These relatively milder conditions in the summer tend to nourish the beach naturally. More details of beach profile modifications in the area of investigation are presented by Harrison and Wagner (1964).

Surf conditions over a three-year period have been compiled by Helle (1958), as observed at the Virginia Beach Life Boat Station approximately 800 m north of the 15th Street pier. Results show that the surf is 1.2 m or higher 10% of the year, 0.9 m or higher 50% of the year, and 0.6 m or higher 95% of the year. The surf tends to be highest in the fall and early winter. The average period of the surf tends to be greatest in late spring and early summer (around 6.0 seconds).

Semi-diurnal tides occur at Virginia Beach which have a mean range of 0.9 m. The tidal currents are mainly of the reversing type and are generally parallel to shore. This reversing current is associated with the strong ebb and strong flood tidal currents exhibited at the entrance to Chesapeake Bay.

DATA COLLECTION AND COMPILATION

Field observations of the environmental variables occurring during the storm period were conducted between November 27, 1964 and December 5, 1964, inclusively. This period contained a 3-day storm with strong winds initially out of the northeast and eventually out of the northwest from November 29 to December 1. The methods of data collection performed during the storm period were similar to those used by Harrison and Krumbein (1964) during relatively calm conditions.

Bottom sediment samples were collected twice daily at 0600 and 1800 hours from November 28 through December 4. The causal variable measurements (the independent variables of Table 1) were either taken or determined from other data-collecting sources daily at 0200, 0600, 1000, 1400, 1800, and 2200 hours. Because a given beach element does not respond immediately to the operating forces of a given set of causal variables, it was necessary to investigate the time lag in the beach response adjustment. For this reason, measurement of causal variables began one day prior to initial sampling of the bottom sediment.

Four-hour lag periods, extending through the previous 20 hours, were arbitrarily established for the analysis in order to determine how readily the beach element responded to the environmental variables. For example, the beach response element observed at 0600 hours was assigned five lag periods terminating at 0200, 2200, 1800, 1400 and

Table 1.--The Ten Major Independent Variables Used in Determining Relative Influence on the Distribution of Average Mean Grain Size [$(\overline{M}_z)s$] in the Shoaling-Wave Zone at Virginia Beach.

Number	Symbol	Dimensions	Description
1.	$\overline{S}_s$	0	Mean angle of slope in shoaling-wave zone
2.	T	T	Wave period
3.	H	L	Wave height
4.	$\overline{U}_{on}$	LT^{-1}	Mean wind speed in an onshore direction
5.	$\overline{U}_{of}$	LT^{-1}	Mean wind speed in an offshore direction
6.	$\overline{U}_p$	LT^{-1}	Mean wind speed parallel to shore
7.	α	0	Angle of wave approach
8.	h	L	Still-water depth
9.	σ_t	0	Sigma-t
10.	C	LT^{-1}	Speed of tidal current

1000 hours respectively. Similarly, for the beach response element observed at 1800 hours, the five lag periods terminated at 1400, 1000, 0600, 0200 and 2200 hours respectively.

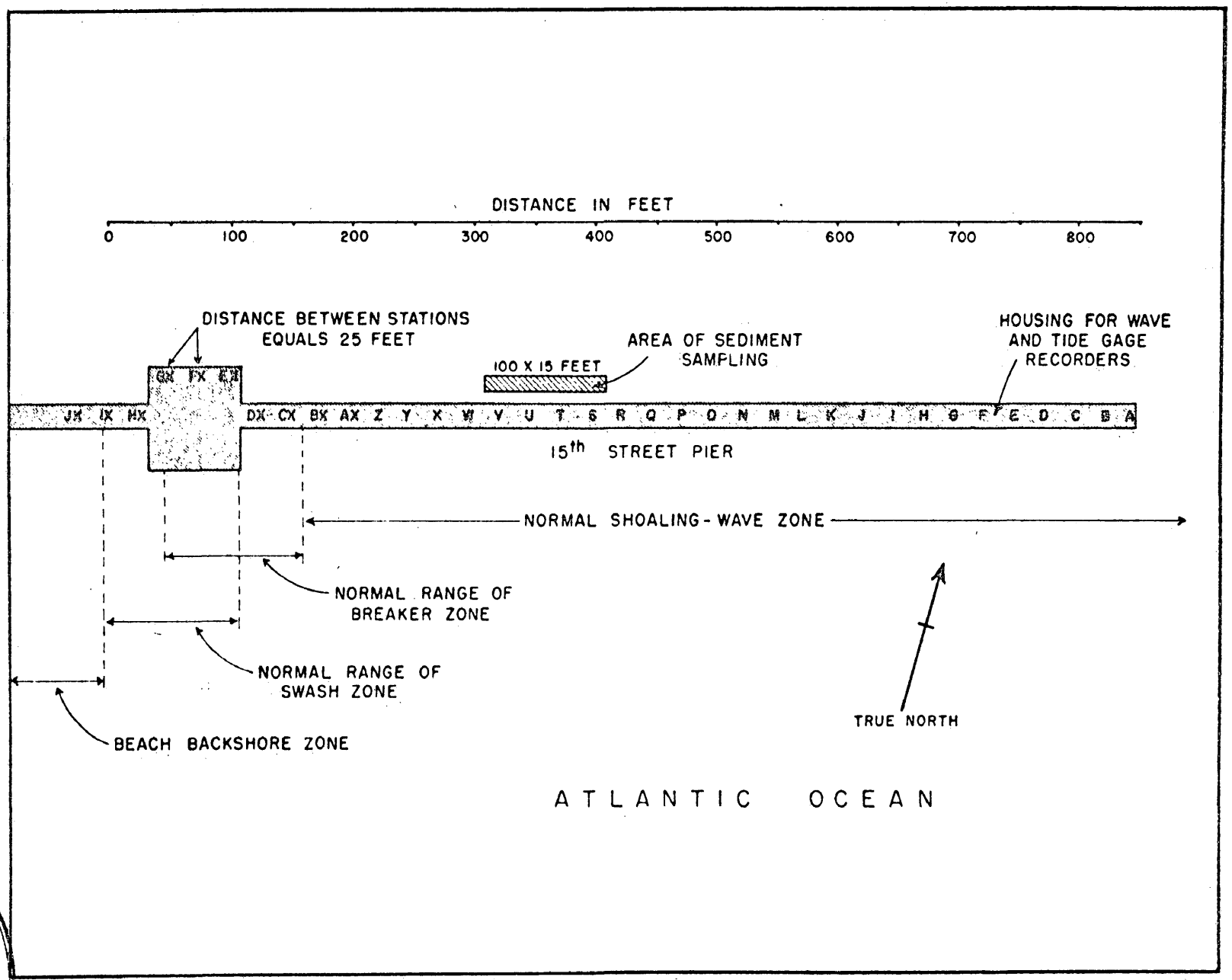
Sand samples were collected from the surface layer of the sediment bed with a pipe dredge, 4 cm in diameter. Sampling depths ranged from 0.5 to 2 cm below the sediment surface. The dredge was normally drawn along a transect approximately 4.6 m perpendicular to the pier. As mentioned earlier, the length of the study zone (Fig. 3) was 30.5 m, thus making the actual size of the zone 30.5 x 4.6 m. Samples were taken from four fixed stations (designated by S. T. U. and V., Fig. 3), and the average value of the analyzed mean grain sizes (which is termed "average mean grain size" in this study) of the four stations was employed in the multiregression analysis. Mean grain size of each sample was determined using a Woods Hole Rapid Sand Analyzer (Zeigler, Whitney, and Hayes, 1960), and the procedure outlined in Harrison and Morales-Alamo (1964). The statistic used to estimate the mean nominal diameter was

$$\overline{M}_z = \frac{P_{10} + P_{30} + P_{50} + P_{70} + P_{90}}{5}$$

where P are percentiles determined in the analysis.

The angle of bottom slope was determined from soundings off the pier at the same four fixed stations where the sand samples were taken and one additional station at each end of the study area (7.6 m between each station). These soundings along with tidal records were used in determining the still-water depth. The angle of wave approach was measured with a pelorus mounted at the end of the pier. Various littoral current speeds and

Figure 3.--Schematic diagram of the 15th Street pier and the general area of sediment sampling.



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directions (designated as "tidal" currents) one meter above the bottom were measured with a Savonius rotor and vane installed on the pier immediately seaward of the study area. Sigma-t was determined from salinity-temperature observations. Surface water samples for salinity and temperature measurements were taken at four-hour intervals. Temperatures were read directly from a bucket thermometer. Salinities were determined by titration with silver nitrate.

The U. S. Coast and Geodetic Survey Bureau maintains a tide gage near the seaward end of 15th Street pier, and the U. S. Army Corps of Engineers has a relay-type wave gage unit on the same pier (Fig. 3). Tidal elevations with respect to time and wave data (i.e., wave height and wave period) were acquired from these two agencies. The U. S. Weather Bureau has a regional station at Cape Henry, approximately 10 km miles north of the study area. This agency supplied information on wind direction and wind speed for each hour.

METHOD OF ANALYSIS

The distribution of sand grains of various sizes is controlled by the interaction of many beach process elements. It would be a difficult task to measure all the possible process variables and correlate them with average mean grain size distribution. In this comparative study the process elements were limited, presumably, to the ten most influential variables.

A sequential linear multiregression analysis was selected for determining the relationship between the ten variables and average mean grain size. In the first step of the analysis, the linear relation between average mean grain size and each of the process variables was determined from regression coefficients calculated by the least squares method. At this initial stage the most influential variables affecting average mean grain size normally become apparent. Next, the relation between average mean grain size and all possible pairs of the process variables were computed. From the most influential pair of process variables, the second most influential single variable could be identified. Sequential steps of analyzing combinations of three, four, or more variables at a time served the two-fold purpose of ranking the process variables in their mathematical order to physical significance as well as acquiring the most influential set of variables in the various multiple combinations. Thus, the variable combinations are referred to as "strong" or "weak" in

terms of the least squares search results.

The multiregression analysis, as reviewed by Krumbein (1959 and 1961), was performed on an IBM 1620 computer for the initial steps, and for more time-consuming steps, an IBM 7090 computer was used. Data prepared for the multiregression analysis are presented in Appendix A.

In the first step, when the process variables are being considered one at a time, the complete order of importance cannot accurately be determined by the amount in which each variable reduces the percent sum of squares of the response variable. Because there are many complex interrelations among the various process variables, an individual analysis may be misleading as to their true control when acting in combination. Some of the process variables may be redundant because their relation to the response variable is partially influenced by their interaction with other process variables. This is shown by the fact that the addition of the sum of squares reduction values is greater than 100 percent when the variables are computed individually. Most pairs and sequential combinations of the stronger variables will have a smaller effect on the sum of squares reduction than the total of the sum of squares reduction of all the involved process variables when computed individually. These progressive combinations tend to reduce redundancy and possibly approach the true statistical relationship between any combination of the process variables and the response variable.

In arranging the data for analysis, the distribution of average mean grain size was considered as a function of bottom slope angle, local wave period, local wave height, wind speed

onshore, wind speed offshore, wind speed parallel to shore, angle of wave approach, still-water depth, sigma-t, and tidal-current speed (Table 1) over five 4-hour lag periods (t 1-5).

Thus:

$$(\overline{M}_Z)s = f\ (\overline{S}_S,\ T,\ H,\ \overline{U}on,\ \overline{U}of,\ \overline{U}p,\ \alpha,\ h,\ \sigma_t,\ C)_{t1-5}$$

For consistency, the data in this study were analyzed in the same way the data in the study of Harrison and Krumbein (1964) were analyzed. A brief review of the multiregression technique is present in Appendix B.

OBSERVED STORM CONDITIONS

Virginia Beach is subjected to frequent "northeaster" storms (referring to wind velocities > 11 m/s) of varying intensity throughout the winter. For two days before the observed storm occurred, the winds, which were blowing primarily from the northeast, gradually increased in intensity. As the wind speeds increased, the direction of approach swung to the north (blowing parallel to shore), and, after three days, to the northwest (blowing out to sea). Wind speeds reached a maximum of 18.8 m/s during the height of the storm and maintained an average speed slightly over 11 m/s during the storm period. After the storm subsided, the winds blew mainly from the south (parallel to shore). The angle of wave approach changed with the shifting wind directions; from the northeast before and during the storm and from the southeast after the storm. The salinity of the local water was not significantly affected by the variable winds; however, the local water temperatures during the storm decreased over 4.5°C below the mean water temperatures observed the day before and the day after the storm.

The mean local wave height observed before the storm was 0.6 m and the mean wave period averaged 7 seconds. During the storm the local wave height ranged from 1.2 to 3.95 m, which was relatively high considering that most of the waves had broken at least once on storm-built sandbars before reaching the study zone. The wave period in the early stages of the storm averaged between 5 and 6

seconds, and as the disturbance continued, the period and height increased slightly. Immediately after the storm the local wave height and period decreased substantially. Throughout the storm, the mean tidal-current speeds were 1.3 times greater than the speeds observed before and after the storm. Before and during the initial impact of the storm, the shoaling-wave zone mean bottom slope in the sampling area was approximately 1:50, containing sand grains ranging between 0.320 and 0.370 mm in average mean grain size. As the storm intensified, the mean slope steadily increased and the sand grains varied between 0.250 and 0.300 mm in average mean grain size. After the storm the mean slope was found to be approximately 1:30, containing sand grains ranging between 0.320 and 0.370 mm in average mean grain size. Deposition, averaging about 0.5 m, occurred within the study zone during the storm. Hence, the still-water depth, which averaged 3.2 m before the storm, was found to be approximately 2.7 m immediately after the storm.

COMPUTED RESULTS AND COMPARISONS

Table 2 contains the results of the sequential linear multi-regression analysis of the initial phase in the present study. As shown, the results indicated that the beach-ocean-atmosphere conditions manifested in lag period 2 (4-8 hours prior to beach response sampling) had the greatest influence on average mean grain size distribution. Additional results of the analysis (Tables 3-7, storm data) indicated that the strongest four-variable combination in the most dominant lag period (Table 4B) consisted of wind speed offshore, still-water depth, sigma-t, and tidal-current speed. In considering the three strongest sets of four-variable combinations in all of the five lag periods (Table 8, storm data), the dominant variables are wave height, still-water depth, sigma-t and tidal current speed. The weakest variable was found to be angle of wave approach.

By way of comparison, the earlier study (Harrison and Krumbein, 1964) found that beach-ocean-atmosphere conditions in lag period 3 (Table 2), occurring 8-12 hours prior to sediment sampling, had the most significant influence on beach response. Results of four-variable combinations for each of the five lag periods in the earlier work are presented in Tables 3-7, non-storm data: From the earlier work, it was found that the strongest four-variable combination in the most dominant lag period (Table 5A) consisted of bottom slope, wave period, angle of wave approach and tidal-current

Table 2.--Percent Reduction in Average Mean Grain Size (Shoaling-wave Zone) Sum of Squares Attributable to Ten Independent Variables, Taken Individually, for Lag Periods 1-5, Including Both the Non-storm (Harrison and Krumbein, 1964), shown in parentheses, and the Storm Weather Conditions.

Variable	Percent Reduction in SS by Lag Periods				
	Period 1	Period 2	Period 3	Period 4	Period 5
Total % SS Reduction	77.66 (82.59)	86.95 (81.99)	54.87 (96.20)	72.50 (93.95)	70.03 (91.48)
Mean Grain Size Shoaling-wave Zone	----- -----	----- -----	----- -----	----- -----	----- -----
Slope Angle Shoaling-wave Zone	4.36 (63.20)	4.15 (60.33)	2.94 (58.74)	2.50 (48.69)	1.79 (42.09)
Wave Period	2.55 (1.59)	0.30 (2.49)	1.16 (1.29)	2.89 (2.08)	0.80 (1.91)
Wave Height	15.84 (1.27)	8.34 (9.06)	11.17 (0.72)	8.56 (11.58)	7.22 (16.82)
Wind Velocity(Onshore)	2.95 (8.94)	2.46 (4.93)	5.06 (15.60)	0.92 (1.06)	0.65 (0.03)
Wind Velocity (Offshore)	2.05 (1.19)	5.89 (12.51)	0.14 (0.02)	0.31 (0.07)	0.02 (1.41)
Wind Velocity (Parallel to Shore)	11.74 (5.09)	21.13 (24.24)	5.26 (0.81)	6.63 (8.27)	5.37 (4.00)
Angle of Wave Approach	3.65 (16.77)	11.92 (33.23)	4.43 (15.78)	0.10 (6.34)	0.09 (2.94)
Still-water Depth	8.26 (1.89)	25.64 (0.10)	10.34 (14.86)	9.53 (0.33)	28.22 (1.66)
Sigma-t	28.57 (31.60)	26.02 (26.07)	23.80 (22.48)	20.52 (18.53)	18.09 (14.38)
Tidal-current Velocity	4.44 (7.71)	7.05 (24.34)	0.03 (5.23)	15.84 (28.41)	12.01 (49.58)

Table 3A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 1 (Excluding Storm Data).

Independent Variable Combinations										Percent Reduction in SS
1					7		9	10		78.72
1			4				9	10		77.61
1				5			9	10		77.46

Table 3B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 1 (Including Storm Data).

Independent Variable Combinations										Percent Reduction in SS
		3		5			9	10		69.14
	2	3					9	10		68.05
		3	4				9	10		64.67

Explanation of Variable Numbers

X1 - Slope

X2 - Wave Period

X3 - Wave Height

X4 - Wind Velocity (Onshore)

X5 - Wind Velocity (Offshore)

X6 - Wind Velocity (Parallel to Shore)

X7 - Angle of Wave Approach

X8 - Still-water Depth

X9 - Sigma-t

X10 - Tidal-current Velocity

Table 4A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 2 (Excluding Storm Data).

Independent Variable Combinations										Percent Reduction in SS
1			5				9	10		72.42
			5		7		9	10		71.83
		4	5				9	10		71.25

Table 4B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 2 (Including Storm Data).

Independent Variable Combinations										Percent Reduction in SS
			5			8	9	10		78.11
1		3	5			8				75.55
					7	8	9	10		75.30

Explanation of Variable Numbers

X1 - Slope Angle	X6 - Wind Velocity (Parallel to Shore)
X2 - Wave Period	X7 - Angle of Wave Approach
X3 - Wave Height	X8 - Still-water Depth
X4 - Wind Velocity (Onshore)	X9 - Sigma-t
X5 - Wind Velocity (Offshore)	X10 - Tidal-current Velocity

Table 5A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 3 (Excluding Storm Data).

Independent Variable Combinations										Percent Reduction in SS
1	2				7				10	82.75
1	2	3							10	82.69
1	2						8		10	81.24

Table 5B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 3 (Including Storm Data).

Independent Variable Combinations										Percent Reduction in SS
1		3		5				8		52.10
1		3				6		8		49.06
1		3	4					8		48.90

Explanation of Variable Numbers

X1 - Slope Angle	X6 - Wind Velocity (Parallel to Shore)
X2 - Wave Period	X7 - Angle of Wave Approach
X3 - Wave Height	X8 - Still-water Depth
X4 - Wind Velocity (Onshore)	X9 - Sigma-t
X5 - Wind Velocity (Offshore)	X10 - Tidal-current Velocity

Table 6A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 4 (Excluding Storm Data).

Independent Variable Combinations										Percent Reduction in SS
1	2				5				10	89.53
1				4	5				10	89.47
1			3		5				10	89.46

Table 6B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 4 (Including Storm Data).

Independent Variable Combination										Percent Reduction in SS
	2	3					9	10		67.68
1		3					9	10		61.00
		3			6		9	10		60.93

Explanation of Variable Numbers

X1 - Slope Angle
X2 - Wave Period
X3 - Wave Height
X4 - Wind Velocity (Onshore)
X5 - Wind Velocity (Offshore)
X6 - Wind Velocity (Parallel to Shore)
X7 - Angle of Wave Approach
X8 - Still-water Depth
X9 - Sigma-t
X10 - Tidal-current Velocity

Table 7A.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 5 (Excluding Storm Data).

Independent Variable Combinations										Percent Reduction in SS
	3				7		9	10		81.12
1	3		5					10		78.90
1			5	6				10		77.79

Table 7B.--The Three Strongest Percent Reduction in Average Mean Grain Size Sum of Squares Attributable to Four Xs at a Time Combinations of the Ten Independent Variables, for Lag Period 5 (Including Storm Data).

Independent Variable Combinations										Percent Reduction in SS
1						8	9	10		67.15
	3					8	9	10		66.18
			5			8	9	10		66.03

Explanation of Variable Numbers

X1 - Slope Angle
X2 - Wave Period
X3 - Wave Height
X4 - Wind Velocity (Onshore)
X5 - Wind Velocity (Offshore)
X6 - Wind Velocity (Parallel to Shore)
X7 - Angle of Wave Approach
X8 - Still-water Depth
X9 - Sigma-t
X10 - Tidal-current Velocity

speed. However, in compiling the three strongest sets of four-variable combinations in all of the five lag periods (Table 8, non-storm data), the results suggested that the dominant variables were bottom slope, wind speed offshore, sigma-t and tidal-current speed. The weakest variable was still-water depth. Table 9 shows a comparison of the range of values of the environmental variables observed during both the earlier and the more recent study.

Table 8.--Variable Frequency of Occurrence in the Three Strongest Combinations for Four Xs at a Time in All Five Lag Periods Under Non-storm and Storm Conditions.

Variable	Occurrence Under Non-storm Conditions	Occurrence Under Storm Conditions
Slope Angle	12	6
Wave Period	4	2
Wave Height	4	11
Wind Speed Onshore	3	2
Wind Speed Offshore	9	5
Wind Speed Parallel to Shore	1	2
Angle of Wave Approach	4	1
Still-water Depth	1	9
Sigma-t	7	11
Tidal-current Speed	15	11

Table 9.--Comparative Table of the Observed Range of Values of the Environmental Variables Under Non-storm and Storm Conditions.

Variable	Range of Values Under Non-storm Conditions	Range of Values Under Storm Conditions
Grain Size	0.234-0.843 mm	0.237-0.384 mm
Slope Angle	0.45-2.22°	0.54-1.75°
Wave Period	3-13.9 s	3-12 s
Wave Height	0.15-1.95 m	0.3-3.9 m
Wind Speed Onshore	0-11.9 m/s	0-16.6 m/s
Wind Speed Offshore	0-15.2 m/s	0-17.8 m/s
Wind Speed Parallel to Shore	0-14.8 m/s	0-18.8 m/s
Angle of Wave Approach	20-125°	20-75°
Still-water Depth	2.4-4.9 m	3.3-4.3 m
Sigma-t	13.6-25.0	19.6-24.9
Tidal-current Speed	0-21.3 cm/s	0-35.6 cm/s

DISCUSSION

In the earlier study, Harrison and Krumbein (1964, pp. 45-48) found a strong inverse correlation existing between mean bottom slope and average mean grain size in the shoaling-wave zone under non-storm conditions (Fig. 4, inset). Because of this strong "bottom slope-grain size" relationship, bottom slope appeared as the dominant independent variable influencing average mean grain size distribution (Table 2, period 3, data in parentheses) when all the independent variables observed during the non-storm period were analyzed individually. Under storm conditions, the data suggested that a position correlation of bottom-slope-grain size existed in the same area of investigation (Fig. 4). With the increased turbulence along the water-sediment interface, a quasi-fluidization of the bed surface developed (cf. Shepard, 1963; Scheidegger, 1961), and presumably the bottom slope or lack of a rigid slope greatly modified the influence of the slope angle on the average mean grain size.

Generally, storm waves develop two, three, and sometimes more breaker zones with accompanying "breaker" sandbars and "breaker" troughs. Such was the case in the zone of investigation during and after the storm (Fig. 5). The seaward edge of the study zone (Fig. 3) contained the second breaker bar and trough, and the remaining shoreward portion contained a "pseudo-foreshore" slope. As mentioned earlier, there was a positive relationship between

Figure 4.--Graphic representation of mean bottom slope-average mean grain size relationship during the storm period.

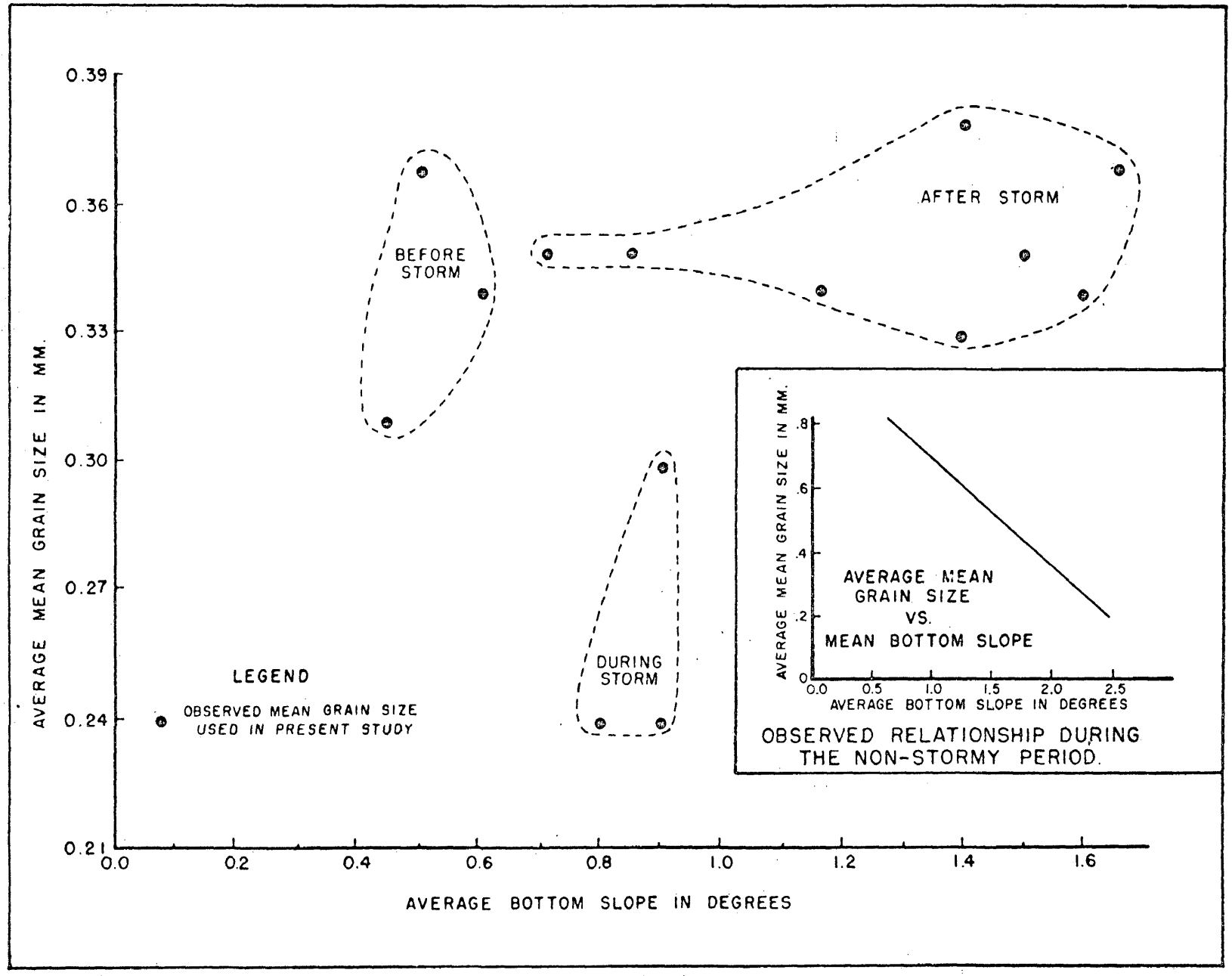
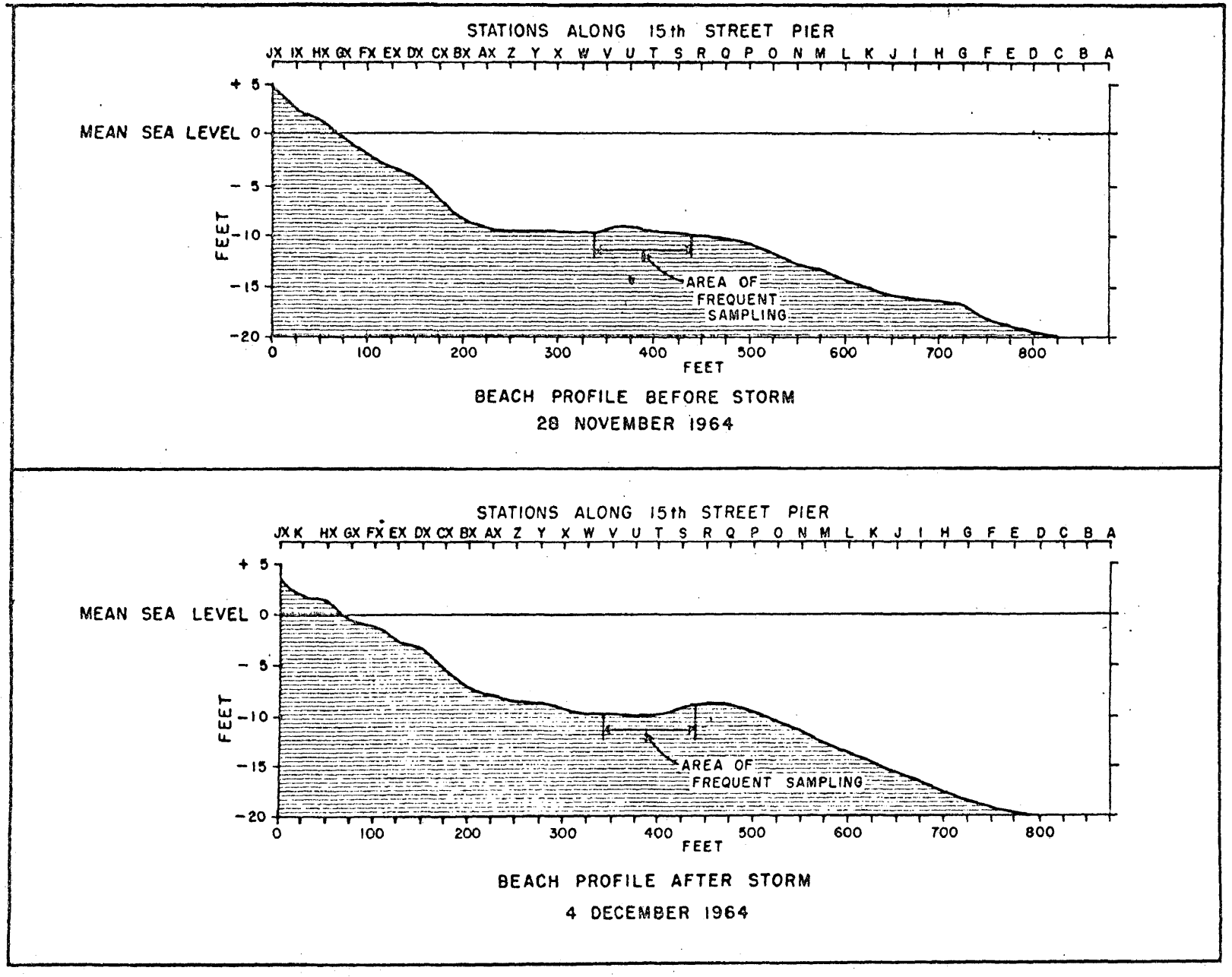

0.39
0.36
0.33
0.30
0.27
0.24
0.21
AVERAGE MEAN GRAIN SIZE IN MM.
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
AVERAGE BOTTOM SLOPE IN DEGREES
BEFORE STORM
AFTER STORM
DURING STORM
LEGEND
OBSERVED MEAN GRAIN SIZE USED IN PRESENT STUDY
AVERAGE MEAN GRAIN SIZE VS. MEAN BOTTOM SLOPE
AVERAGE MEAN GRAIN SIZE IN MM.
.8
.6
.4
.2
0
0.0
0.5
1.0
1.5
2.0
2.5
AVERAGE BOTTOM SLOPE IN DEGREES
OBSERVED RELATIONSHIP DURING THE NON-STORMY PERIOD.

Figure 5.--Schematic diagram of beach profiles at 15th Street pier before and after storm.


STATIONS ALONG 15th STREET PIER
JX IX HX GX FX EX DX CX BX AX Z Y X W V U T S R Q P O N M L K J I H G F E D C B A
+ 5
MEAN SEA LEVEL 0
- 5
-10
-15
-20
FEET
AREA OF FREQUENT SAMPLING
0 100 200 300 400 500 600 700 800
FEET
BEACH PROFILE BEFORE STORM
28 NOVEMBER 1964
STATIONS ALONG 15th STREET PIER
JX K HX GX FX EX DX CX BX AX Z Y X W V U T S R Q P O N M L K J I H G F E D C B A
+ 5
MEAN SEA LEVEL 0
- 5
-10
-15
-20
FEET
AREA OF FREQUENT SAMPLING
0 100 200 300 400 500 600 700 800
FEET
BEACH PROFILE AFTER STORM
4 DECEMBER 1964

bottom slope and grain size, which is the case on a true foreshore (Bascom, 1951). The observed change of the original study zone, from one exhibiting bottom slope-grain size characteristics similar to a near-shore shoaling-wave zone to one having bottom slope-grain size characteristics similar to a foreshore, altered the observed strong inter-relationship between bottom slope angle and average mean grain size distribution exhibited in the earlier analysis.

Waves have two basic methods in initiating movement of sand grains; one involves the orbital movement of water particles, and the other involves the unidirectional flow of water induced by the passing wave front (Arlman, Santema, and Svasek, 1958). Both of these methods are directly related to wave height (Shepard, 1963). As the local wave height increases, within limits, the size of the sand grains which are set in motion increases. However, smaller sand grains were measured in the area during the actual storm; the grains ranged from 0.250 to 0.300 mm. Previous studies (cf. Eagleson, Glenne, and Dracup, 1961, p. 45) have shown that waves with steepness less than 0.025 build up a beach shoreward of the breaker zone and waves with steepness greater than 0.025 erode a beach shoreward of the breaker zone. (Wave steepness is defined as $^{H}/_{L}$, where H is wave height and L is wave length.) Further observations suggest that the steeper waves not only erode the foreshore slope, but deposit relatively smaller sand grains in the offshore region via significantly strong rip currents that may be induced by a storm. This phenomenon possibly occurred in the study zone since the average mean grain sizes observed during the storm were smaller than the average mean grain sizes observed for the earlier non-storm period. The newer analysis indicated that the steepness

characteristic of waves during storms has a strong relationship with average mean grain size. Most all of the waves during the storm had a steepness greater than 0.025, which set up conditions for a seaward movement of sand grains into the near-shore shoaling-wave zone.

In reviewing the data (Table 8), the strong winds during the storm were not from the northeast, but were dominantly from the north and northwest. Winds blowing from the latter two directions were parallel to shore and "offshore," respectively. Pore (1964) observed that extratropical storm surges, such as existed during the observed storm, are more dependent on the winds blowing parallel to shore than on the onshore winds. Results suggested that the induced currents generated by the observed northerly winds parallel to shore were refracted toward the shore. The shoreward, wind-induced currents may have reinforced the wave-induced currents and thereby caused the wave variables, especially wave height, to become more influential in its effects on average mean grain size distribution. The influence of winds parallel to shore were possibly "masked" by the increased influence of wave height. The winds blowing onshore and offshore may generate currents normal to the wind direction. Such currents will be generally parallel to shore and would become interrelated with the tidal currents in the area. With the strong tidal currents occurring during the peak of the storm, it is believed that whatever effect the onshore and offshore winds exerted on distribution of grain size, such influence was masked by the dominant southerly flowing tidal currents.

The angle of wave approach had relatively minor influence on

grain size distribution in the present analysis. During the storm the waves approached from the northeast, and after the storm the waves approached from the southeast. The basic difference in wave characteristics associated with the two directions of wave approach was wave height, and apparently most all of the influence exerted by the wave conditions was contained in that wave variable.

The sediment deposited during the maximum intensity of the storm contained sand grains smaller in average mean grain size than the grains found in the study area prior to the storm. This observation may be due, in part, to the transport of fine sand grains by seaward flowing rip currents and/or mid-depth return flows such as that observed by Miller and Zeigler (1958). Upon reaching the study area, where a breaker zone had developed during the storm, these seaward currents possibly dissipated and deposited the relatively finer sand grains upon the sediment bed. After the storm had passed and the oceanic and atmospheric conditions became relatively calm, the observed average mean grain size increased, covering a range larger than that present prior to the storm. This increase could have been expected since the still-water depth had decreased, thus placing the sand grains closer to the acting forces of passing waves. There were no rapid depth changes in the earlier analysis; consequently, little change occurred in average mean grain size due to the still-water depth. In the present study, rapid depth changes and seemingly related average mean grain size distributions occurred. The present analysis indicated that variation in still-water depth, indeed, was a very influential factor on average mean grain size distribution. It is realized that still-water depth is not an energy term in the environment, but it is

important in mediating the application of energy terms.

Water viscosity has been found to have a significant effect on the dynamic properties of immersed sand grains at Virginia Beach (Harrison and Morales-Alamo, 1964). The water viscosity varies considerably over the seasons owing to temperature and salinity variations in the Chesapeake Bay runoff and in the local ocean water. Temperature and salinity fluctuations associated with tidal currents and heating and cooling during the day also affect the water viscosity. Storms, which may alter water temperature and salinity, will consequently have an effect on water viscosity as indicated by the observed sigma-t values in the present study. The net change of the sigma-t values in the study area caused by the observed storm was in the range of ten percent. Winds may indirectly affect water viscosity, especially the winds causing an offshore movement of surface water. Such winds, if sufficiently strong, cause a mild overturn along the coast, resulting in the shoreward movement of colder more-saline water in the summer months and slightly more-saline water in the winter months. Alterations in viscosity may affect fluid stress on the sand grains. With a significant decrease in water temperature and slight increase in salinity, as observed during and immediately following the storm period, water viscosity may increase thereby increasing fluid stress on the sediment surface. An increase in fluid stress entrains more sediment, causing an increase in sand grain distribution. An increase in grain size was observed with diminution of the storm. Results indicated that the increased viscosity of the water after the storm acting in less water depth under similar induced forces was influential in increasing average mean grain size distribution.

In the earlier analysis (Tables 3-7, non-storm data), the influence of viscosity was significant; however, the full effect was apparently suppressed owing to the dominance of the shoaling-wave zone slope variable. In a separate analysis of the earlier data (Harrison and Krumbein, 1964, Tables B52 - B56), slope was deleted and water viscosity became highly significant. Under storm conditions, when slope became a less influential variable, water viscosity was observed to be a rather dominant variable in affecting average mean grain size distribution.

As mentioned earlier, the tidal-current speeds during the storm were approximately fifty percent greater than those during the non-storm period. With currents of this magnitude, some of the smaller sand grains may be held in suspension and transported without the combined action of other environmental forces (Scheidegger, 1961, pp. 213-216). The usual direction of sand transport caused by reversing tidal currents alone would be parallel to the beach. It is reasonable to assume that storm wave-induced currents caused sand to be transported in an offshore direction. This interlocking relationship between wave-drift and tidal currents possibly explains the significant influence that each exerts on the average mean grain size distribution as indicated by the present study. In the earlier study (Tables 3-7, non-storm data) tidal currents also appeared influential. However, the accompanying wave-induced currents were insignificant, apparently caused by the masking effect of the shoaling-wave zone slope variable.

SUMMARY

Results of the present study indicated that sigma-t was the most dominant variable in affecting average mean grain size distribution when the independent variables were ranked individually by a simple regression procedure. This observation is in agreement with the earlier study (Harrison and Krumbein, 1964) in which sigma-t was among the more dominant variables when the independent variables were ranked individually. Other influential variables, when taken individually, observed in the present study were tidal currents, still-water depth, wave height, and wind speed parallel to shore. When the variables were analyzed in combinations of four variables at a time, the results suggested that the four strongest variables, considering all lag periods, were sigma-t, tidal currents, wave height, and still-water depth in that order. Wind speed parallel to shore became less influential in four-variable combinations, apparently due to the masking effect of wave height and tidal currents.

Whereas the most significant four-variable combinations for the non-storm conditions manifested 8-12 hours prior to the time of measurement of average mean grain size distribution; the most significant combinations for the combined weather conditions manifested 4-8 hours prior to the time of measurement of the dependent variable. Thus, the multiregression analyses indicated that average mean grain size distribution responded more readily

to vigorous environmental conditions than to less vigorous environmental conditions; that is, the rate of change in the dependent variable varied directly with the magnitude of the applied forces. Results of the regression analysis suggested that, although the causal variables observed under non-storm conditions maintained considerable influence on average mean grain size distribution for at least twenty hours (Table 2), those observed under storm conditions exhibited their major influence within 4-8 hours after measurement (Table 2).

The significant interdependence between bottom slope and average mean grain size was reflected in the dominance of slope angle as a determinative variable in the regression analysis under non-storm conditions. Under storm conditions, bottom slope angle became a rather insignificant causal variable, and other forces (i.e., wave-drift currents and tidal currents), which may be strengthened by storms, became more influential in affecting the distribution of average mean grain size, according to the multi-regression analyses.

APPENDIX A

A print-out of the data used in this study and explanations of the data fields on the print-out.

APPENDIX A

The following pages contain a "print-out" of the data as prepared and fed into IBM 7090 and IBM 1620 computers used in this study. The system could handle only eighty spaces per line (or card); however, the data associated with one response required more than the available spaces, therefore an additional line (or card) was needed for each set of responses. As shown on the following several pages, each two print-out lines contain the values of the ten environmental variables, occurring at one specific time, as related to the given beach response observed at a specific time. This procedure was conducted through five lag periods.

A key to the code lettering over the individual "fields" is presented below.

KEY

First Line:

A - A field of six spaces containing the project number of the specific analysis.

B - A field of four spaces containing the control number which applies to a specific beach response through the five lag periods.

Y - A field of six spaces containing the beach response data (average mean grain size) in mm with the decimal point between the third and fourth digits in the field.

X_1 to X_8 - Each X has a field of six spaces containing the environmental variable data of bottom slope angle (X1) in degrees, wave period (X2) in seconds, wave height (X3) in feet, wind velocity onshore (X4) in mph, wind velocity offshore (X5) in mph, wind velocity parallel to shore (X6) in mph, angle of wave approach (X7) in degrees, and still-water depth (X8) in feet. The decimal point for each field is between the fourth and fifth digits.

C, D, and E - The blank fields of six, six, and three spaces respectively are for convenience.

LP - A field of one space containing the lag period numbers.

Second Line:

A' and B' - These fields correspond to A and B respectively in the first line.

X_9 and X_{10} - Each X has a field of six spaces containing the environmental variable data of the sigma-t anomaly (X9) and tidal-current speed (X10) in ft/s. In both fields the decimal point is between the fourth and fifth digits.

F and G - The blank fields of six and forty-nine spaces respectively are for convenience.

PN - A field of three spaces containing process numbers which is merely a way of designating the various lag periods for all beach response observations.

PROJ A010 11 VARIABLES
RUN NO 0001'MEAN SIZE 15 ST PIER VS
MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
ANG WV APP' WATER DEP'RHO' TID CURR VEL
LAG PERIOD 1

A	B	Y	X_1	X_2	C	X_3	D	X_4	X_5	X_6	X_7	X_8	E	LP
HA00100001	000	843	000	680	09.00	0001.10		0003	500	000	000000.	0	40.000012.60	1
A'	B'	F	X_9	X_{10}	G									PN
HA00100001			001	470	000038									6
HA00100002	000	606	000	085	000800	000150		0008	000	000	000000	0	3500001100	1
HA00100002			001	580	000000									41
HA00100003	000	763	000	066	000800	000100		0004	000	000	000000	0	4000001060	1
HA00100003			001	590	000026									84
HA00100005	000	234	000	186	000550	000130		000	00		650	003	000001070	1
HA00100005			001	980	000000									504
HA00100007	000	256	000	217	000400	000340		0024	000	000	000000	0	2500001280	1
HA00100007			002	200	000025									510
HA00100009	000	552	000	168	001100	000150		0000	000	013	500	000	000003000001330	1
HA00100009			002	500	000038									516
HA00100010	000	474	000	205	000900	000130		0000	000	001	600	000	000003000001410	1
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HA00100015			001	960	000014									534
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HA00100017	000	370	000	151	000500	000160		0006	000	000	000000	0	2000001400	1
HA00100017			001	900	000022									540
HA00100018	000	381	000	138	000350	000050		000	00		120	000	4000001440	1
HA00100018			002	280	000030									543
HAA0100001	000	307	000	054	000400	000200		0017	000	000	000000	0	1500001090	1
HAA0100001			002	060	000042									8
HAA0100002	000	359	000	056	000450	000200		0011	500	000	000000	0	1500001100	1
HAA0100002			002	050	000050									011
HAA0100003	000	339	000	059	000600	000210		0000	0000	650	000	000	004000001120	1
HAA0100003			002	080	000025									014

Lag Period 1, continued.

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HAA0100004000243000116000500      000270      000 00          1700003000001160   1
HAA0100004      002090000034                                                     017
HAA0100005000237000084000500      000360      000 0           2400002500001170   1
HAA0100005      002060000025                                                     020
HAA0100006000307000084000600      000640      000 0           4200003000001180   1
HAA0100006      002040000075                                                     023
HAA0100007000384000087000900      000550      00000000340000000000500000l110     1
HAA0100007      002010000050                                                     026
HAA0100008000336000130001100      000330      000000001800000000003000000970     1
HAA0100008      002030000008                                                     029
HAA0100009000326000145001100      000150      000 00            800002250000960  1
HAA0100009      002140000017                                                     032
HAA0100011000343000127000350      000130      000 00          1550003250001020   1
HAA0100011      002260000017                                                     038
HAA0100012000333000133001000      000130      000850000000000 0 05000000960      1
HAA0100012      002240000008                                                     041
HAA0100013000350000147000500      000110      000 00          1100003000000920   1
HAA0100013      002160000008                                                     044
HAA0100014000347000070000700      000140      000 00          1500003000000960   1
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HA00100006000246000233001000      000120      0009000000000000 0  2500001110     1
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HA00100008000414000183001100      000360      000000001850000000001000001330     1
HA00100008      002490000063                                                     513
HA00100014000516000182000300      000130      000 00          1500003000001440   1
HA00100014      001960000042                                                     531
HAA0100010000369000175000300      000110      000 00          1150004500000940   1
HAA0100010      002240000008                                                     035
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PROJ 0010 II VARIABLES
RUN NO. 0001' MEAN SIZE 15 ST. PIER VS
MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
ANG WV APP' WATER DEP'RHO' TID CURR VEL
LAG PERIOD 2

```
HA0010000100084300006600053O      000170      000 000  650000000003000001420   2
HA00100001      001469000000                                                      5
HA0010000200060600008100080O      000150      0008000000000000 0  4000001320   2
HA00100002      001560000050                                                    040
HA0010000300076300006300080O      000100      000 0000 550000000004000001350   2
HA00100003      001620000030                                                    083
HA0010000500023400017000060O      000250      000 00         1200003000001380   2
HA00100005      001940000068                                                    503
HA0010000700025600022200035O      000200      0014500000000000 00 2000001490   2
HA00100007      002140000030                                                    509
HA0010000900055200017300110O      000200      000000001700000000003000001510   2
HA00100009      002490000000                                                    515
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HA00100010      002360000000                                                    518
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HA0010001200047400018400060O      000130      000000001600000000003000001450   2
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HA0010001500046800018400040O      000120      000 0          1200002500001300   2
HA00100015      001960000041                                                    533
HA0010001600041700017800035O      000150      000 000        1850002500001340   2
HA00100016      001970000055                                                    536
HA0010001700037000015900050O      000130      000 00         1250002000001240   2
HA00100017      001900000027                                                    539
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Lag Period 2, continued.

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HAA0100009       002110000000                                                    31
HAA0100011000343000140000350      000100      000 0           1300003500000910   2
HAA0100011       002250000008                                                    037
HAA0100012000333000135000350      000050      00000000 700000000005000000900   2
HAA0100012       002270000008                                                    040
HAA0100013000350000145000600      000120      000 00          1050003500000890   2
HAA0100013       002180000017                                                    043
HAA0100014000347000097001000      000150      000 00          1650003500000900   2
HAA0100014       002150000000                                                    46
HA00100004000695000050000900      000080      000000001100000000006000001370   2
HA00100004       001740000018                                                    148
HA00100006000246000216001000      000150      000 00           900003000001350   2
HA00100006       002070000054                                                    506
HA00100008000414000194000900      000600      000000001600000000002000001590   2
HA00100008       002400000018                                                    512
HA00100014000516000183000800      000050      000 00          1150003500001350   2
HA00100014       001990000054                                                    530
HAA0100010000369000145001000      000110      000 000         1250004500000900   2
HAA0100010       002260000000                                                    34
```

PROJ A010 11 VARIABLES
RUN NO 0001'MEAN SIZE 15 ST PIER VS
MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
ANG WV APP' WATER DEP'RHO' TID CURR VEL
LAG PERIOD 3

```
HA0010000100084300006400064O   000110    000 0          650002500001250   3
HA00100001      001468000040                                                 4
HA0010000200060600007700075O   000150    000 00         700003500001370   3
HA00100002      001540000047                                                039
HA0010000300076300006000070O   000080    00000000 450000000003500001180   3
HA00100003      001650000062                                                82
HA0010000500023400015400045O   000250    000000002000000000003000001400   3
HA00100005      001900000056                                                502
HA0010000700025600022700100O   000200    0011000000000000 0  2000001350   3
HA00100007      002170000065                                                508
HA0010000900055200017800100O   000170    000000001750000000002000001270   3
HA00100009      002490000043                                                514
HA0010001000034740001800009O0  000130    000000001100000000003000001420   3
HA00100010      002460000038                                                517
HA0010001100058800019700090O   000100    000000002400000000003000001280   3
HA00100011      002210000011                                                520
HA0010001200047400018300060O   000050    000000001150000000003500001250   3
HA00100012      002220000012                                                523
HA0010001300049700018500060O   000050    000000001000000000003000001170   3
HA00100013      002130000000                                                526
HA0010001500046800018300035O   000100    000 0          145000300000l110   3
HA00100015      001950000025                                                532
HA0010001600041700018200030O   000150    000 00         165000200000l200   3
HA00100016      001970000024                                                535
HA0010001700037000016700040O   000250    000 00         180000250000l290   3
HA00100017      001940000048                                                538
HA0010001800038100014700060O   000130    0006500000000000 0002500001260   3
HA00100018      001980000050                                                541
HAA010000100030700005000090O   000240    001550000000000000 0001500001020 3
HAA0100001      002050000017                                                6
HAA010000200035900006300040O   000270    001400000000000000 0  1750000920 3
HAA0100002      002070000058                                                9
```

Lag Period 3, continued.

```
HAA0100003000339000053001000      000210      000 00          800002000000890   3
HAA0100003       002060000008                                                    012
HAA0100004000243000076000700      000250      000 00         3200004000000940   3
HAA0100004       002100000042                                                    015
HAA0100005000237000089000500      000260      000 00         1800003500001010   3
HAA0100005       002080000017                                                    018
HAA0100006000307000084000500      000350      000 00         2200002500001015   3
HAA0100006       002060000025                                                    021
HAA0100007000384000091000700      000650      00000000400000000000003000001100   3
HAA0100007       002030000117                                                    024
HAA0100008000336000095000550      000400      00000000320000000004000001110   3
HAA0100008       001990000025                                                    027
HAA0100009000326000155001100      000200      00000000150000000002750001030   3
HAA0100009       002080000025                                                    030
HAA0100011000343000152000700      000150      000 000        1250003750001030   3
HAA0100011       002240000000                                                    36
HAA0100012000333000130000350      000100      000 0          1350003250001090   3
HAA0100012       002270000017                                                    039
HAA0100013000350000143000600      000130      000 00         1100003000001030   3
HAA0100013       002200000050                                                    042
HAA0100014000347000137000600      000120      000 00         1050003000000970   3
HAA0100014       002140000034                                                    045
HA00100004000695000050000850      000100      000 0          1050005000001230   3
HA00100004       001665000034                                                    147
HA00100006000246000200000500      000190      0007500000000000 0  3000001330    3
HA00100006       002030000055                                                    505
HA00100008000414000106000700      000740      0022500000000000 0 02500001410    3
HA00100008       002300000054                                                    511
HA00100014000516000185000550      000050      00000000 900000000003500001140    3
HA00100014       002020000009                                                    529
HAA0100010000369000122001200      000140      000 00          800003000001130   3
HAA0100010       002200000034                                                    033
```

```
          PROJ A010 11 VARIABLES
RUN NO 0001'MEAN SIZE   15 ST PIER VS
MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
ANG WV APP' WATER DEP'RHO' TID CURR VEL
LAG PERIOD 4

HA0010000400069500005000075O      000110      000 0000 8000000000004000001160   4
HA00100004      001600000044                                                    146
HA0010000600024600018600055O      000130      000 00          650003000001070   4
HA00100006      001980000000                                                    504
HA0010000800041400021700040O      000340      0024000000000000 0  2500001280   4
HA00100008      002200000025                                                    510
HA0010001400051600018700030O      000050      0000000013000000000003500001330   4
HA00100014      002030000044                                                    528
HAA0100010000369000145001100      000150      000 00          800002250000960   4
HAA0100010      002140000017                                                    032
HA0010000100084300006200078O      000080      0016500000000000 0003000001240   4
HA00100001      001467000041                                                    3
HA0010000200060600007300070O      000150      0006000000000000 0  2500001140   4
HA00100002      001520000000                                                    38
HA0010000300076300005700080O      000100      00000000 4000000000003500001070   4
HA00100003      001680000030                                                    081
HA0010000500023400013800040O      000190      0000000024500000000003000001130   4
HA00100005      001860000000                                                    501
HA0010000700025600023300100O      000120      0009000000000000 0  2500001110   4
HA00100007      002220000012                                                    507
HA0010000900055200018300110O      000360      0000000018500000000001000001330   4
HA00100009      002490000063                                                    513
HA0010001000047400016800110O      000150      0000000013500000000003000001330   4
HA00100010      002500000038                                                    516
HA0010001100058800020500090O      000130      0000000016000000000003000001410   4
HA00100011      002260000068                                                    519
HA0010001200047400018300030O      000050      0000000011000000000003500001340   4
HA00100012      002220000048                                                    522
HA0010001300049700018400060O      000150      0000000012000000000003000001350   4
HA00100013      002190000054                                                    525
HA0010001500046800018200030O      000130      000 00          1500003000001440   4
HA00100015      001960000042                                                    531
HA0010001600041700018500035O      000100      000 0           1250002000001410   4
HA00100016      001960000014                                                    534
HA0010001700037000017500035O      000250      000 00          1900003000001530   4
HA00100017      001960000000                                                    537
```

Lag Period 4, continued.

```
HA001000180003810001510005000      000160      0006000000000000 0  2000001400   4
HA00100018      001900000022                                                    540
HAA0100001000307000054001000       000250      0009500000000000 0 01500001140   4
HAA0100001      002060000017                                                    5
HAA0100002000359000054000400       000200      0017000000000000 0  1500001100   4
HAA0100002      002060000042                                                    8
HAA0100003000339000560000450       000200      0011500000000000 0001500001100   4
HAA0100003      002050000050                                                    011
HAA0100004000243000059000600       000210      00000000 650000000004000001120   4
HAA0100004      002080000025                                                    014
HAA0100005000237000116000500       000270      000 00          1700003000001160   4
HAA0100005      002090000034                                                    017
HAA0100006000307000084000500       000360      000 00          2400002500001170   4
HAA0100006      002060000025                                                    020
HAA0100007000384000084000600       000640      000 00          4200003000001180   4
HAA0100007      002040000075                                                    023
HAA0100008000336000087000900       000550      0000000034000000000005000001110   4
HAA0100008      002010000050                                                    026
HAA0100009000326000130001100       000330      0000000018000000000003000000970   4
HAA0100009      002030000008                                                    029
HAA0100011000343000175000300       000110      000 00*         1150004500000940   4
HAA0100011      002240000008                                                    035
HAA0100012000333000127000350       000130      000 000         1550003250001020   4
HAA0100012      002260000017                                                    038
HAA0100013000350000133001000       000130      0008500000000000 0005000000960   4
HAA0100013      002240000008                                                    041
HAA0100014000347000147000500       000110      000 00          1100003000000920   4
HAA0100014      002160000008                                                    044
```

```
          PROJ A010 11 VARIABLES
RUN NO 0001'MEAN SIZE   15 ST PIER VS
MEAN SLOPE' WV T'WV HO'UON'UOFF' UPARALLEL
ANG WV APP' WATER DEP'RHO' TID CURR VEL

LAG PERIOD 5

HA0010000100084300006000077O      000080      000 0          1250003500001400   5
HA00100001      001466000000                                                      2
HA0010000200060600006900070O      000120      0007500000000000 0 02000001270   5
HA00100002      001500000056                                                    037
HA0010000300076300005400080O      000080      000 00           550003000001330   5
HA00100003      001710000033                                                    080
HA0010000500023400012200040O      000250      0000000025000000000003000001380   5
HA00100005      001820000063                                                    500
HA0010000700025600021600100O      000150      000 00           900003000001350   5
HA00100007      002100000054                                                    506
HA0010000900055200019400090O      000600      0000000016000000000002000001590   5
HA00100009      002400000018                                                    512
HA0010001000047400017300110O      000200      0000000017000000000003000001510   5
HA00100010      002490000000                                                    515
HA0010001100058800019300090O      000130      0000000012000000000003000001610   5
HA00100011      002360000000                                                    518
HA0010001200047400019000030O      000170      0000000021500000000003500001450   5
HA00100012      002220000019                                                    521
HA0010001300049700018400060O      000130      0000000016000000000003000001450   5
HA00100013      002210000028                                                    524
HA0010001500046800018300080O      000050      000 00           1150003500001350   5
HA00100015      001990000054                                                    530
HA0010001600041700018400040O      000120      000 00           1200002500001300   5
HA00100016      001960000041                                                    533
HA0010001700037000017800035O      000150      000 000          1850002500001340   5
HA00100017      001970000055                                                    536
HA0010001800038100015900050O      000130      000 00           1250002000001240   5
HA00100018      001900000027                                                    539
HAA010000100030700006200090O      000250      0011500000000000 0001500000960   5
HAA0100001      002070000050                                                      4
```

Lag Period 5, continued.

```
HAA0100002000359000050000800   000220   0013500000000000 0 01500000960   5
HAA0100002       002050000017                                             7
HAA0100003000339000072000500   000250   0012500000000000 0001750000960   5
HAA0100003       002050000008                                             010
HAA0100004000243000056001000   000180   000 00          1000003000000970   5
HAA0100004       002070000008                                             013
HAA0100005000237000115000600   000300   000 0           2300003500000950   5
HAA0100005       002100000058                                             016
HAA0100006000307000086000500   000320   000 00          1900003000000920   5
HAA0100006       002070000050                                             019
HAA0100007000384000082000550   000500   000 00          2850003000001000   5
HAA0100007       002060000067                                             022
HAA0100008000336000089000800   000500   0000000037000000000004000000880   5
HAA0100008       002020000067                                             025
HAA0100009000326000103001000   000320   0000000026500000000003000000880   5
HAA0100009       001980000067                                             028
HAA0100011000343000145001000   000110   000 000         1250004500000900   5
HAA0100011       002260000000                                             34
HAA0100012000333000140000350   000100   000 0           1300003500000910   5
HAA0100012       002250000008                                             037
HAA0100013000350000135000350   000050   00000000 7000000000005000000900   5
HAA0100013       002270000008                                             040
HAA0100014000347000145000600   000120   000 000         1050003500000890   5
HAA0100014       002180000017                                             043
HA00100004000695000050000650   000130   00000000 5500000000003000001380   5
HA00100004       001520000014                                             145
HA00100006000246000170000600   000250   000 00          1200003000001380   5
HA00100006       001940000068                                             503
HA00100008000414000222000350   000200   0014500000000000000002000001490   5
HA00100008       002140000030                                             509
HA00100014000516000186000400   000050   0000000014000000000003000001330   5
HA00100014       002030000033                                             527
HAA0100010000369000150000900   000130   0000000014500000000002500000800   5
HAA0100010       002110000000                                             31
```

APPENDIX B

An explanation of the computer process in a sequential multiregression analysis.

APPENDIX B

In the linear sequential regression analysis, all possible combinations of the ten major environmental variables were analyzed in determining the effect each variable or group of variables had on the average mean grain size in the area of investigation. As discussed in the text, a combination of four variables would suffice; the single most influential combination was found to be that containing wind velocity (offshore) (X5), still-water depth (X8), sigma-t anomaly (X9), and tidal current speed (X10). With the dependent variable of average mean grain size represented by Y, then the general linear model would be:

$$\beta_0 + \beta_5 X_5 + \beta_8 X_8 + \beta_9 X_9 + \beta_{10} X_{10} = Y.$$

In a more concise form, the model would be:

$$\underline{S}\,\underline{\hat{\beta}} = \underline{g}$$

where $\underline{g}$ is a 5 X 1 vector of Y, $\underline{S}$ is a 5 X 5 matrix of squares and cross-products of the Xs, and $\underline{\hat{\beta}}$ is a 5 X 1 vector of the estimated βs. The expanded matrix equation would be:

$$\begin{bmatrix} N & \Sigma X5 & \Sigma X8 & \Sigma X9 & \Sigma X10 \\ \Sigma X5 & \Sigma X5^2 & \Sigma X5X8 & \Sigma X5X9 & \Sigma X5X10 \\ \Sigma X8 & \Sigma X5X8 & \Sigma X8^2 & \Sigma X8X9 & \Sigma X8X10 \\ \Sigma X9 & \Sigma X5X9 & \Sigma X8X9 & \Sigma X9^2 & \Sigma X9X10 \\ \Sigma X10 & \Sigma X5X10 & \Sigma X8X10 & \Sigma X9X10 & \Sigma X10^2 \end{bmatrix} \cdot \begin{bmatrix} \beta_0 \\ \beta_5 \\ \beta_8 \\ \beta_9 \\ \beta_{10} \end{bmatrix} = \begin{bmatrix} \Sigma Y \\ \Sigma X5Y \\ \Sigma X8Y \\ \Sigma X9Y \\ \Sigma X10Y \end{bmatrix}$$

The computer inverts the matrix and multiplies by g to obtain the coefficients ($\hat{\beta}$). The proportion of the total sum of squares of Y explained by the four variables is then computed and expressed as a percentage.

In examining the variables individually, the matrix for the first variable would simply be:

$$\begin{bmatrix} N & \Sigma X1 \\ \Sigma X1 & \Sigma X1^2 \end{bmatrix} \cdot \begin{bmatrix} \beta_0 \\ \beta_1 \end{bmatrix} = \begin{bmatrix} \Sigma Y \\ \Sigma X1Y \end{bmatrix}$$

For a pair of variables in combination, another row and column of the appropriate X values would be added to the matrix. From the base matrix given above, any reasonable number of X variables and subsequent combinations could be employed in the linear sequential regression analysis.

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