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U.S. Army Coastal Engineering Research Center

SEDIMENTATION AT AN INLET ENTRANCE

RUDEE INLET-VIRGINIA BEACH, VIRGINIA

TECHNICAL MEMORANDUM NO. 8

December 1964

DEPARTMENT OF THE ARMY
CORPS OF ENGINEERS

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FOREWORD

Few data are available on the patterns of sorting and size gradation of sediments at the mouths of tidal inlets. Also lacking is a rapid, objective, and statistically rigorous method for defining the limits of the effects of the ebb flow from an inlet on the normal littoral process of sorting and size gradation. This study was undertaken with the objective of formulating a general model of the distribution of sorting and mean size parameters around the mouth of an inlet, for a rather restricted set of dynamic conditions. A further objective was the testing of trends in patterns of sedimentation predicted by the model by means of a rapid method of formal statistical analysis known as trend-surface analysis.

Diagrams showing steps in the development of the conceptual fluid process-sediment response model are presented, as well as a series of trend-surface and residual maps for the observed natural inlet data. An objective method for delineating the pattern, magnitude, and limits of inlet influence on the otherwise unaltered beach sediments is also presented.

This report was prepared by Dr. Wyman Harrison, Associate Marine Scientist of the Virginia Institute of Marine Science, in pursuance of Contract DA-49-055-CIVENG-63-6 with the U. S. Army Coastal Engineering Research Center, in collaboration with Dr. William C. Krumbein, Professor of Geology, Northwestern University, and consultant to the Coastal Engineering Research Center, and Mr. W. Stanley Wilson, graduate student at the Virginia Institute of Marine Science.

This study was supported by the Coastal Engineering Research Center (formerly the Beach Erosion Board of the Corps of Engineers), under the general supervision of J. V. Hall, Jr., G. M. Watts, and N. E. Taney of the Engineering Development Division. The Computing Center at Northwestern University extended every cooperation, and the programs used in the analysis were largely developed with supporting funds from the Geographic Branch of the Office of Naval Research, under general supervision of Miss Evelyn Pruitt and R. A. Alexander.

Mr. C. Kiley, Virginia Beach City Engineer, and Mr. A. Gregg aided by laying groundwork for the field work. The following graduate students of the Virginia Institute of Marine Science aided in sampling: Messrs. M. P. Lynch, R. Morales-Alamo, R. B. Stone, C. Kyte, and R. Tuck. Lt. G. M. Griswold, U. S. Navy Fleet Weather Facility, arranged for aerial photographic coverage of the study area. Wave data were furnished by the Research Division of the Coastal Engineering Research Center. The U. S. Army Transportation Corps, Ft. Story, Virginia, provided amphibious support for offshore sampling. Weather data were supplied by the U. S. Weather Station at Ft. Story.

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SEDIMENTATION AT AN INLET ENTRANCE

Rudee Inlet-Virginia Beach, Virginia

by

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ABSTRACT

A physical model is presented of the wave, longshore-current, and ebb-tidal-current systems as they determine the distribution of mean particle size and the degree of sorting at the mouth of a controlled inlet. The model is based upon theoretical considerations as well as observations on both scale-model and natural inlets. Forty-one bottom samples were taken at Rudee Inlet, Virginia Beach, Virginia, under conditions appropriate for testing the model. Resultant size and sorting data were subjected to trend-surface analysis in an effort to verify trends predicted by the model. Correspondence between the model and the natural situation was found to be good. The pattern, magnitude, and extent of inlet influence on the otherwise unmodified beach sediments could be determined by subtracting a trend surface for mean size for the unmodified beach from its counterpart for the area of the inlet entrance. The area of inlet-current influence was found to be rather limited in extent.

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INTRODUCTION

General Considerations

Despite new and improved methods for measuring waves, currents, and other shore process elements, it remains relatively difficult to gain full understanding of the effects of wave and current systems on the size grading and sorting of beach and nearshore sands under natural field conditions. Simultaneous observation of water and sediment movement is complicated by the number of variables that must be measured, and by the local "noise" that tends to obscure underlying systematic effects. As a result, an empirical model is commonly used, in which the patterns of areal variation in sediment properties are used to infer the nature of the process elements that are operative, and to evaluate their relative influence on the sediment properties. The empirical method generally includes preparation of contour-type maps of the observed sedimentary attributes. These maps are useful for dynamical interpretations, but they may fail to bring out secondary effects; or, where these are discernible, the maps may require highly subjective evaluation to distinguish between "meaningful" variations and local "noise." Formal methods of map analysis (trend-surface analysis) have been applied successfully in various branches of geology, including the study of beach phenomena. In this paper the use of trend analysis is illustrated in a beach area involving a tidal inlet.

Problem and Approach

The problem under study is two-fold, involving (1) the distribution pattern of sediment size and sorting in the vicinity of the mouth of an inlet during an "instant" of maximum outflow, and (2) the pattern magnitude, and extent of inlet influence on the otherwise normal sediment distribution along the shore during this instant. Our approach to this problem is likewise two-fold, and involves (1) formulation of a model of the fluid-velocity distributions and resulting sediment responses associated with the wave, longshore-current, and ebb tidal-current systems, and (2) analysis of the predicted trends in sedimentary responses, using appropriate natural data.

THE MODEL

A fluid process - sedimentary response model of an inlet entrance can be developed by first constructing the process-response model for an unmodified beach; i.e., one without an inlet. The general fluid motions over a gradually shoaling beach within the shoaling-wave, breaking-wave, and swash-backwash zones are described in various studies (*cf.* Eagleson, Glenne, and Dracup, 1963). Dynamic zones and directions of increase in fluid velocities are sketched diagrammatically in the left half of Figure 1. A model of the changes (responses) in grain size and sorting for this dynamic pattern was proposed by Miller and Zeigler (1958), and it is shown in the right half of Figure 1. The largest grain sizes and best sorting may be expected in the highest energy zone - that of the breaking waves - where the greatest turbulence exists. Because the fluid velocities diminish in directions away from the breaker zone, the mean particle size decreases and the sorting becomes poorer, as explained below. (Sorting worsens as more size classes are significantly represented in the size distribution.) The second step in construction of the inlet model studies here involves consideration of the velocity distribution of the "jet" issuing from the inlet channel into the ocean (Figure 2A) and its effect, in the presence of waves, upon the sediments at the entrance. French (1960) derives the velocity distribution at the exit for a two-dimensional channel issuing into relatively deep water. Bates and Freeman (1952) demonstrate that the theory of a two-dimensional jet issuing from a slot may be applied to sediment-laden inlet water entering the ocean, and that the theory explains the lunate shape of bars found off tidal inlets. For the velocity of outflow and channel dimensions of the inlet studied here, the angle of separation of the still-water boundaries approximates that shown in Figure 2B.

A more realistic dynamic model requires assessment of the idealized jet flow (Figure 2B) both in the presence of waves and at a shoaled entrance. Figure 3A shows the general geometry of the nearshore bottom, based partly upon the scale model study of inlet development made by Saville, Caldwell, and Simmons (1957, Test 5) for an inlet system of similar dimensions to the natural inlet of this study, and partly upon the model postulated by Bruun and Gerritsen (1960, Figure 53). The zone of greatest turbulence in this model lies within the zone of breakers where they are intersected by outflow from the inlet (Figure 3B). The model predicts that the mean particle size (M_z) will decrease and the degree of sorting (S_o) will generally become poorer in directions of decreasing velocity gradient, as shown in Figure 3C. The progressive decrease in mean size is anticipated because of the well-established relation between bottom shear stress and transporting power (cf. Bruun and Lackey, 1962). A study of the sediments of the Beaufort Inlet area, North Carolina, by Batten (1962) shows this expected distribution of mean particle size. The fact that sorting will generally become poorer in directions of decreasing velocity gradient is dependent upon certain additional factors and assumptions.

The sediment load in the outflowing current of the particular inlet under study has its origin in essentially one source, that caused by stirring up of material from the channel under turbulent flow conditions. This material consists of sand with a grain size distribution extending over five Wentworth sizes classes, as well as coarse silt and granules, usually as less than 8 percent of a given sample.

The sorting tendencies for the inlet are modeled in part from Inman's (1949, p. 63) analysis of sorting of shallow-water sediments under unidirectional flow. For the particular inlet studied [gorge depth of 6 to 9 feet (180-270 cm)], the out-flowing current [3.3 ft/sec. (110 cm/sec.) at the surface] in the channel is assumed to produce a stress on the bottom sufficient to move all bottom material. Toward the seaward extremity of the inlet entrance, and laterally from its sides (Figure 3A), we postulate a rapid decrease in the threshold velocity, producing the rapid decrease in mean diameter of the bottom samples. As the out-flowing current passes into the relatively quiescent water of the entrance, just shoreward of the breakers in Figure 3B, the average friction velocity will drop somewhat. We assume that the friction velocity in the waters of the inlet entrance will tend to fluctuate between the threshold velocity for fine and coarse sand. If this is so, the bottom samples will show a tendency to be rather well sorted (Inman, 1949, p. 64).

It can be further assumed that as the outflowing current enters the breaker zone, the turbulence conditions are such that nearly all but the largest sized particles (which will have previously dropped out of suspension) will be maintained in suspension. Bottom samples here can be expected to be better sorted than elsewhere and the mean diameter to be larger than that of the surrounding samples. Figure 3C shows this situation schematically. Just seaward of the breakers, a rapid decrease in friction velocities and turbulence can be expected, and the larger particles that pass through the breaker zone will come to rest almost immediately; these larger particles will rest upon or become mixed with the finer particles of the beach sands of the shoaling-wave zone (Figure 1) of the previous tide. Because progressively finer particles drop rapidly out of suspension in a seaward direction, sorting beyond the breakers will abruptly become poorer, and the poorest sorting will occur at a relatively short distance beyond the breakers. Sorting farther out into the sea will improve, but will not equal that of the breaker zone where it is best (Figure 1). Batten's (1962) study of the Beaufort Inlet sediments indicates the relatively well-sorted nature of the sediments in his "zone of wave action" seaward of the surf zone. The mean diameter of the bottom particles will decrease gradually in a seaward direction, as summarized in Figure 3C.

The ultimate model to be used here provides for the wave fronts approaching at an angle to the shoreline, rather than parallel to it as in Figure 2A. The longshore current thus generated adds a final complicating feature to the model. (Figure 4A shows the relations, assuming moderate to low wave heights and moderate longshore-current velocity.) To simplify the dynamic model somewhat, we assume that the inlet outflow is of such velocity that it is deflected only a moderate amount by the longshore current (Figure 4A). Both currents will then intermix and become a single current in a direction dictated by simple vector addition.

Given this dynamic picture, we must now account for the suspended sediment stirred up by wave action and transported as littoral drift into the zone of inlet outflow (Figure 4B). A final simplifying assumption provides that the materials transported by the longshore current are of consistently large mean particle size and of relatively good sorting. Areas of the poorest and of the best sorted materials may be expected to take somewhat irregular shapes, as a result of interaction effects at the juncture of the two currents. Figure 4B shows the expected response relations, and the idealized shape of the areas of best and poorest sorting in the figure are based on considerations of velocity and turbulence dropoff.

The field observations and the methods of trend analysis used with them are described in succeeding sections, leading to a field test of the several aspects of the final model just described.

STUDY AREA

The Borough of Virginia Beach (Figure 5) of the City of Virginia Beach, Virginia, is situated on the Atlantic seaboard 22 miles (35 km.) north of the Virginia-North Carolina line and 3.5 miles (5.6 km.) south of Cape Henry. Rudee Inlet, a "controlled" inlet, is located at the southern end of the borough and connects Lakes Wesley and Rudee with the Atlantic Ocean. At high tide, water flows from the ocean through Rudee Inlet into the lakes, and flow is reversed at low tide. At the time of sampling of bottom sediments around the entrance, the inlet channel was approximately 400 feet (120 m.) long and 150 feet (45 m.) wide. Owing to a sandbar on the north side of the channel, maximum flow occurred in a gorge ranging from 30 to 70 feet (9-21 m.) wide and 1 to 9 feet (0.3-2.7 m.) deep. The inlet lagoon had an area approximating 1/13 square mile (0.2 sq. km.) and the tidal prism approximated 6.0×10^6 cubic feet (1.7×10^5 cu. m.).

FIELD OBSERVATIONS

Forty-one sand samples from the immediate vicinity of the inlet (Figure 6) were taken "simultaneously" (within a 15-minute period) from 2 to 3 hours before low water on the morning of 25 March 1963. The number of sample stations was limited by available personnel and the time-consuming process of accurately positioning those taking samples. Sand samples were recovered by moving bags by hand through the upper 2 cm. of the bottom sediments. Shortly thereafter, 67 samples were taken along transects A, part of B, and C (Figure 5) at stations 25 feet (7.5 m.) apart. Sampling along the three transect lines was accomplished with pipe dredges having maximum penetration of about 2.5 cm. Details of the sampling procedures are given by Harrison and Morales-Alamo (1964) and Harrison and Wagner (1964).

During the period of bottom sampling the rate of seaward flow of surface water in the Rudee Inlet gorge was 3.3 feet per second (110 cm./sec.). This was determined by timing the movement of floures-cein-dyed water over a 100-foot (30 m.) distance along the middle portion of the stone jetty on the south side (Figure 6) of the inlet. The central zone of outflow (Figure 7) from the inlet was also observed using floures-cein dye. Although neither was measured accurately, the velocity was observed to decrease and the mixing to increase as the outflow left the inlet and approached the fishing pier to the north (Figures 6 and 7). The dyed outflow could not be discerned north of the pier, as at that distance it had been well mixed with the surrounding water.

Just prior to the sampling time, the average velocity of the long-shore current (inshore of the breaker zone) was determined at a point approximately 800 feet (240 m.) south of the inlet. This current was flowing in a northward direction at 0.76 foot per second (23 cm./sec.). A red dye (rhodamine B) was introduced into the longshore current just south of Rudee Inlet and was observed to flow northward. When the current came into the area of the outflow (dyed green) from the inlet, it was deflected seaward, and the longshore current itself deflected the inlet outflow. Just before reaching the fishing pier, both streams had become intermixed.

The average height of breaking waves at sampling time was 0.75 foot (23 cm.) and the average wave period, as determined from a relay-type wave gage, was 6.5 seconds. Wave fronts made an angle (opening northward) of 29° with the shoreline at a point 1,000 feet (300 m.) from shore. Wind was from the southwest at 12 to 15 m.p.h. (19 to 24 k./hr.). The position of the breaker line has been plotted on Figures 7-20 from aerial photos made at sampling time by the U. S. Navy.

LABORATORY MEASUREMENTS

Determination of Sediment Parameters

Each sand sample was analyzed for its size-distribution curve using a Woods Hole Rapid Sand Analyzer (Whitney, 1960) with the procedure out-lined in Zeigler, Whitney, and Hayes (1960). Details of the methods, and assumptions involved in the analyses, are given by Harrison and Morales-Alamo (1964). The following descriptive measures of the resultant grain-size distributions were calculated:

Mean Nominal Diameter, $M_z = 1/3\ (P_{20} + P_{50} + P_{80})$

Sorting, $S_o = (P_{80} - P_{20})/P_{50}$

where P_i is the value of the grain diameter in mm. at a given percentile of the grain-size distribution. The measure of sorting is one used as a matter of convenience in terms of the settling tube. The estimate of mean nominal diameter used employs the same values used in determination of S_o and, in addition, is considered relatively "efficient" (McCammon, 1962).

ORGANIZATION OF DATA

The forty-one sampling stations in the vicinity of Rudee Inlet were numbered serially and plotted on the base map (Figure 7), using a U-V co-ordinate system (Krumbein, 1959) that was geographically true. The U co-ordinate starts with U = 0 at the top of the swash-backwash zone in the northwest corner of the map and proceeds south along the shore to U = 553 at the top of the swash in the southeast corner. The V co-ordinate extends from V = 0 at the northwest corner to V = 300 in the northeast corner. Water depth at this last point was 8 feet. Each station was numbered and the values for M_z and S_o were listed for each station. These data comprise an irregularly spaced set of stations; i.e., the sampling points do not lie on a rectangular grid.

Data for the three transects were treated separately. Stations were also numbered serially and coded in true geographic (U, V) co-ordinates. The origin of this system was at the most inshore station of Transect A (Figure 5), with the U axis extending southward parallel to shore. The sampling points of this second system lie at the intersection points of an orthogonal grid.

TREND SURFACE ANALYSIS

A trend surface may be visualized as a smooth contour surface showing the systematic pattern of variation of a mapped variable from one map edge to another. This contrasts with the small-scale fluctuations from one point of observation to the next, superimposed on the trend as a seemingly non-systematic component.

Most techniques of trend analysis are based on least squares fitting of polynomial surfaces to the data by a multiregression technique. When (as is usually the case) geological observations are scattered irregularly over a map area, the method of analysis commonly includes fitting successively higher order surfaces to the map data, including usually the linear, quadratic, and cubic terms. These computed surfaces and their deviations are examined for their geological implications. The geologist thus "takes his data apart" in various ways, sharpening the interpretation of the observed map data. The complete trend, defined by Grant (1957) as the polynomial of the best fit to the data, may not always be identified by these low-order surfaces. However, in many maps the linear and quadratic trends are strongest, with those of cubic and higher degree diminishing relatively in importance.

The Virginia Beach data were analyzed at the Northwestern University Computing Center with an IBM 709. The program computes a (U,V) matrix and a series of vectors for each variable. The matrix is inverted and post-multiplied by the vectors to obtain a set of polynomial coefficients. These in turn are used to compute the trend-surface values. Some of the underlying theory and a description of the program are given by Krumbein (1959). Whitten (1963) describes the program in detail.

When a trend surface is fitted to map data, a computed value is obtained for each control point. These are plotted on a base map and contoured by hand; alternatively, the computer generates a field of computed values and prepares a trend map either directly or through use of an X-Y plotter. The computed trend value for a given map point commonly does not agree exactly with the observed value, so that a deviation (which may be positive or negative) is associated with each map point. Thus, if X is the observed value of the mapped variable at point (U,V), and if X' is the computed trend value, then the deviation from the fitted surface is defined as R = X - X'. These deviations may also be mapped to see what the variation pattern is after one or more low-order trend surfaces have been extracted. Deviation maps are commonly contoured by hand; and, because some freedom in drawing contours is usually present, the deviation maps presented here were all prepared by linear interpolation between a given point and surrounding points.

Linear Surface. The linear surface is fitted to irregularly spaced map data by setting up the relation:

$$X = A_L + B_L U + C_L V + R_L$$

where X is the observed value at point (U,V); A_L is a constant that represents the "height" of the trend surface at (U,V) = (0,0); and B_L and C_L are the coefficients of the linear surface. The deviation, R_L, contains trend components higher than linear, plus some unknown content of non-systematic, seemingly random fluctuations.

The computed linear trend value, X_L', is obtained from the relation $X_L' = A_L + B_L U + C_L V$ by multiplying the U-coordinate of a given point by B_L, multiplying its V-coordinate by C_L, and adding A_L to the sum of the two products. R_L, as stated, is simply the numerical difference between the observed and computed values at each point of observation.

Quadratic Surface. The complete quadratic surface includes two linear and three quadratic terms, and is fitted by setting up the relation:

$$X = A_Q + B_Q U + C_Q V + D_Q U^2 + E_Q UV + F_Q V^2 + R_Q$$

Here, X is again the observed value of the mapped variable at a given (U,V) point, A_Q is a constant, and B_Q, C_Q, ... , F_Q are the polynomial coefficients of the quadratic surface. The quadratic is computed as a whole because the numerical values of the constant and of the coefficients change as higher surfaces are considered, as shown by the change in subscripts from L to Q.

The remainder R_Q now contains trend components higher than quadratic plus purely random fluctuations. As before, if X_Q' is the computed value of the quadratic surface at a given control point, then $R_Q = X - X_Q'$.

Cubic Surface. The complete cubic trend contains two linear, three quadratic, and four cubic terms, as well as a constant A. Inasmuch as the numerical values of the coefficients again change, the coefficients on the cubic surface are subscripted as shown:

$$X = A_C + B_C U + C_C V + D_C U^2 + E_C UV + F_C V^2 + G_C U^3 + H_C U^2 V + J_C UV^2 + K_C V^3 + R_C$$

The deviations on the cubic surface, R_C, contain trend terms higher than cubic, as well as some content of random variations. Our analysis did not extend beyond the cubic surface.

Sum of Squares Evaluation of Trend-Surface Maps. The total sum of squares of a mapped variable is a measure of the variability of map data. It is expressed as the sum of the squared differences of the observed values from their mean:

$$SS_X = (X - \bar{X})^2$$

The expression represents the sum of the squared deviations of X from their mean value, $\bar{X}$, at all control points. The sum of squares of the deviations is computed as:

$$SS_R = R^2$$

since the sum of R over the whole map is zero.

The sum of squares associated with the computed values, X', can be expressed as:

$$SS_X' = (X' - \bar{X})^2$$

where $\bar{X}$ is the mean of the observed X; in trend analysis the computed mean, $\bar{X}'$, is the same as the mean of the observed data, $\bar{X}$.

The "strength" of a trend surface can be evaluated informally by noting how much of the total map variability is "accounted for" by the fitted surface. This is computed as $100(SS_{X'}/SS_X)$.

Evidently, if the percentage reduction is small, the trend surface is weak; indeed, if the deviations are truly random components in such instances, the question could be raised whether there is in fact any trend present at all. We shall see that this latter assumption is not correct in the Rudee Inlet study. Computer programs for more formal analysis of fitted surfaces, including setting confidence intervals around them (Krumbein, 1963), became available while this final draft was written, and reliance here is placed upon substantive evaluation of the trend maps computed in this study.

ANALYSIS OF MEAN PARTICLE SIZE DATA

Figure 8 shows the pattern of mean particle size observed in the study area. "Observed maps" show the contour pattern of the original "raw data," and in many instances these maps are very informative, especially when the contours show relatively strong patterns. When the pattern is weak, or complicated by numerous irregularities in the contour lines, substantive evaluation is more difficult, and there may be some doubt whether a definite trend is present.

In the present map we notice a "ridge" of relatively large values that coincides with the zone of outflowing current shown on Figure 3. At a point just seaward of the breaker line (dotted) is a pronounced hump of high values. The linear trend surface fitted to these data is shown on Figure 9. The linear surface dips to the northeast at 0.02 mm. per 87 feet (26 m.), indicating a decrease in mean size in the direction of current flow. This reflects the negative current velocity gradient from Rudee Inlet seaward, because of the known variation (cf. Bruun and Lackey, 1962) in the diameter of sediment particles with the critical tractive force, which is in turn velocity dependent. The linear surface for mean size is in fact quite weak, inasmuch as only 11.3 percent of the total sum of squares can be attributed to it.

Figure 10 shows the deviations from the linear mean size surface. These deviations show a pattern trending roughly parallel to outflow from the inlet, and an area of high values similar to the one noted on the observed map. This suggests the presence of trend components higher than linear in the deviations. Hence, it was deemed worth while to examine the quadratic surface.

The quadratic surface for mean grain size is shown in Figure 11. The contours parallel to the shore are to be ignored for the moment; the quadratic surface itself is a simple ellipsoid with maximum values near the inlet mouth, and a systematic decrease in mean grain size symmetrically away from the higher portion. The quadratic surface accounts for 47.7 percent of the total sum of squares; and because the linear surface accounted for only 11.3 percent, the contribution of the "pure quadratic" is 36.4 percent. The deviations on the quadratic surface are shown in

Figure 12. Comparison with the deviations from the linear surface (Figure 10) shows that the area of relatively high positive deviations again delineates the general area of maximum mean particle size that occurs in the observed map of Figure 8.

The deviations from the quadratic surface for mean size contain 100.0 - 47.7 = 52.3 percent of the total map variability. Inasmuch as the deviation map still carries geologically identifiable patterns, it was decided to fit the cubic surface to the mean size data. The cubic surface map is shown in Figure 13, and the deviations from it are shown in Figure 14.

The cubic surface is noteworthy in that it shows a bulge of coarse mean sizes associated with the inlet mouth, but this bulge is somewhat skewed to the northeast, and in a broad way it is aligned with the path of the outward-flowing current shown in Figure 6. The deviations on the cubic surface show clearly that the alignment of the major trend of larger diameter grains is centered on the zone of inlet outflow. The trend of the zero-deviation contour in the region of inlet outflow suggests a weak effect of the outflow current on mean size all the way to the pier in the northeast corner of the map. This was suggested in a previous study of the same data (Harrison and Morales-Alamo, 1964) that employed conventional contouring techniques. The inference from Figure 14 is that a weak effect of the inlet current on grain size in the vicinity of the pier may indeed have existed. That is, the trend surface technique constitutes a sensitive and objective method for examining the influence of the inlet on grain size both over the full inlet area and over the smaller zone of the dominant current.

Patches of the deviation map of Figure 14 that are outlined by negative contours (-0.05) reveal weak secondary trends toward finer sizes roughly parallel to the "ridge" of coarse sizes. At least two hypotheses can be advanced for this pattern: (1) the tendency of the finest particles to lie on the flanks of the "ridge" is merely a reflection of the magnitude of the discrepancy between coarse grains (associated with outflow from the inlet), and the finer grains already present in the inlet prior to initiation of the outflow; or, (2) the tendency toward finer sizes on the flanks of the ridge reflects an actual realm of sedimentation dynamics in which successively finer grained particles are progressively deposited over areas of continuously decreasing current velocity.

Examination of Figure 14 suggests that the latter hypothesis is probably the more satisfactory one. The weak trend of slightly coarse-grained materials associated with the breaker zone at the pier is not present on the north side of the "ridge" of higher values. This suggests deposition of finer particles on coarse ones that would ordinarily be present in the breaker zone. If the observed ridge pattern is due to the addition of larger sizes in the area of the inlet mouth, then the weak trend of slightly larger sizes associated with the breaker zone would have been expected to continue from the vicinity of the pier to an intersection with the "peak" of highest values near the breaker zone, i.e., at the +0.1 contour.

As to the limit of influence of the inlet mouth on nearshore bottom changes in mean particle size, we returned to the quadratic trend surface for an experiment in finding this limit to a first approximation. Use of the quadratic surface rather than the cubic was in part dictated by our approach, which is described in the next section. As a closing remark on the cubic surface and its deviation map, we may conclude the sum of squares discussion with the following summary:

Surface	Percent Sum of Squares Attributable to Surface	Percent Sum of Squares of Deviations From the Surface
Linear	11.3	88.7
Total Quadratic	47.7	52.3
Total Cubic	59.6	40.4

Thus, there still remains 40.4 percent of the total map variability in mean grain size in the deviations from the cubic. Moreover, the contribution of the "pure" cubic alone is only 11.9 percent, as against the 36.4 percent attributable to the "pure" quadratic. The linear contribution, as was stated, is 11.3 percent, implying that the total quadratic component is perhaps the most important one in the complete trend. In our study of the limit of inlet influence then, we take the cubic and higher order trend components as being merged with the local, non-systematic fluctuations that may be present, and return to the total quadratic surface of Figure 11 for further discussion.

THE AREA OF INLET INFLUENCE ON MEAN PARTICLE SIZE

Figure 11 contains two sets of contour lines of mean particle size. The heavy lines parallel to the shore represent a portion of the quadratic surface fitted to the sample data obtained from the three transects of Figure 5, which were mentioned earlier in passing. This surface for the whole beach area accounts for only 6.6 percent of the total sum of squares of mean particle size from all samples from the three transects.

Inasmuch as the map based on the three transects does not include the sampling points in the immediate vicinity of the inlet (except for the pier samples on the left of Figure 6), this map represents the large-scale systematic effects present along the whole stretch of beach. The local quadratic map in Figure 11, on the other hand, contains the regional effect as well as the influence of the inlet. As a result, we may subtract one map from the other to obtain a map of the area of influence of the inlet itself. This (Figure 15) shows that the inlet affects an area that extends as a bulge seaward from the inlet mouth, diminishing to zero in the vicinity of the pier as well as oceanward to the southeast. This bulge is somewhat asymmetrical, reflecting its distortion and displacement by the northward-flowing shore current. The maximum departure of particle size equals 0.12 mm.

The implications of Figure 15 are that Rudee Inlet exerts an appreciable effect on the nearshore bottom sediment in a very limited area, in contrast to the length of the beach segment between Transects 1 and 3 in Figure 5. That is, the distance between the limiting zero contours in Figure 11 is of the order of 0.1 mile (0.16 km.), as against a length of more than 1.5 miles (2.4 km.) between the end transects. This, in turn, is a short segment of the essentially straight coastline extending south of Cape Henry for a number of miles. It may be anticipated from these relative scales that the influence of an inlet similar to the one studied here could very easily be missed in subsurface exploration of ancient sediments for oil or gas, say, or even in the study of present day beach patterns involving a closed inlet, where its effect would be that of a small deviation on a large-scale trend surface map.

ANALYSIS OF SAND SORTING DATA

The preceding discussion is based wholly on the patterns of areal variation in mean grain size. It is appropriate to ask whether the areal pattern of sediment sorting sheds any additional light on the area of influence of the inlet, or on the dynamic processes that take place in its vicinity.

Figure 16 shows the observed map of the sorting coefficient, S_o, in the study area. Its pattern is distinctly different from that of mean particle size in Figure 8, although there is a tendency for low values (that is, good sorting) to lie approximately in the area of largest mean grain size. For example, the contour line 0.5 on the sorting map lies peripherally to the contour of maximum mean grain size (0.50 mm.). A dominant area of high values (poor sorting) lies beyond the breaker zone on the seaward side of the inlet current. In general, sorting becomes poorer to the east, whereas the mean particle size tends to increase northward.

Trend Surfaces of the Sorting Coefficient. The linear, quadratic, and cubic surfaces were fitted to the observed S_o data of Figure 16. The surfaces are very weak in comparison even with the mean size surfaces, as shown by the following sum of squares summary for S_o:

Surface	Percent Sum of Squares Attributable to Surface	Percent Sum of Squares of Deviations from Surface
Linear	11.2	88.8
Quadratic	15.5	84.5
Cubic	20.9	79.1

Thus, the net contribution of the quadratic component is only 4.3 percent, and that of the cubic is only 5.4 percent. Nevertheless, we present the linear and cubic surfaces and their deviations to illustrate some aspects of the sorting pattern.

Figures 17 and 18 show the linear surface and the deviations from it. The linear S_o trend surface slopes to the east, or roughly perpendicular to the slope of the linear trend surface for mean grain size. The linear deviation map for sorting shows that the best sorting can be expected at the point where the inlet current intersects the breaker zone. This position coincides with the zone of greatest turbulence, as supported by field measurements (Harrison and Morales-Alamo, 1964) and theoretical models of beach dynamics (Miller and Zeigler, 1958), which suggest that it is in this zone that the best sorting and the largest grain sizes occur.

Figures 19 and 20 show the cubic surface of the sorting coefficient and the deviations from the surface. The pattern on the cubic trend map is noticeably different from the cubic mean size map, in that the sorting surface rises from a low just north of the Rudee Inlet jetty, to high areas (i.e., poor sorting) seaward to the southeast of the inlet and to the northeast along the pier.

Analysis of the cubic deviation map for S_o shows the best sorting to be centered at the intersection of the breaker zone with the combined flow of the inlet current and the longshore current. This is the zone of maximum turbulence, as noted previously. The zone of best sorting rapidly gives way to the zone of worst sorting (contour + 0.4) in a down-current (decreasing-velocity) direction. The actual center of the poorest sorting is seen to be just seaward of the central zone of inlet outflow. This is believed to reflect the rapid decrease of the longshore current component of the combined flow as it passes through the breaker zone. Hence, the coarser materials in transport along the shore appear to be deposited over a region of originally fine-grained sand. Thus the spread of the particle size distribution is greatest here, as shown by the large values representing poorest sorting.

SUMMARY REMARKS

A model (Figure 4B) of sedimentation at the mouth of a small, controlled tidal inlet has been developed from anticipated fluid-velocity distributions. It deals with the distributions of mean size (M_z) and degree of sorting (S_o), in response to forces induced by the ebb flow from the inlet channel and by wave fronts that approach the shoreline obliquely.

The model predicts that the largest particle sizes and the best sorting will occur in the region where the longshore and inlet currents intersect, that sorting will be poorest just seaward of this intersection (also seaward of the breaker zone), and that mean size will decrease and sorting improve in directions of decreasing velocity gradient beyond the breaker zone. Observed patterns of M_z and S_o agree with these predictions.

The model also predicts that particles of relatively small diameter (originating in the inlet and longshore currents) will be deposited upon a surface of normally sized and sorted beach sands on either side of the outflowing current. The prediction is confirmed by analysis of weak trends for M_z and S_o shown on residual maps for cubic trend surfaces, for the regions flanking the inlet outflow. (The trends can be understood by assuming that the M_z and S_o patterns of the depositional surface have been inherited from normal fluid-velocity distributions common to the shoaling wave zone of the previous high tide.)

It is demonstrated that it is possible to delimit the boundary, estimate the magnitude, and describe the pattern of inlet influence for a given sediment property (such as M_z and S_o) upon an otherwise unmodified beach by subtracting the trend surface for the area of the inlet entrance from the corresponding trend surface for the unmodified beach.

The present study illustrates that trend surface analysis furnishes a method for "taking apart" raw observations in order to distinguish between large-scale (systematic) effects and small-scale (presumably non-systematic) effects in map data. It is noteworthy in this study that the deviation maps are on the whole more informative than the trend surface maps, although the low-order surfaces, despite their relative weakness on a sum of squares basis, do present geologically reasonable patterns in relation to outflow from Rudee Inlet. The large content of the original map variability contained in the deviation maps, especially for the sorting coefficient, implies that a substantial amount of geological information is contained in the deviations, which definitely cannot be discarded simply as random noise.

In the long run an essential element in beach studies will be the dynamic model postulated for the situation. If the particular model can be expressed quantitatively (as it can in some instances), field observations, even though encumbered by noise, can be used effectively to test the applicability of the model. Surface-fitting functions other than polynomials will very likely come increasingly into use as the physical processes underlying a given beach model are better understood. Interest is developing in what have come to be called "secondary trend components" (Allen and Krumbein, 1962), that probably represent some or all of the terms in surfaces of relatively high degree.

ADDENDUM

Since this report was written, additional computer time was obtained for the construction of cubic trend maps for the data from the three pier transects of Figure 5. By subtracting these cubic trend surfaces from the M_z and S_o cubic trend surfaces (Figures 13 and 19) for the inlet entrance, the maps of Figures 21 and 22 have been obtained. They indicate the pattern, magnitude, and limit of inlet influence on the M_z and S_o patterns of the beach.

REFERENCES

Allen, P. and W. C. Krumbein, Secondary Trend Components in the Top Ashdown Pebble Bed; A Case History, J. Geol., 70, 507-538, 1962.

Bates, C. C. and J. C. Freeman, Interrelations Between Jet Behavior and Hydraulic Processes Observed at Deltaic River Mouths and Tidal Inlets, Proc. Third Conf. on Coastal Engr., Cambridge, Mass., 165-175, 1952.

Batten, R. W., The Sediments of the Beaufort Inlet Area, North Carolina, Southeastern Geol., 3, 191-205, 1962.

Bruun, P. and J. B. Lackey, Engineering Aspects of Sediment Transport, Reviews in Engr. Geol., 1, 39-103, 1962.

Bruun, P. and F. Gerritsen, Stability of Coastal Inlets, North Holland Publ. Co., Amsterdam, 1960.

Eagleson, P. S., B. Glenne, and J. A. Dracup, Equilibrium Characteristics of Sand Beaches, Proc. Am. Soc. Civil Engr., Paper No. 3387, 36-57, 1963.

French, J. L., Tidal Flow in Entrances, Comm. on Tidal Hydraul., U. S. Army, Tech. Bull. 3, 1960.

Grant, F., A Problem in the Analysis of Geophysical Data, Geophysics, 22, 309-344, 1957.

Harrison, W. and R. Morales-Alamo, Dynamic Properties of Immersed Sand at Virginia Beach, Va., U. S. Army, Coastal Engr. Res. Center, Tech. Memo. No. 9, 1964.

Harrison, W. and K. A. Wagner, Beach Changes at Virginia Beach, Va., U. S. Army, Coastal Engr. Res. Center, Misc. Paper 6-64, 1964.

Inman, D. L., Sorting of Sediments in the light of Fluid Mechanics, J. Sed. Pet., 19, 51-70, 1949.

Krumbein, W. C., Trend Surface Analysis of Contour-Type Maps with Irregular Control-Point Spacing, J. Geophys. Res., 64, 823-834, 1959.

__________, Confidence Intervals on Low-Order Polynomial Trend Surfaces, Jour. Geophys. Res., 68,5869-5878, 1963.

McCammon, R. B., Efficiencies of Percentile Measure for Describing the Mean Size and Sorting of Sedimentary Particles, J. Geol., 70, 453-455, 1962.

Miller, R. L. and J. M. Zeigler, A Model Relating Dynamics and Sediment Patterns, J. Geol., 66, 417-441, 1958.

Saville, T., Jr., J. M. Caldwell, and H. B. Simmons, Preliminary Report: Laboratory Study of the Effect of an Uncontrolled Inlet on the Adjacent Beaches, U. S. Army, Beach Erosion Board, Tech. Memo. No. 94, 1957.

Whitney, G. G., The Woods Hole Rapid Analyzer, Woods Hole Oceanog. Inst., Ref. No. 60-36, 1960.

Whitten, E. H. T., A Surface-Fitting Program Suitable for Testing Geological Models which Involve Areally Distributed Data, Tech. Report No. 2, ONR Task No. 389-135, Contract NONR 1228 (26), Geography Branch, Off. of Naval Res., 1963.

Zeigler, J. M., G. G. Whitney, and C. R. Hayes, Woods Hole Rapid Sediment Analyzer, J. Sed. Pet., 30, 490-495, 1960.

FIGURES

16. Observed distribution of values of sorting coefficient.

17. Linear trend surface for sorting coefficient.

18. Deviations from linear trend surface for sorting coefficient.

19. Cubic trend surface for sorting coefficient.

20. Deviations from cubic trend surface for sorting coefficient.

21. Deviation of cubic trend surface for M_z over the whole beach from cubic trend surface for M_z in inlet area. Contour values in mm.

22. Deviation of cubic trend surface for S_o over whole beach from cubic trend surface for S_o in inlet area. Contour values are in units of the sorting coefficient.

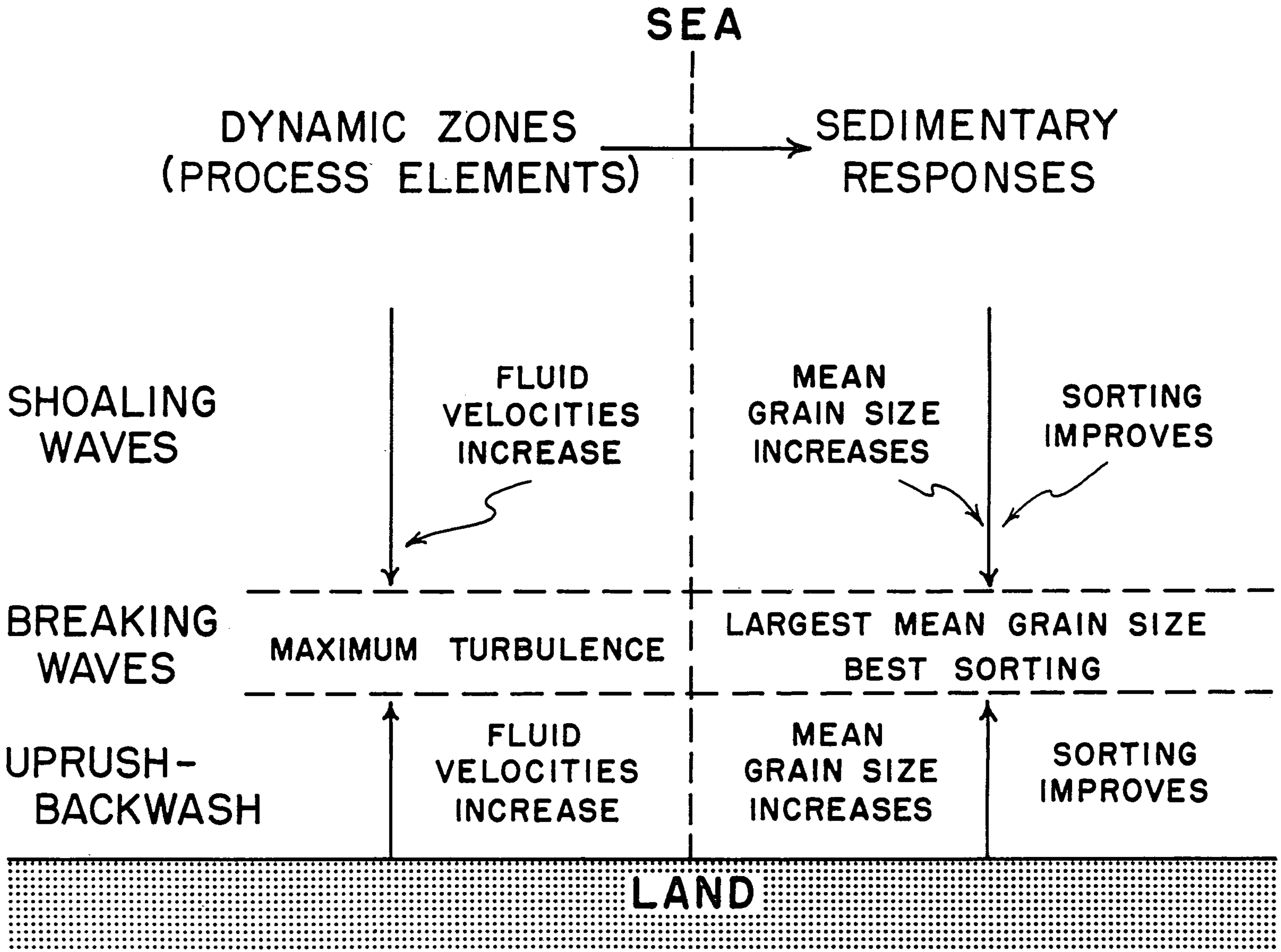


FIGURE 1. MODEL OF BEACH PROCESSES AND RESPONSES

FIGURE 2A. DEFINITION SKETCH OF PROBLEM

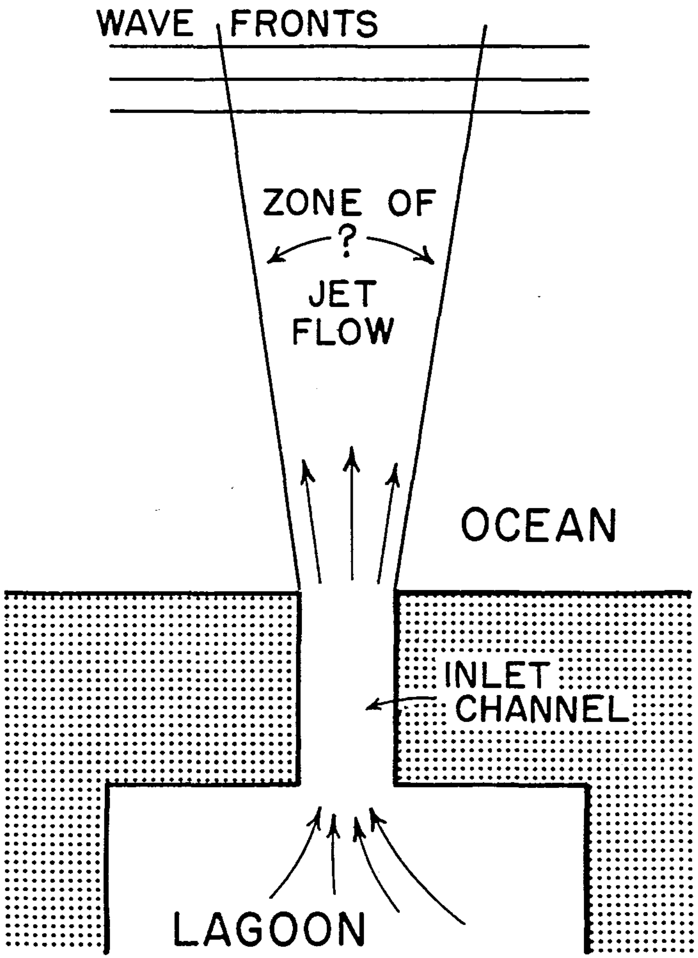


FIGURE 2B. DEGREE OF SEPARATION OF BOUNDARIES OF THE JET FLOW FOR THE NATURAL INLET

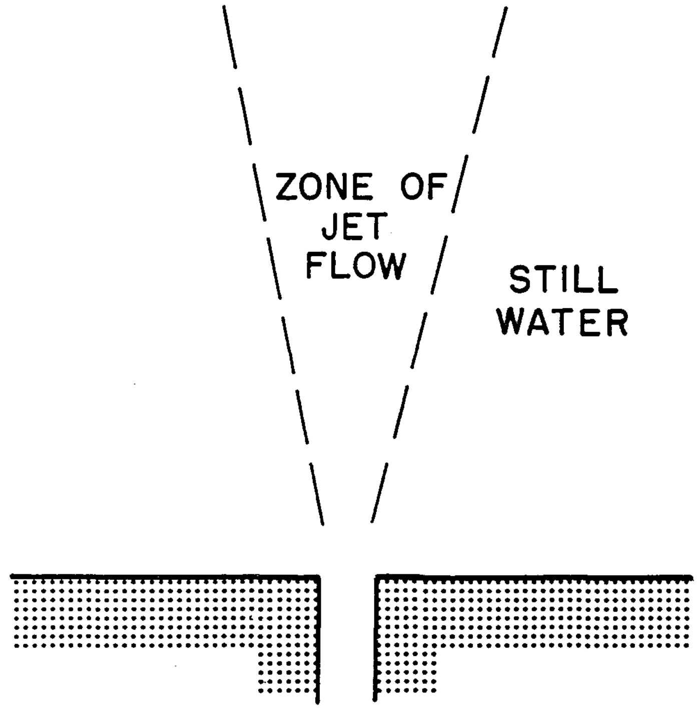


FIGURE 3A. MODEL OF SHOALS AT INLET ENTRANCE

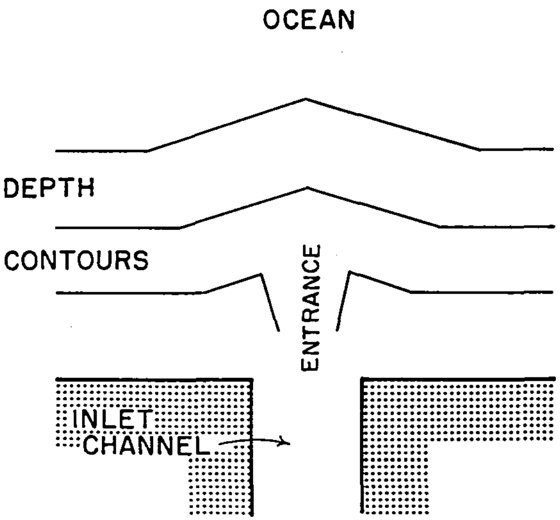


FIGURE 3B. MODEL OF DYNAMIC CONDITIONS DURING INLET OUTFLOW AND UNDER WAVE ACTION

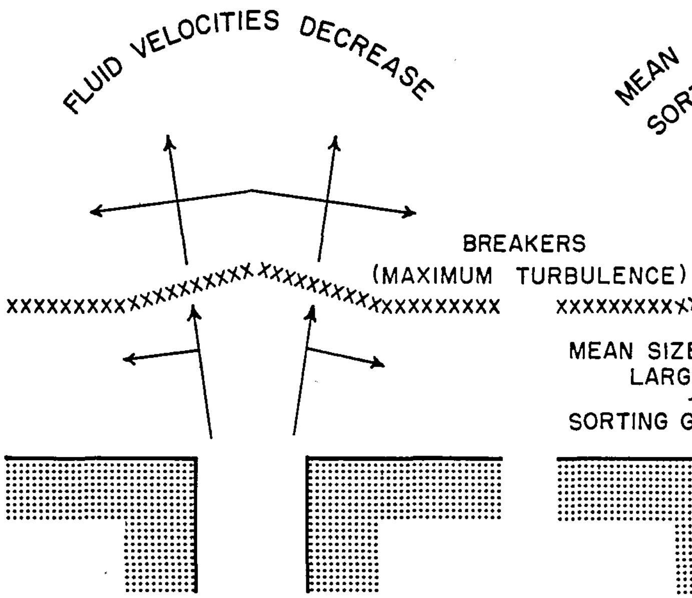
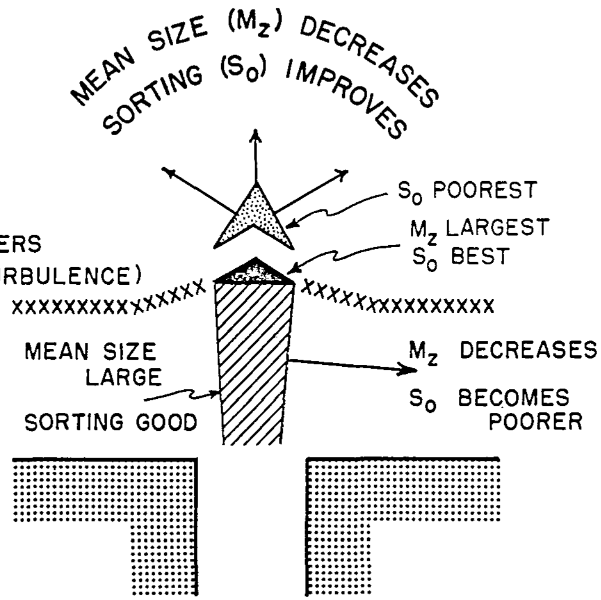


FIGURE 3C. MODEL OF TENDENCIES OF M_z AND S_o IN RESPONSE TO DYNAMIC CONDITIONS (B)



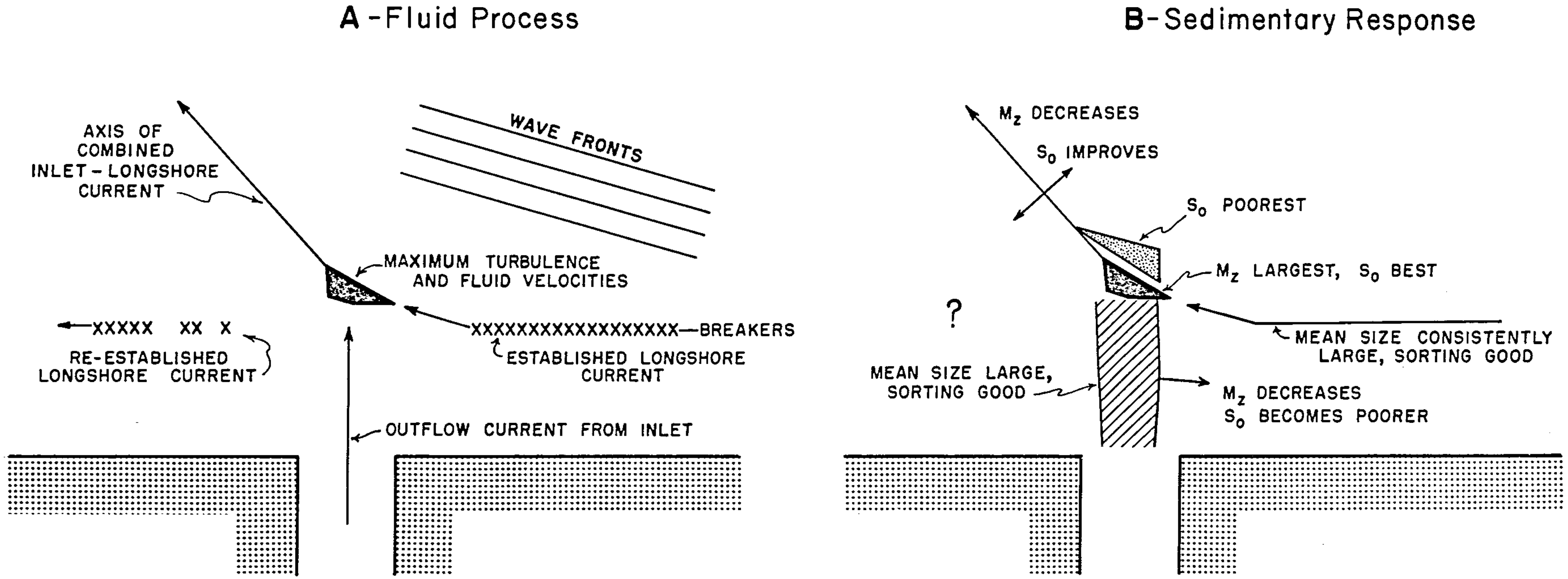


FIGURE 4. CONCEPTUAL FLUID PROCESS — SEDIMENTARY RESPONSE MODEL FOR AREA AROUND INLET ENTRANCE UNDER EBB TIDAL FLOW IN PRESENCE OF OBLIQUE WAVE FRONTS

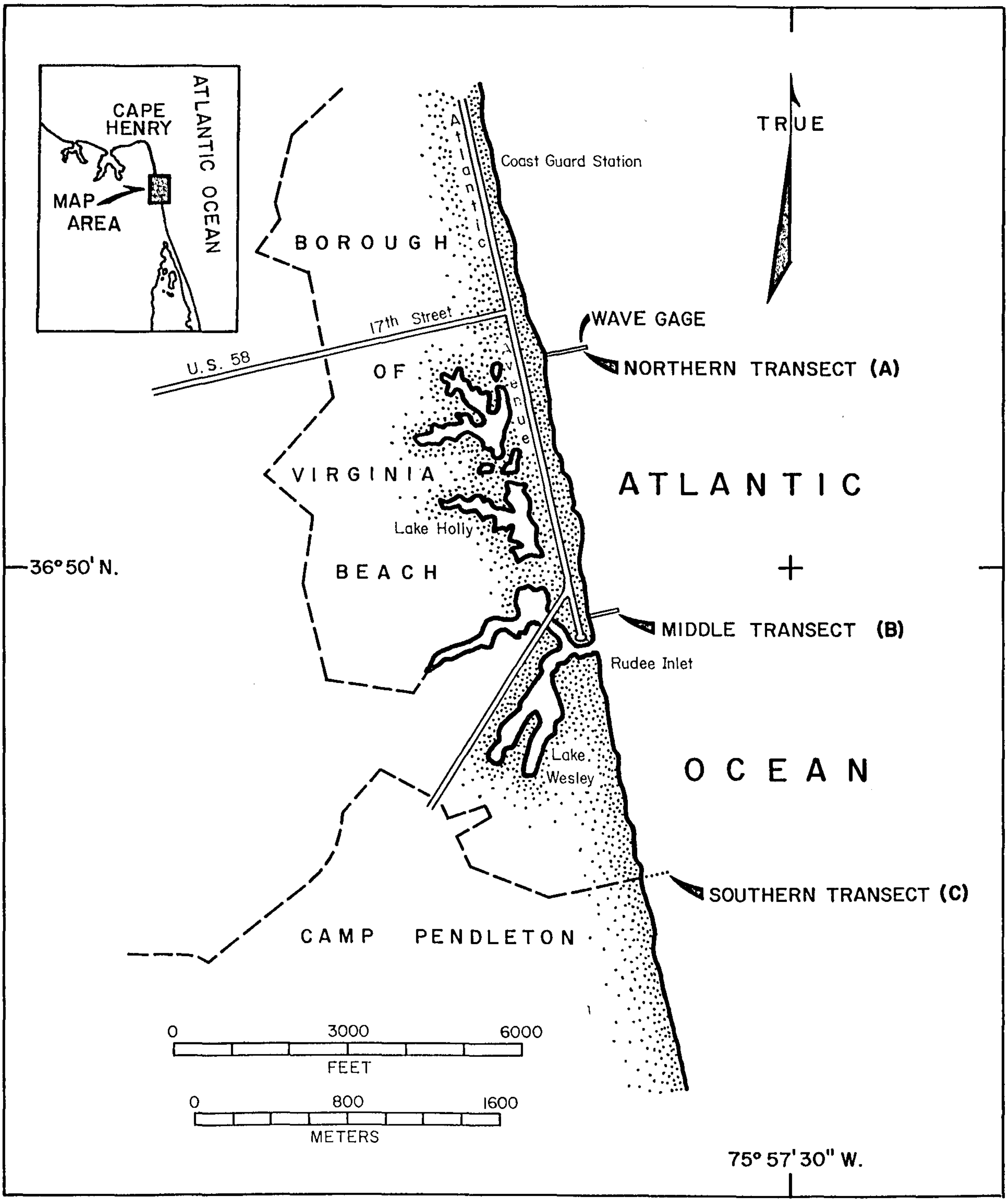


FIGURE 5. AREA OF INVESTIGATION – SHOWING RUDEE INLET AND THREE TRANSECTS

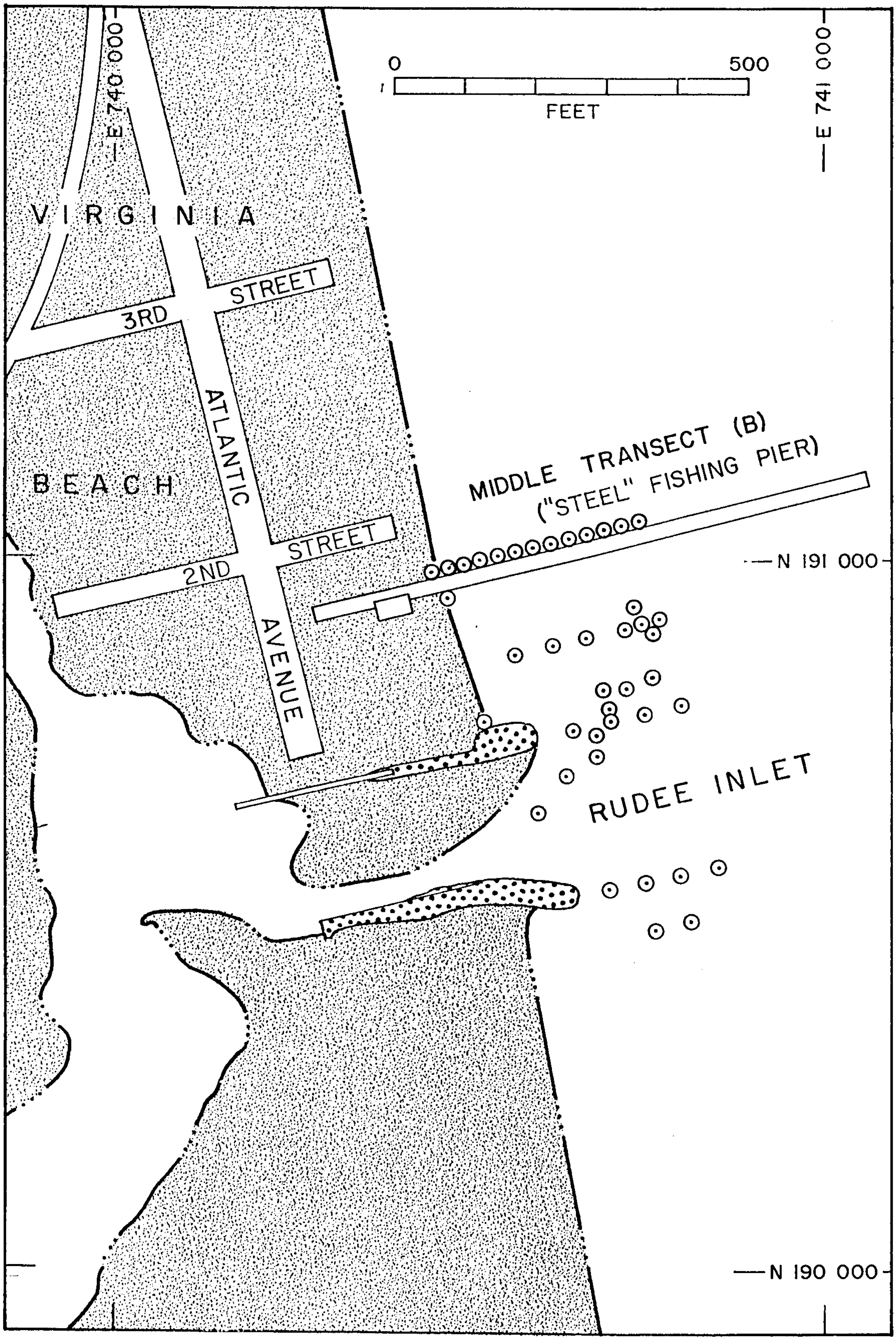


FIGURE 6. POSITION OF INLET CHANNEL AND SAMPLING STATIONS ON 25 MARCH 1963

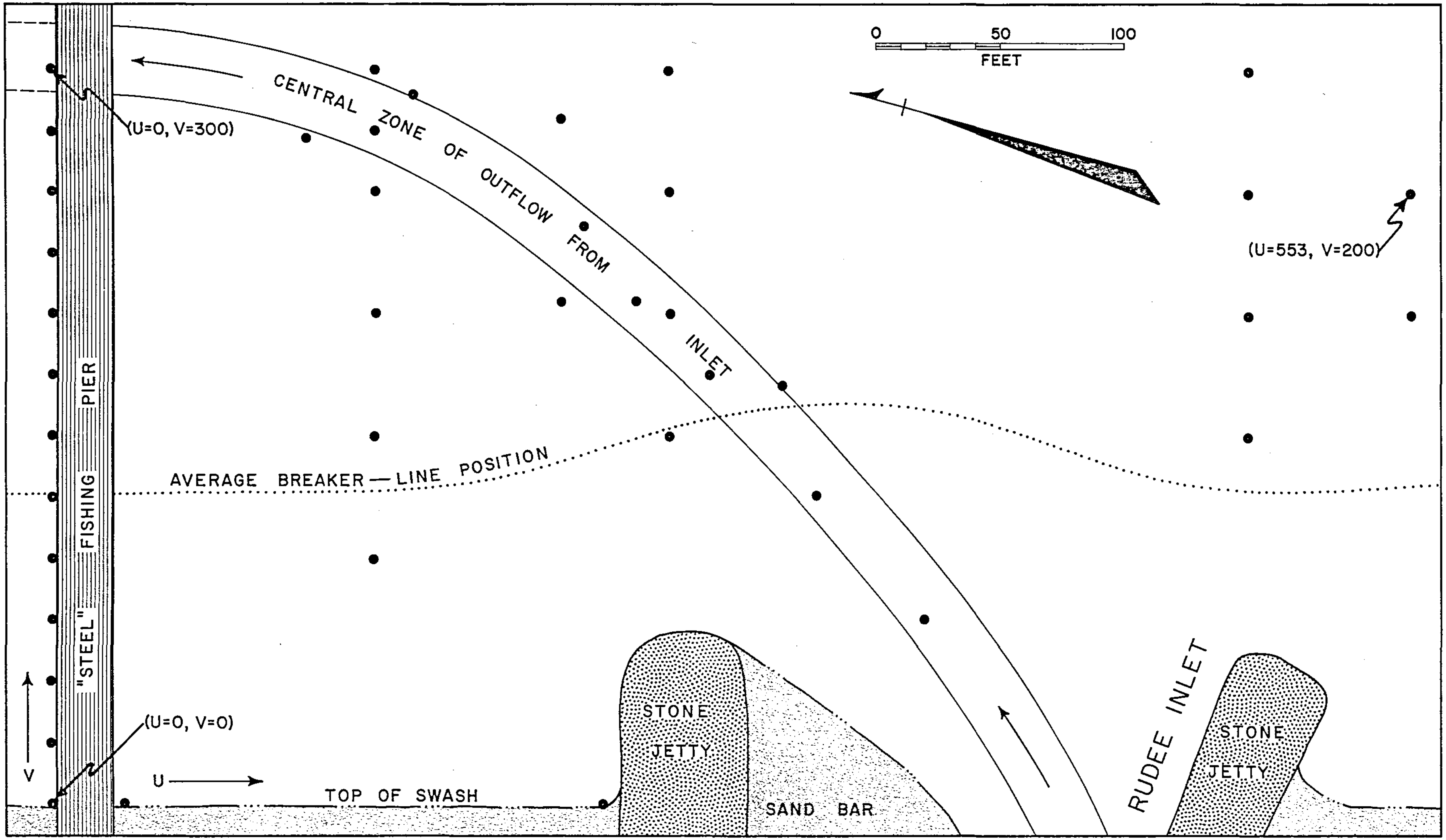


FIGURE 7. SAMPLING STATIONS AND SCHEME FOR U,V-COORDINATE SYSTEM

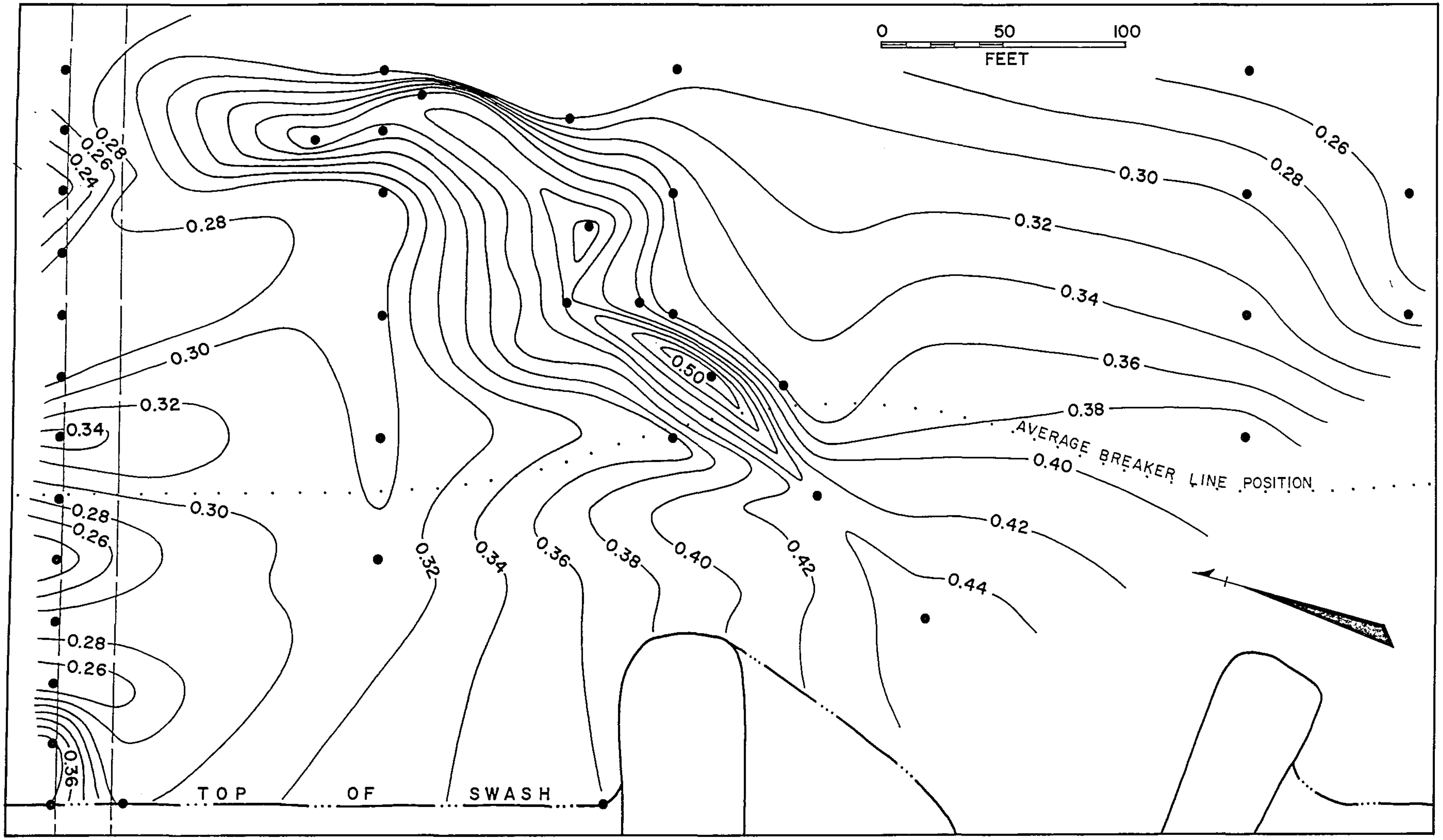


FIGURE 8. OBSERVED DISTRIBUTION OF MEAN-GRAIN-SIZE VALUES, EXPRESSED AS NOMINAL DIAMETERS (mm)

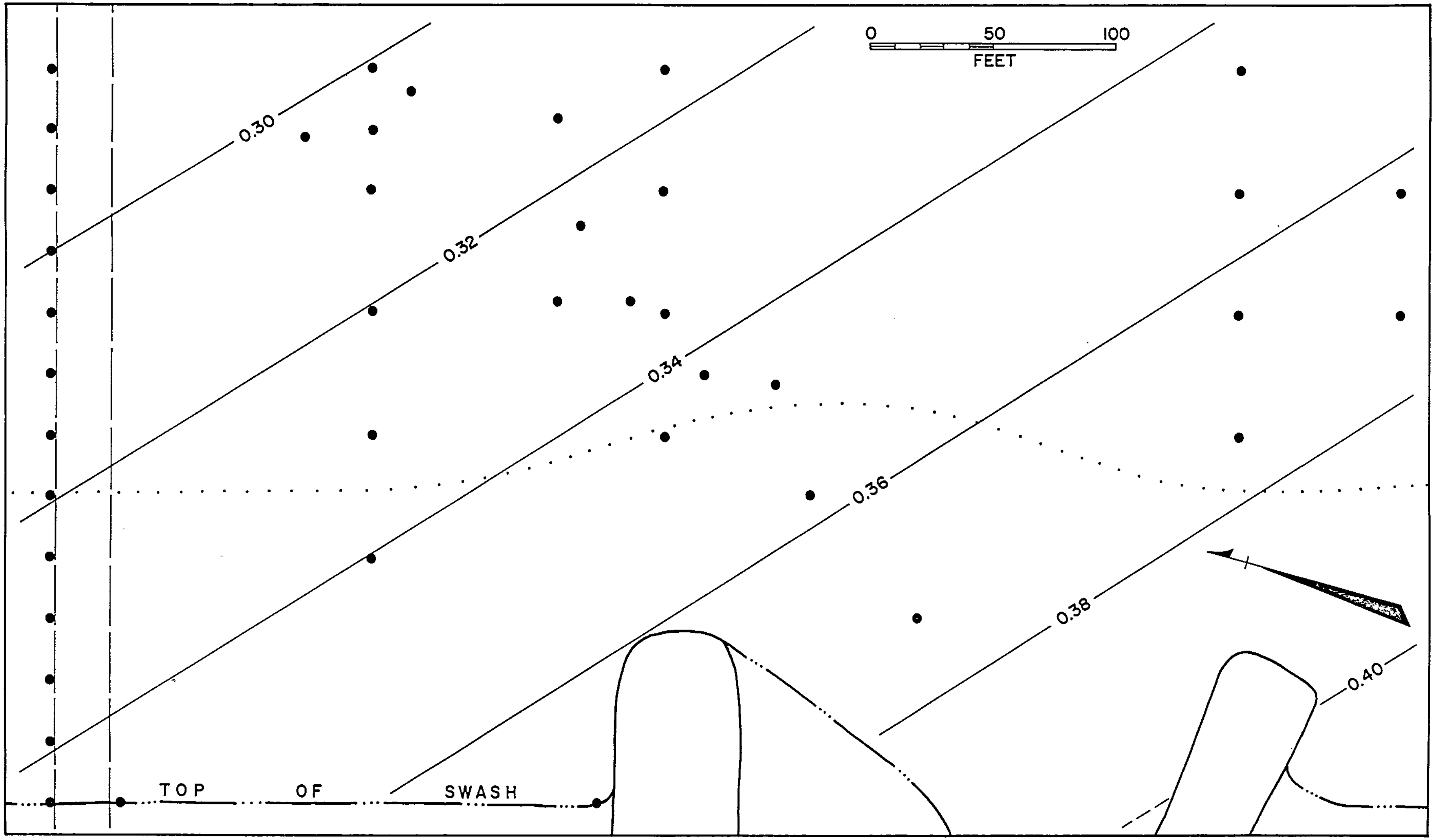


FIGURE 9. LINEAR TREND SURFACE FOR MEAN SIZE (mm)

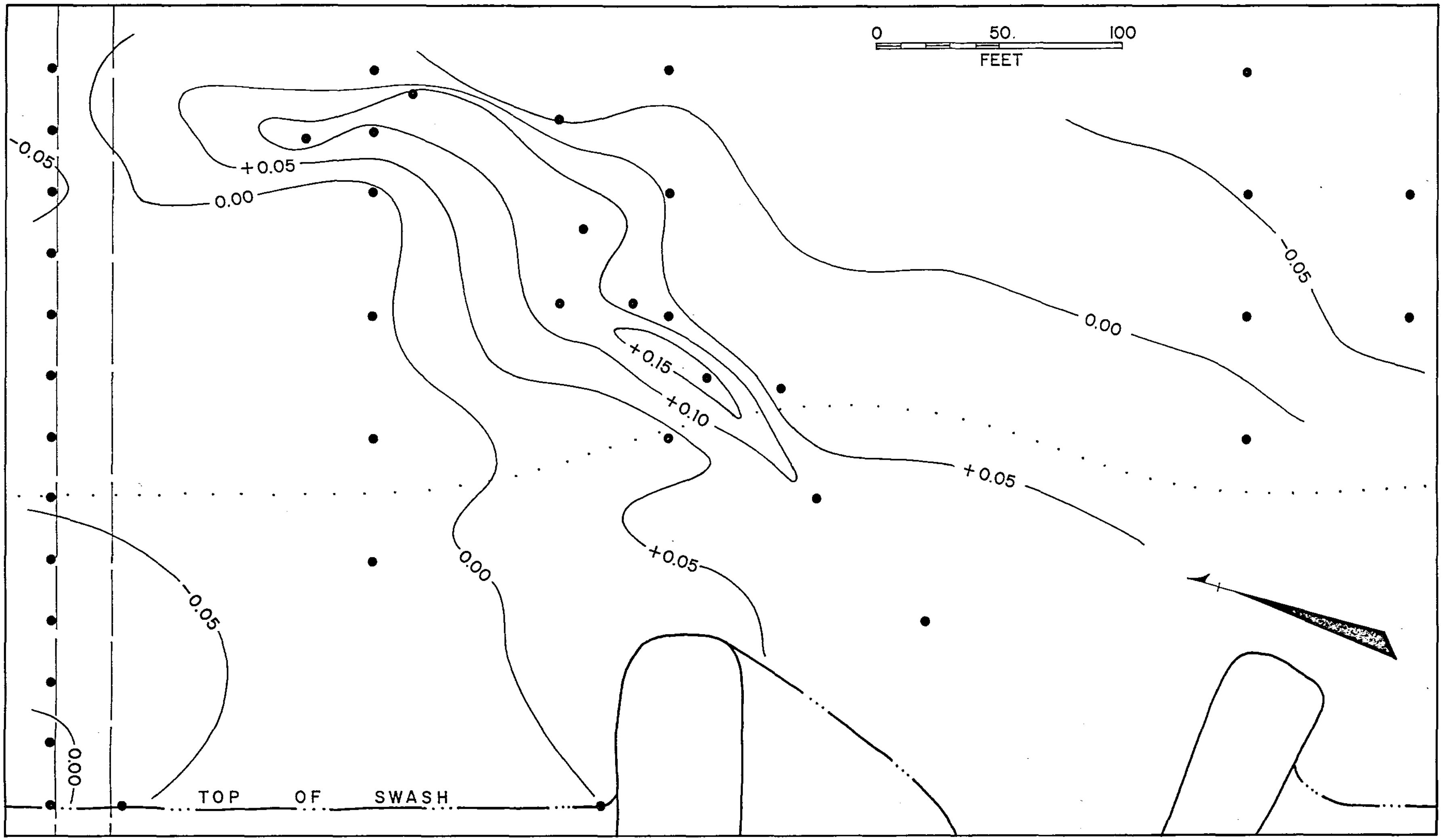


FIGURE 10. DEVIATIONS FROM LINEAR TREND SURFACE FOR MEAN SIZE (mm)

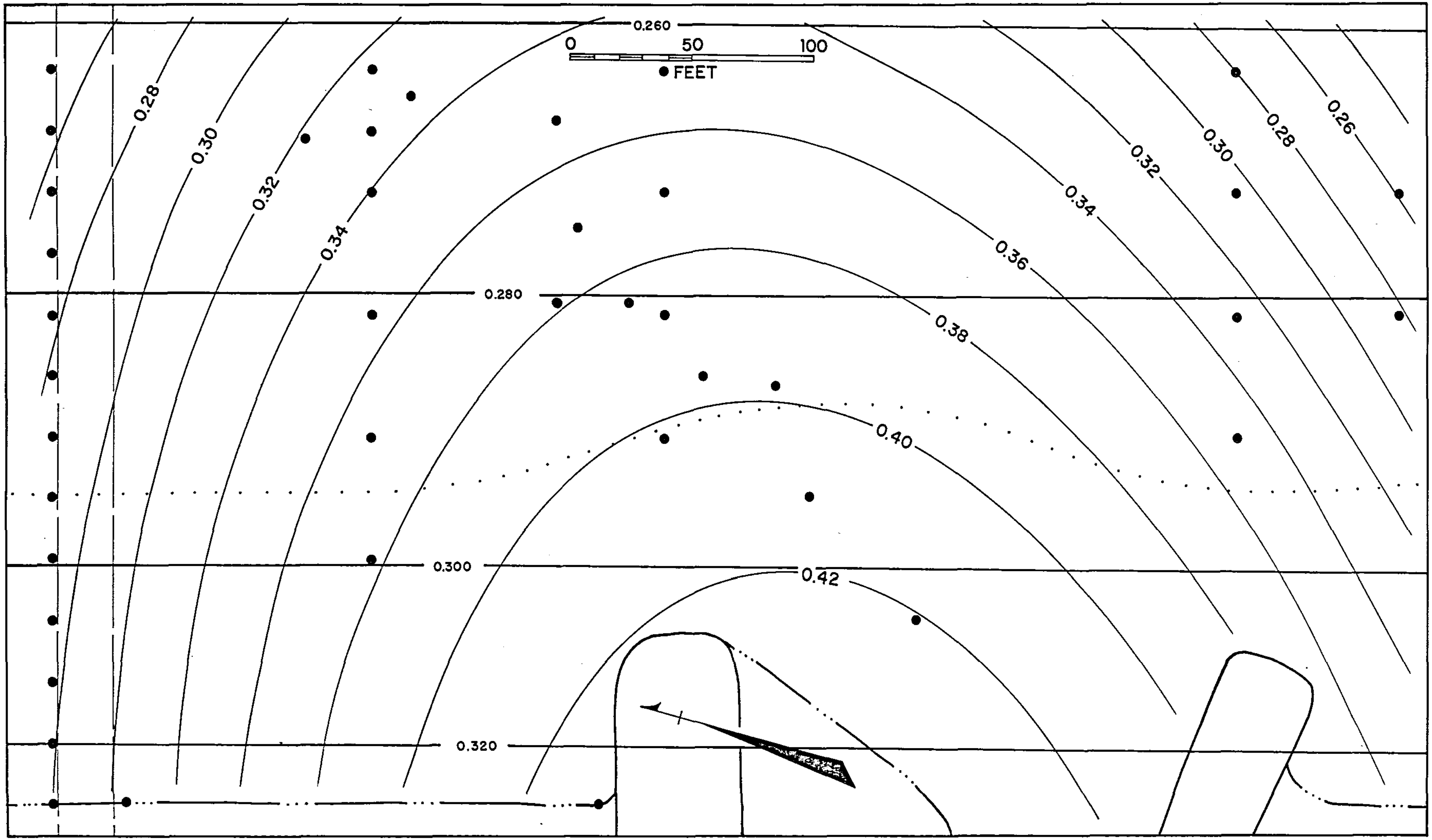


FIGURE 11. QUADRATIC TREND SURFACE FOR MEAN SIZE (mm)
ARCUATE CONTOURS BASED ON RUDEE INLET SAMPLES (LARGE DOTS) AND STRAIGHT–LINE CONTOURS BASED ON SAMPLES FROM THE 3 TRANSECTS SHOWN IN FIGURE 5

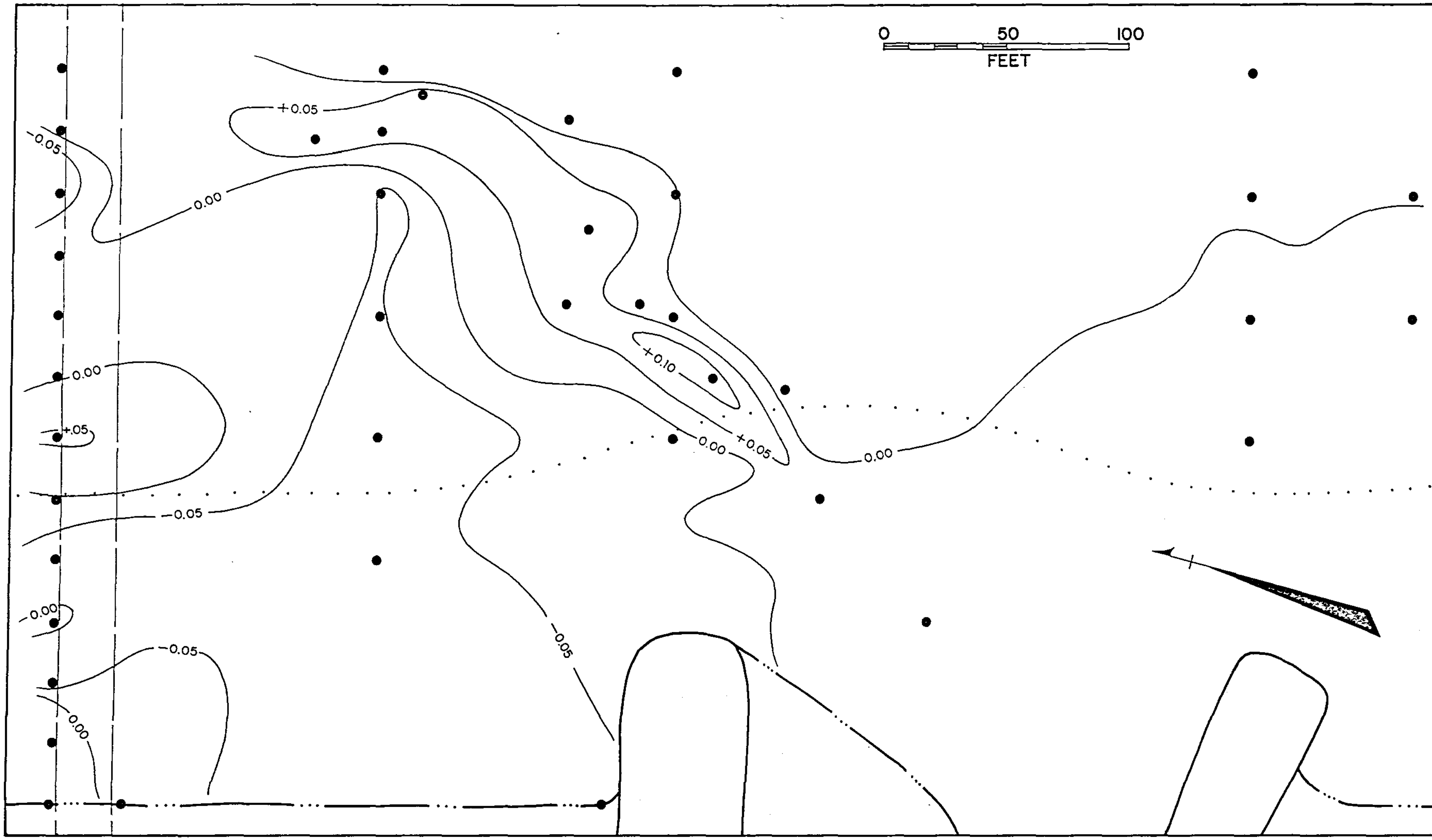


FIGURE 12. DEVIATIONS FROM QUADRATIC TREND SURFACE FOR MEAN SIZE (mm)

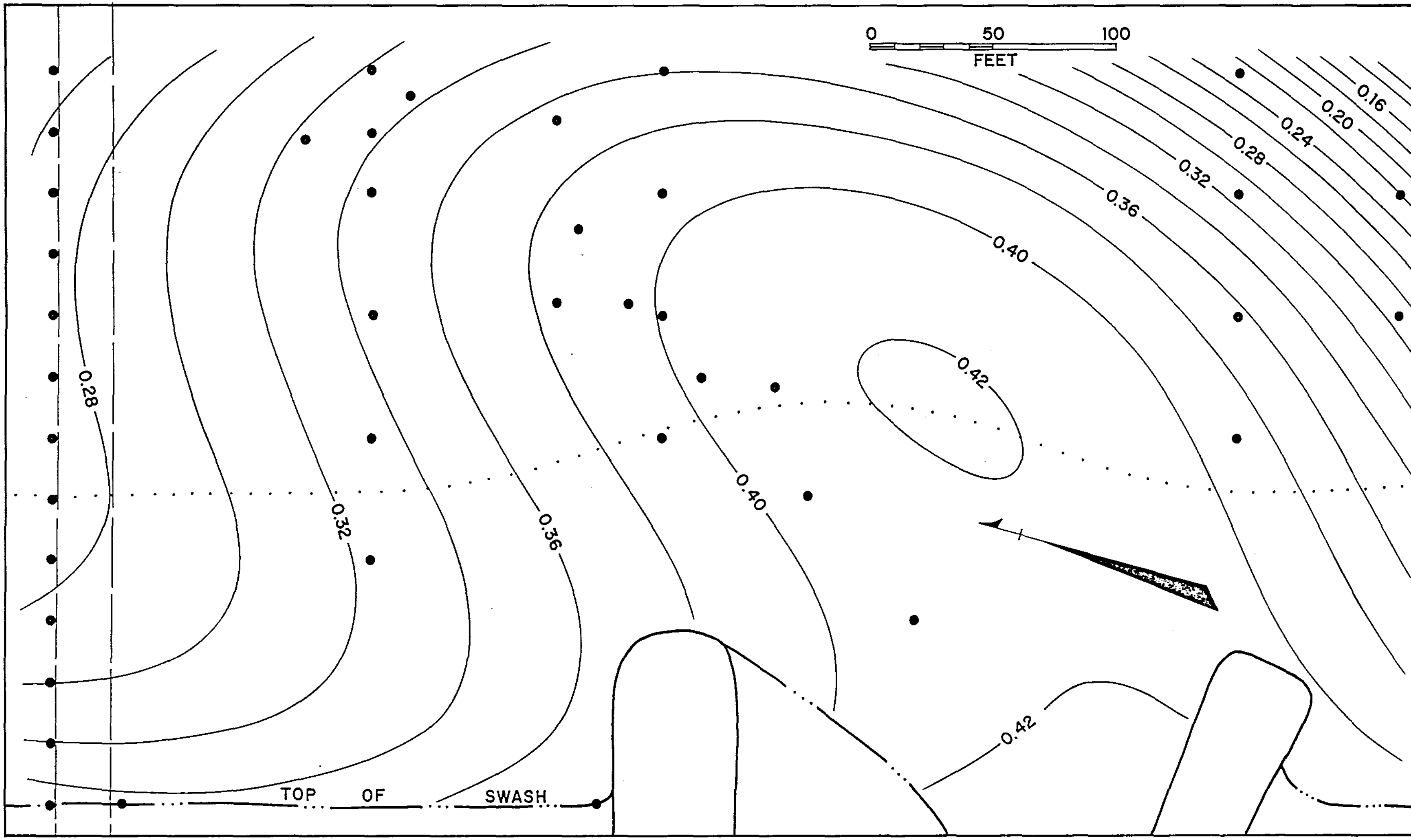


FIGURE 13. CUBIC TREND SURFACE FOR MEAN SIZE (mm)

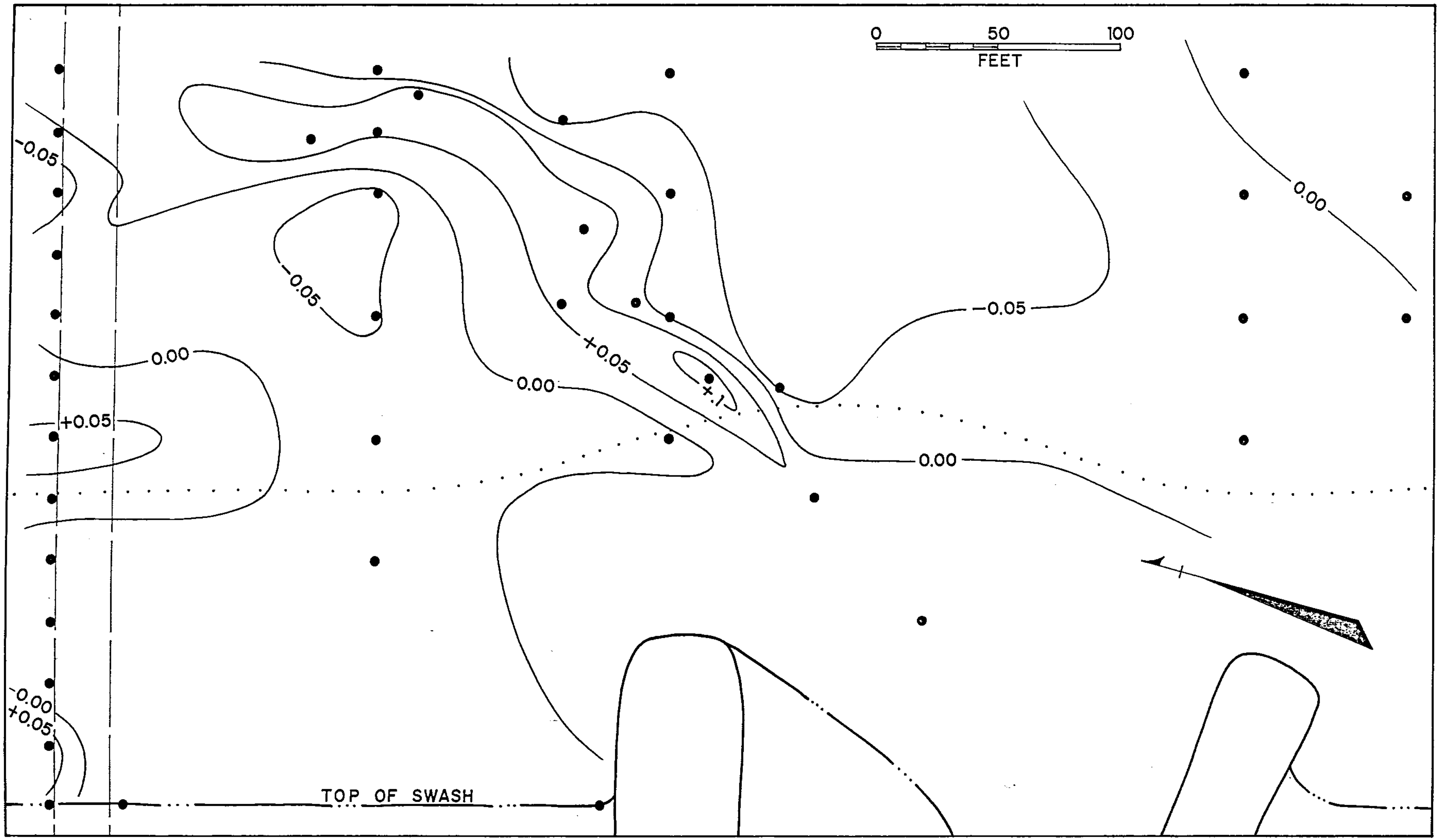


FIGURE 14. DEVIATIONS FROM CUBIC TREND SURFACE FOR MEAN GRAIN SIZE (mm)

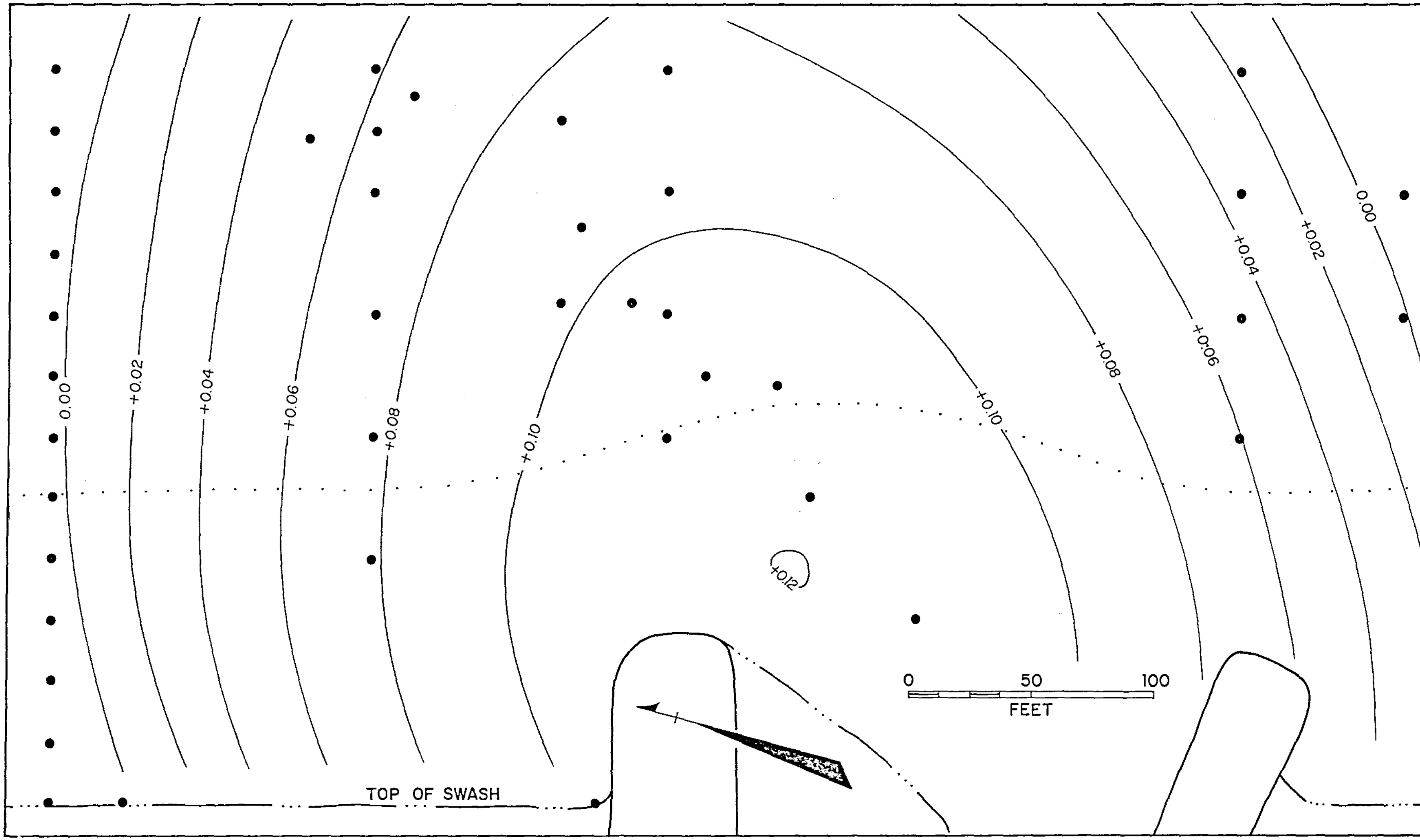


FIGURE 15. DEVIATION OF QUADRATIC TREND SURFACE FOR WHOLE BEACH FROM QUADRATIC TREND SURFACE FOR M_z FOR THE INLET AREA. (CONTOUR VALUES IN mm)

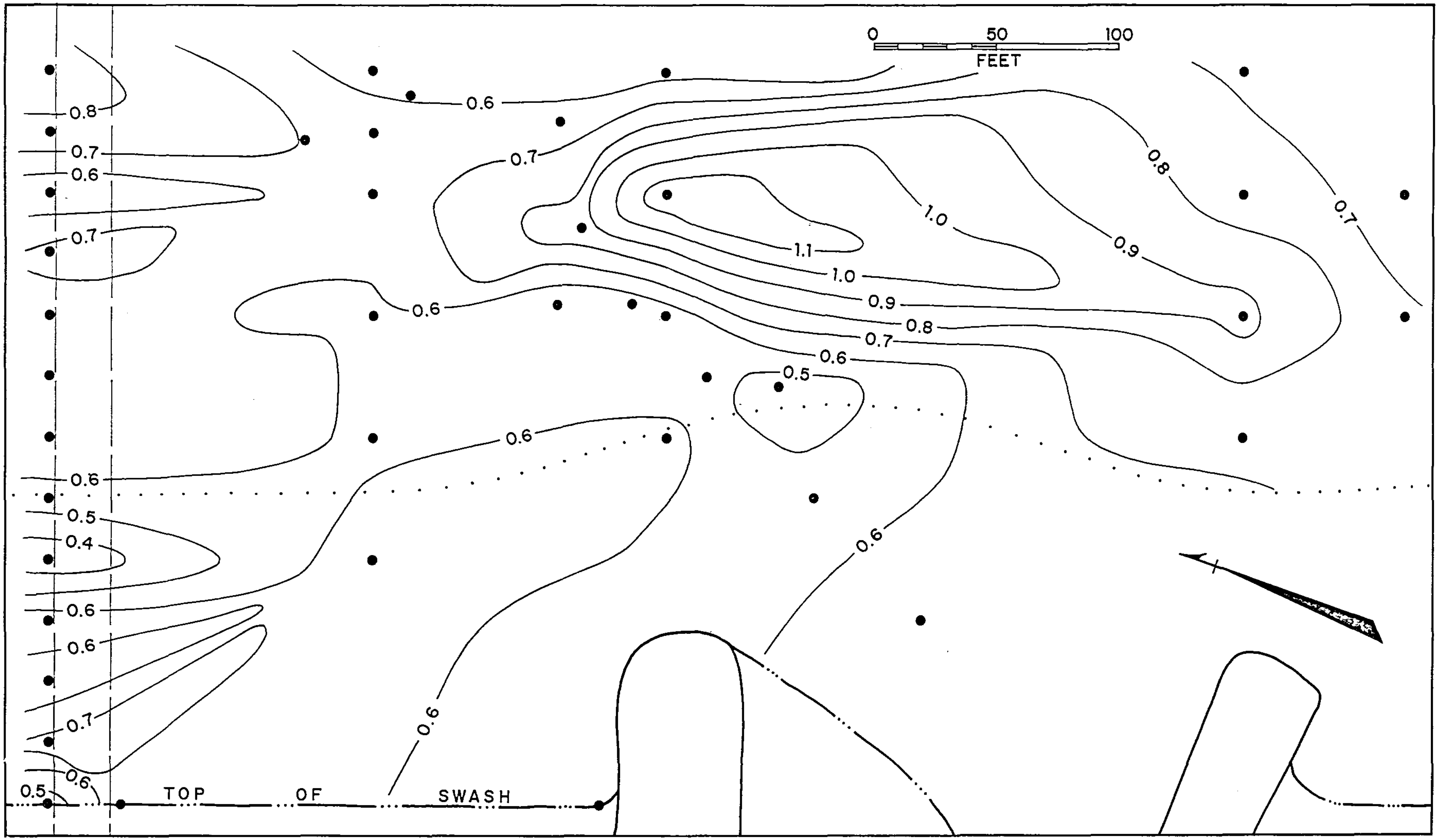


FIGURE 16. OBSERVED DISTRIBUTION OF VALUES OF SORTING COEFFICIENT

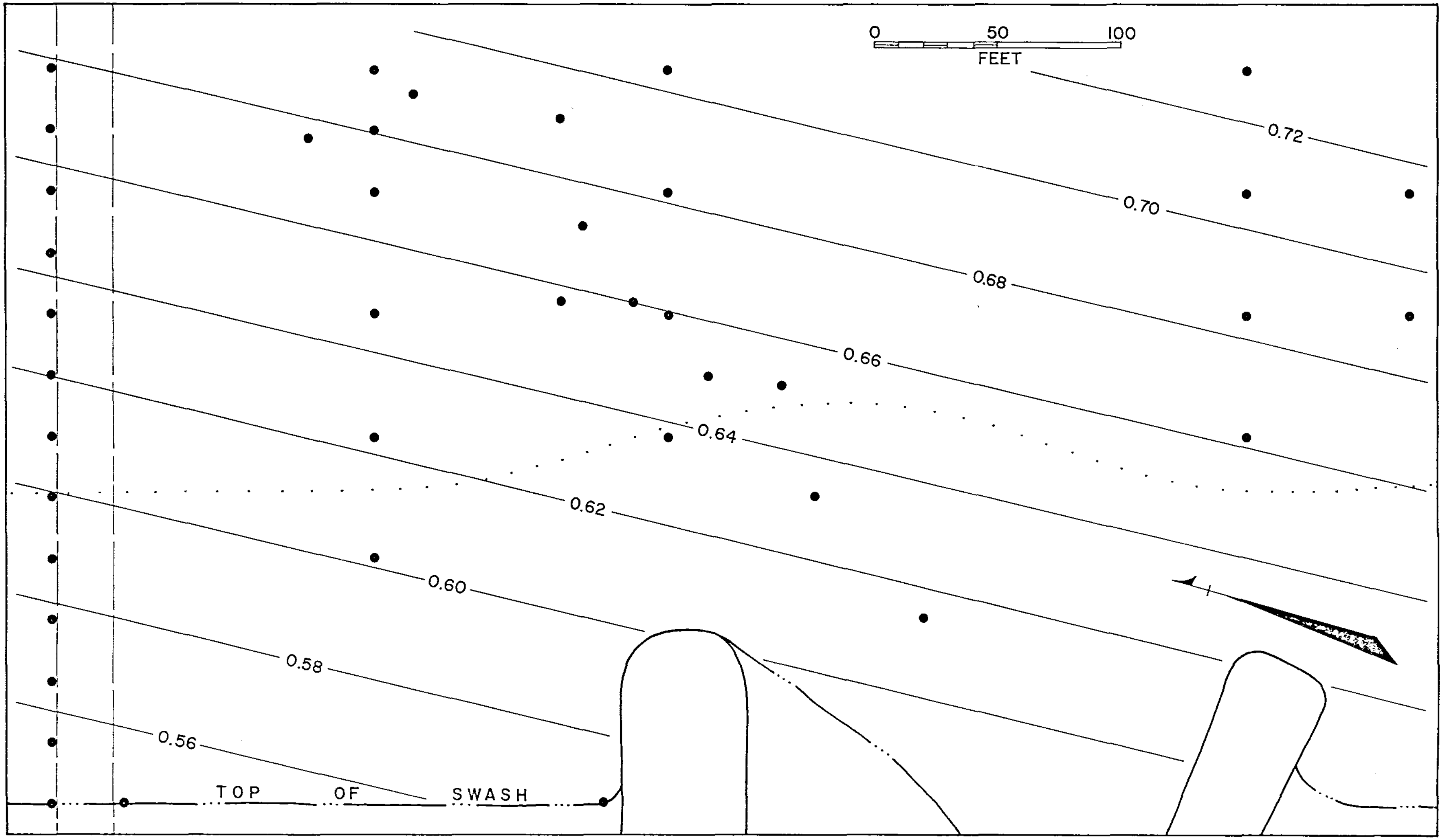


FIGURE 17. LINEAR TREND SURFACE FOR SORTING COEFFICIENT

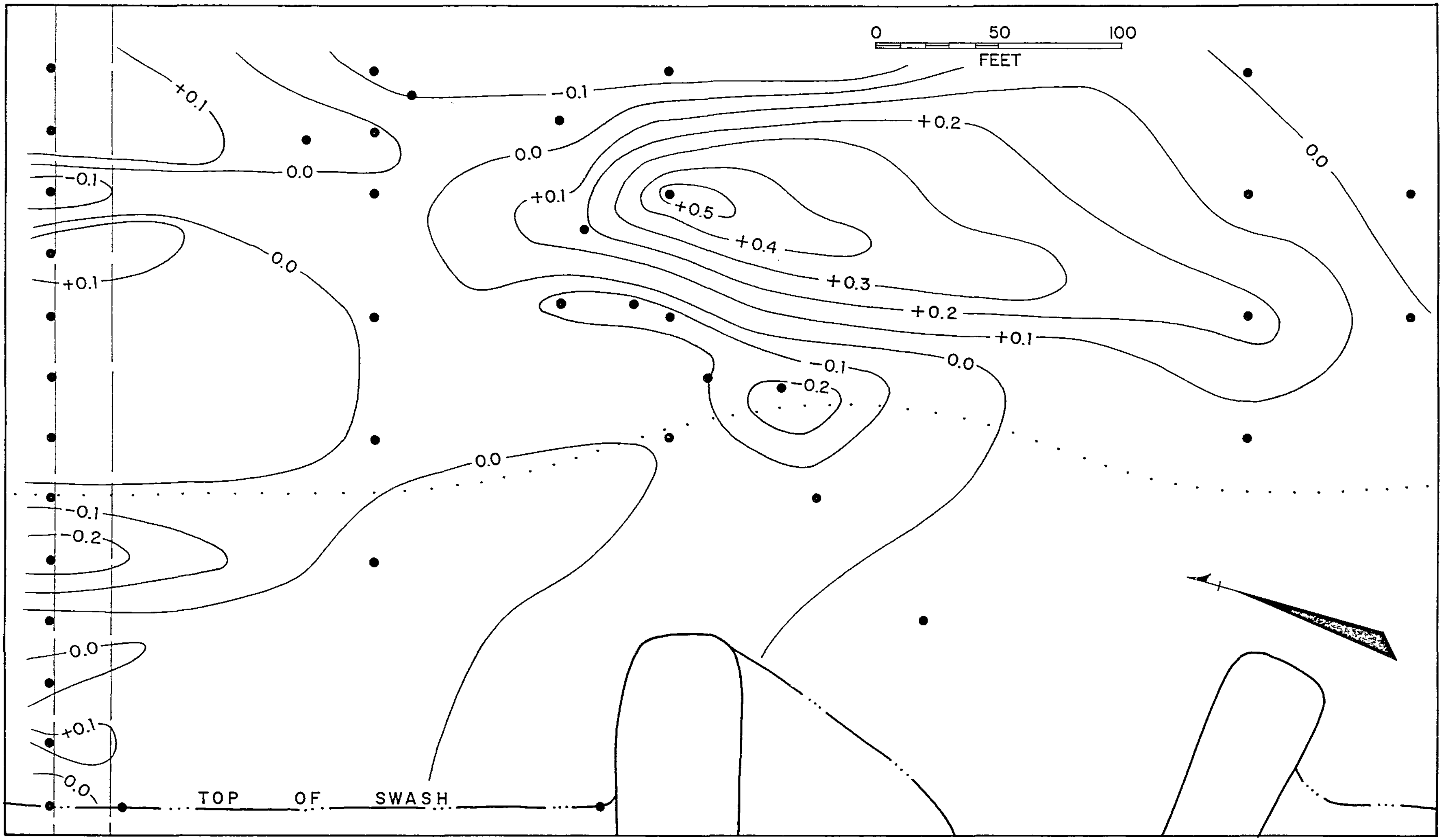


FIGURE 18. DEVIATIONS FROM LINEAR TREND SURFACE FOR SORTING COEFFICIENT

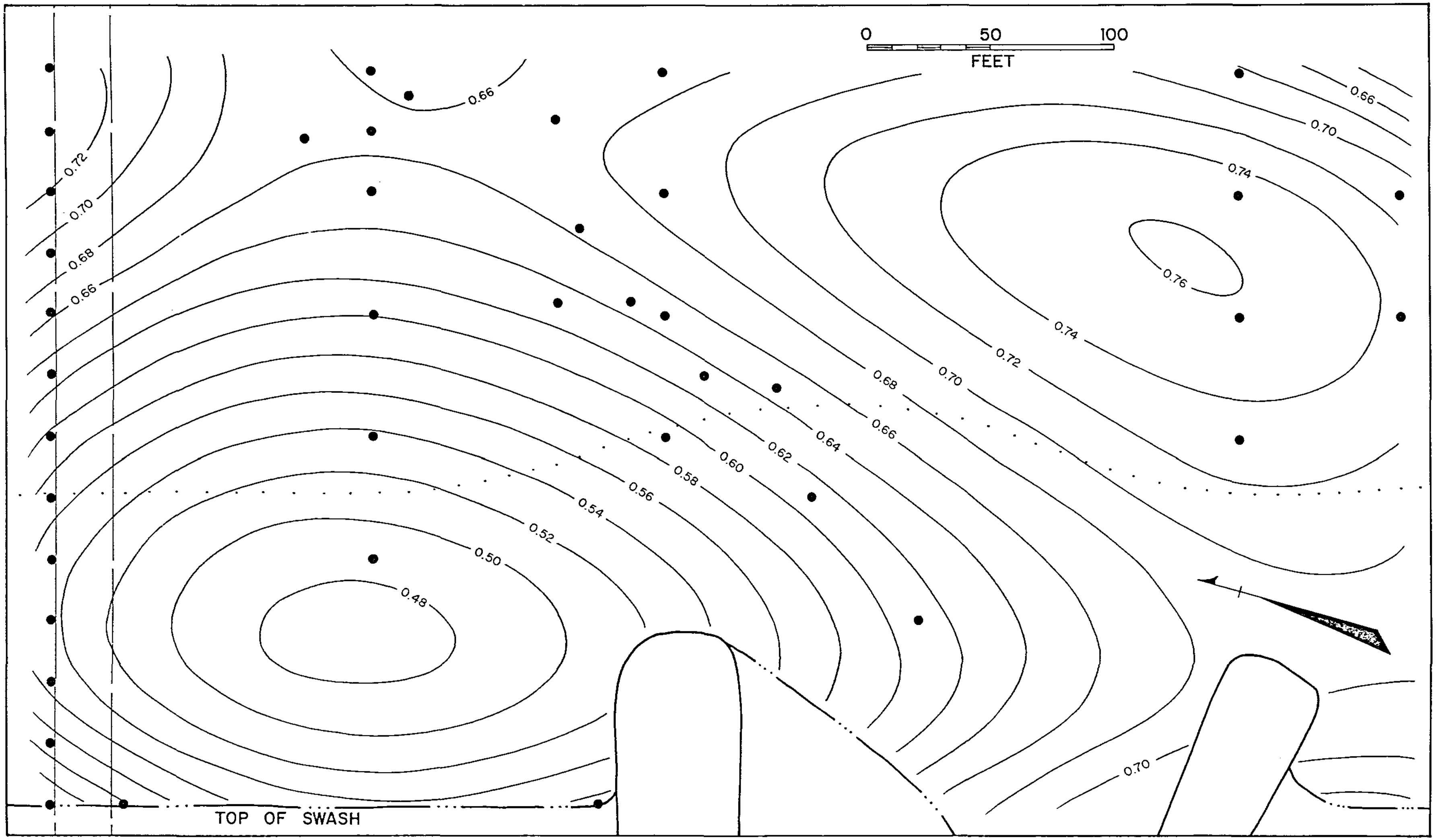


FIGURE 19. CUBIC TREND SURFACE FOR SORTING COEFFICIENT

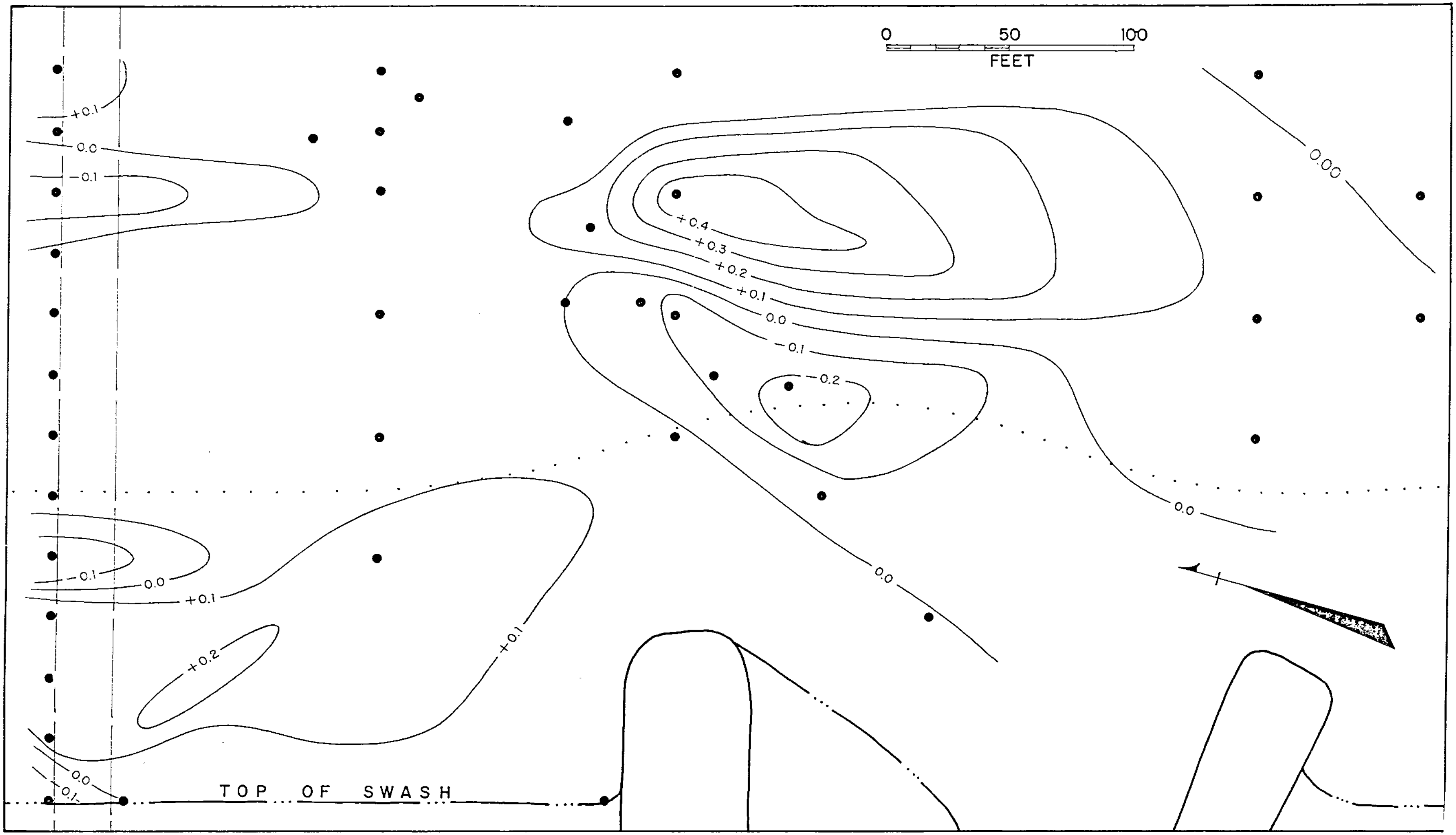


FIGURE 20. DEVIATIONS FROM CUBIC TREND SURFACE FOR SORTING COEFFICIENT

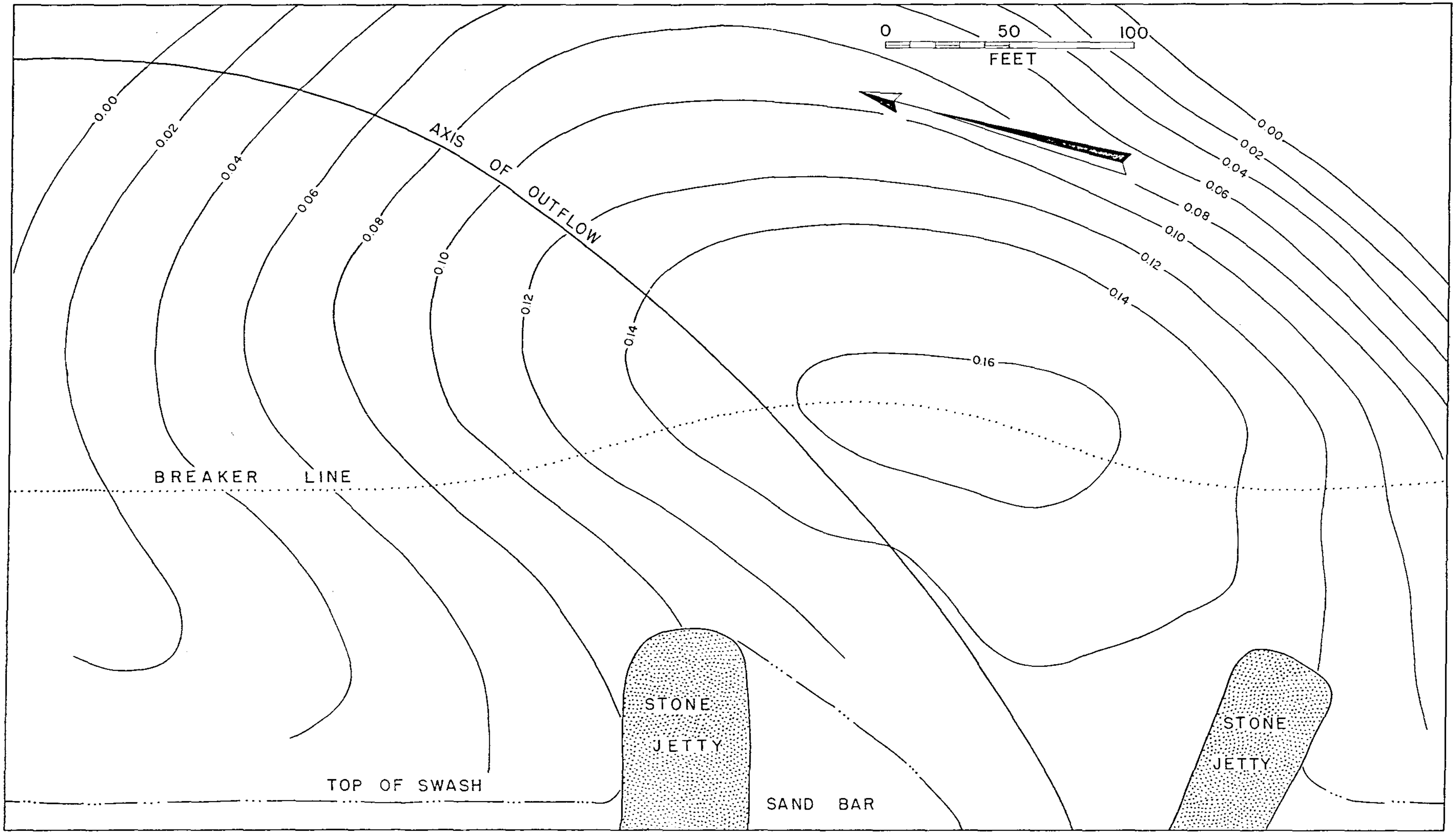


FIGURE 21. DEVIATION OF CUBIC TREND SURFACE FOR M_z OVER WHOLE BEACH FROM CUBIC TREND SURFACE FOR M_z IN INLET AREA. (CONTOUR VALUES IN mm)

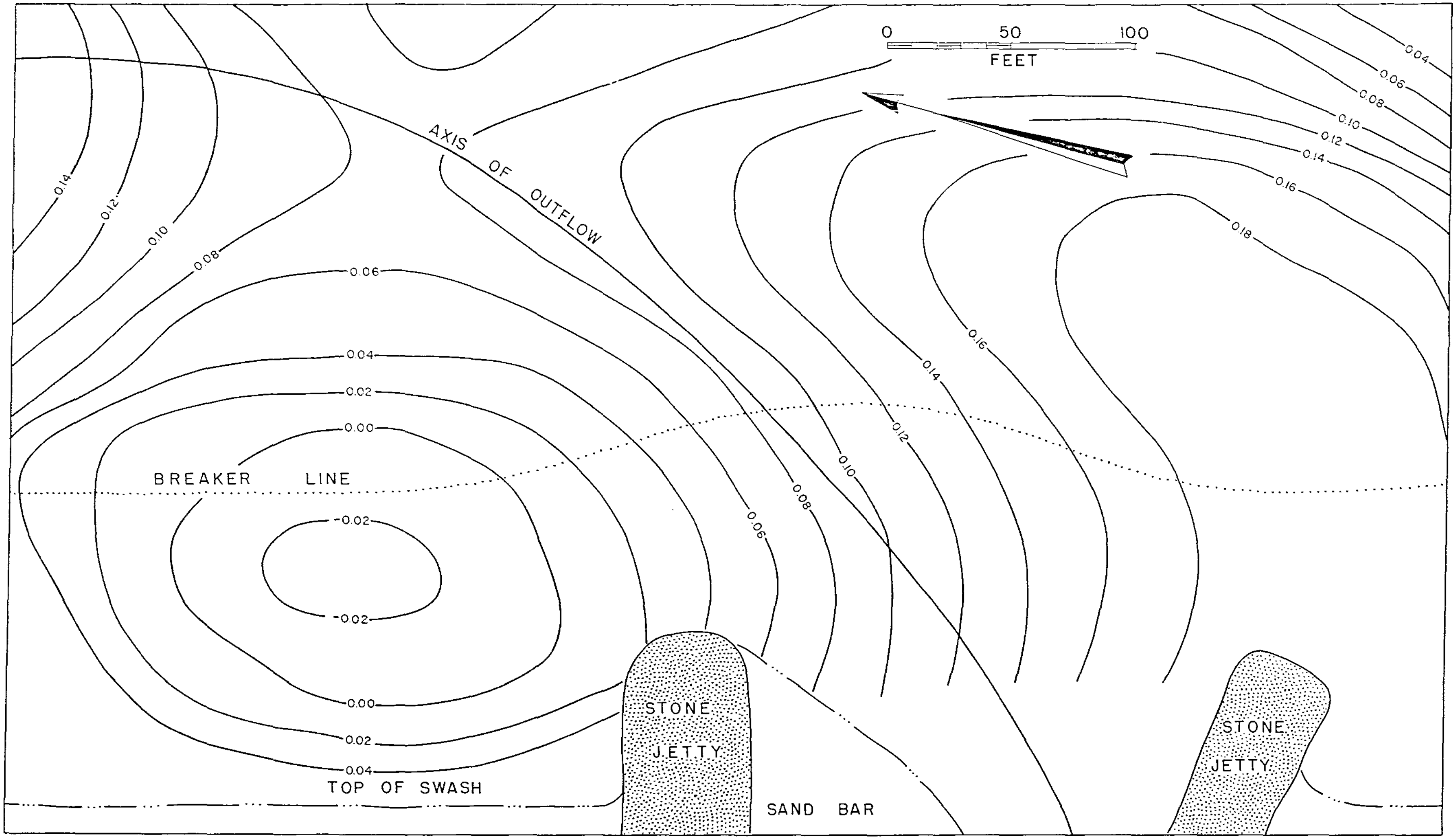


FIGURE 22. DEVIATION OF CUBIC TREND SURFACE FOR S_0 OVER WHOLE BEACH FROM CUBIC TREND SURFACE FOR S_0 IN INLET AREA (CONTOUR VALUES ARE IN UNITS OF THE SORTING COEFFICIENT)

U.S.ARMY COASTAL ENGRG. RES. CENTER, CE., WASH.,D.C.

SEDIMENTATION AT AN INLET ENTRANCE (Rudee Inlet-Virginia Beach, Va.) by W.Harrison, W.C.Krumbein and W. Wilson, December 1964, 42 pp. including 22 illus.

TECHNICAL MEMORANDUM NO. 8 UNCLASSIFIED

1. Shore Processes
2. Virginia Beach, Virginia
3. Tidal Inlets (Rudee Inlet)
4. Inlets

I Title
II Harrison, W.
III Krumbein, W.C.
IV Wilson, W. S.

A physical model is presented of the wave, longshore-current, and ebb-tide current systems as they determine the distribution of mean particle size and degree of sorting at the mouth of a controlled inlet. Bottom samples taken at Rudee Inlet, Virginia Beach, Va., were subjected to trend-surface analysis, to verify trends predicted by model. Correspondence between model and natural situation was found to be good, but area of inlet-current influence was found to be rather limited in extent.

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