

CHAPTER 77

COMPATIBILITY OF BORROW MATERIAL FOR BEACH FILLS

by

R. G. Dean¹

ABSTRACT

A simple method is presented for estimating the relative compatibility of borrow material being considered for beach fill purposes. The method defines the "compatible" fraction of the material as that coarser portion with the same mean diameter (in "phi" measure) as the native material on the beach. A single graph is presented which allows determination of the number of units of borrow material required to obtain one unit of compatible material. Use of this method requires that the size distributions be reasonably represented by the "log-normal" relationship and also requires knowledge of the means of the native and borrow materials and the standard deviation of the borrow material (all in phi measure). This method overcomes shortcomings of the Krumbein-James method published in 1965. Several examples are presented illustrating the application of the method presented in this paper.

INTRODUCTION

The problem of arresting the wide-spread erosion along many of the valuable shorelines of the world represents a major challenge to the engineer and coastal planner. The recent evaluation of shoreline conditions entitled "National Shoreline Study"(1) conducted by the U. S. Army Corps of Engineers in 1972 established a first "remedial cost" of 1.8 billion dollars to restore the "critically eroded" beaches and an annual maintenance cost of 56 million dollars thereafter. Due to the accelerating development along the shoreline, this cost will continue to increase in the future.

The value of high-quality beaches for recreation and protection against extreme storm waves is well-established. For example, in Florida, tourism is the largest industry representing an income of 3 billion dollars a year. Surveys conducted by the Florida Department of Commerce have shown that over 70% of the tourists cite beaches as the single feature providing the greatest enjoyment during their stay. The pro-

¹Professor, Coastal and Oceanographic Engineering Laboratory,
University of Florida, Gainesville, Florida 32611.

tection provided by a natural beach-dune system functions by providing a "reservoir" of sand which, under high wave attack, is eroded and transported offshore where it is alternately stored in a "storm bar". Although the formation of this bar is at the expense of the beach-dune system, the build-up of this bar is self-limiting. As the bar crest increases in elevation, it causes the incoming waves to break, thereby limiting the wave energy attacking the beach dune, see Figure 1. If a protective

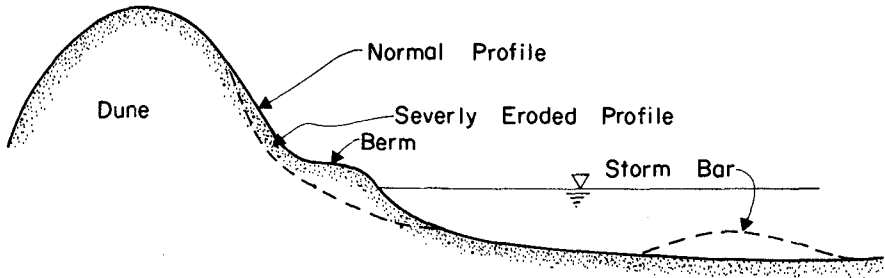


FIGURE 1 NORMAL AND SEVERLY ERODED BEACH PROFILES

beach and dune system are not present, and, if instead, a protective seawall is installed, there is no equivalent "reservoir" of sand and the storm waves will cause erosion immediately in front of the seawall. If there is insufficient material to build the bar, the waves will continue unattenuated to scour the foundation and may lead to eventual collapse. Following a storm, the ensuing normal wave conditions will cause the bar to be transported ashore with eventual rebuilding of the berm and, over several years, the combined action of long waves, high tides, onshore wind and vegetation will reconstruct and heal the dune system, thereby restoring the protective supply of beach material.

In many past cases, the policy of coping with beach erosion has been on a rather piece-meal basis in which individual home owners or small groups of home owners attempt to arrest their localized beach erosion problem. Generally, an unusually severe hurricane or other storm can cause major recession of the shoreline and significant loss to up-land structures. The lack of effectiveness of these piece-meal efforts is evidenced in Florida by many lots platted in areas that are now underwater and by a number of landward displacements of the coastal highway which follows the shoreline. An extreme example is provided by the north end of Jupiter Island, where the average recession is 40 feet per year since St. Lucie Inlet was cut in 1892(2).

Recent planning indicates that more effective beach erosion control programs may be implemented within the present decade. Beach restoration and periodic nourishment maintenance is probably the most attractive method of beach erosion control. A number of such projects of limited

extent have been carried out. To date in Florida, there have been seven such projects encompassing beach segments ranging from 0.6 miles to 3.2 miles in length. Ideally such projects should be based on a coastal physiographic unit, such as between inlets or between headlands. Additionally it may be desirable (more economical) to include structural stabilizing components as an integral part of the project to reduce losses, especially at such places as inlets. Unfortunately beach restoration and maintenance projects, involving the placement of massive volumes of sand on the beach, are expensive, usually costing on the order of one-half to one million dollars per mile. The authorized Miami Beach project is probably the most expensive planned to date and is expected to cost between four and five million dollars per mile for a ten mile segment of shoreline.

The high costs of beach restoration and the probable scale of future nourishment programs, as indicated in the aforementioned National Shoreline Study, demands a much better general understanding of littoral processes and, in particular, a greatly improved capability to reliably predict the performance of beach fills. Ideally, for a placed fill of particular material characteristics and dimensions, one should be able to predict the evolution of the shoreline and the transport and disposition of the fill material. Reliable prediction of beach fill performance would aid the engineer and the public agency providing the funds and would also lead to a more rational judgement regarding the allocation of budgeted funds to additional fill vs. stabilization structures. Needless to say, predictions are also necessary to allow proper budgetary planning for future beach maintenance operations.

The present shortcomings in our ability to carry out such predictions reflects not only an inadequate knowledge of littoral processes, but a dearth of information regarding the "wave climate" affecting the shoreline and the performance of existing beach fill projects; in particular, data concerning wave direction are lacking. There have been surprises in the expected vs. realized performance of beach fills and the present capability to predict loss rates is probably only within a factor of two or three. There are attempts(3),(4) to cast available knowledge in the framework of numerical models to represent shoreline response under prescribed wave conditions; however, at present such efforts must be considered rudimentary and unverified.

One of the key elements in predicting beach fill performance is in evaluating differences in transport rates between the placed ("borrow") material and the "native" beach material. Present beach nourishment projects generally plan to use offshore sources of material and while material is generally plentiful, it is usually of a lesser quality (i.e. finer) than the native beach sand. The problem then arises of rationally selecting between a nearshore finer material or an alternate more costly borrow area of more suitable size distribution.

This paper is concerned with the "compatibility" of beach sands and presents a method for determining the amount of required borrow material to yield one unit that is consistent with the native material.

While it is tempting to refer to this fraction as a retention percentage, this is misleading and is not the case; hence the term "compatibility" signifies consistency from consideration of correspondence with native sand characteristics.

REVIEW OF PREVIOUS WORK

Krumbein and James(5)(K-J) have developed a procedure for evaluating the compatibility of borrow materials which have certain properties relative to the native material. In particular, their method is applicable if the native sand is better sorted than the borrow material. There are features of the K-J approach which limit its use and which are not consistent with our knowledge of beach processes. First, if the borrow material is better sorted than the native material, the method simply does not apply. This may be the case where dune sand is being considered as the borrow sand or where an offshore bar or relic submerged beach of well-sorted material is being considered. Secondly, the compatibility as defined in the K-J model requires the portion of the retained borrow material to have exactly the same size distribution as the original native material. This assumption implies that both finer and coarser fractions of the borrow material will be "lost". It is this feature that is not consistent with knowledge of littoral processes and that results in an unrealistically pessimistic expectation of the suitability of borrow material which contains considerable quantities of material coarser than the native sand. In the following paragraphs, the method of K-J will be reviewed briefly.

Krumbein and James found it convenient to describe sand size in " ϕ " (ϕ) units, where

$$\text{Size in } \phi \text{ units} = -\log_2(D) \quad (1)$$

and D is the sand diameter in millimeters. Furthermore their method is applicable for sand size distributions, $f(\phi)$, which are reasonably well approximated by a so-called "lognormal" relationship, i.e.

$$f(\phi) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(\phi-\mu)^2/2\sigma^2} \quad (2)$$

in which μ and σ represent the mean and standard deviation respectively of the sand size distribution, both measured in ϕ units. Figure 2 is reproduced from Krumbein-James and portrays the distributions of two sands and their lognormal approximations which are straight lines on the arithmetic probability paper.

As stated previously, the K-J model requires that the retained portion of the borrow material have exactly the same distribution as the native material. This leads to definition of a "critical ϕ ratio", $R_{\phi \text{ crit}}$, which represents the required placed weight units of borrow material to result in one weight unit of "retained" material with

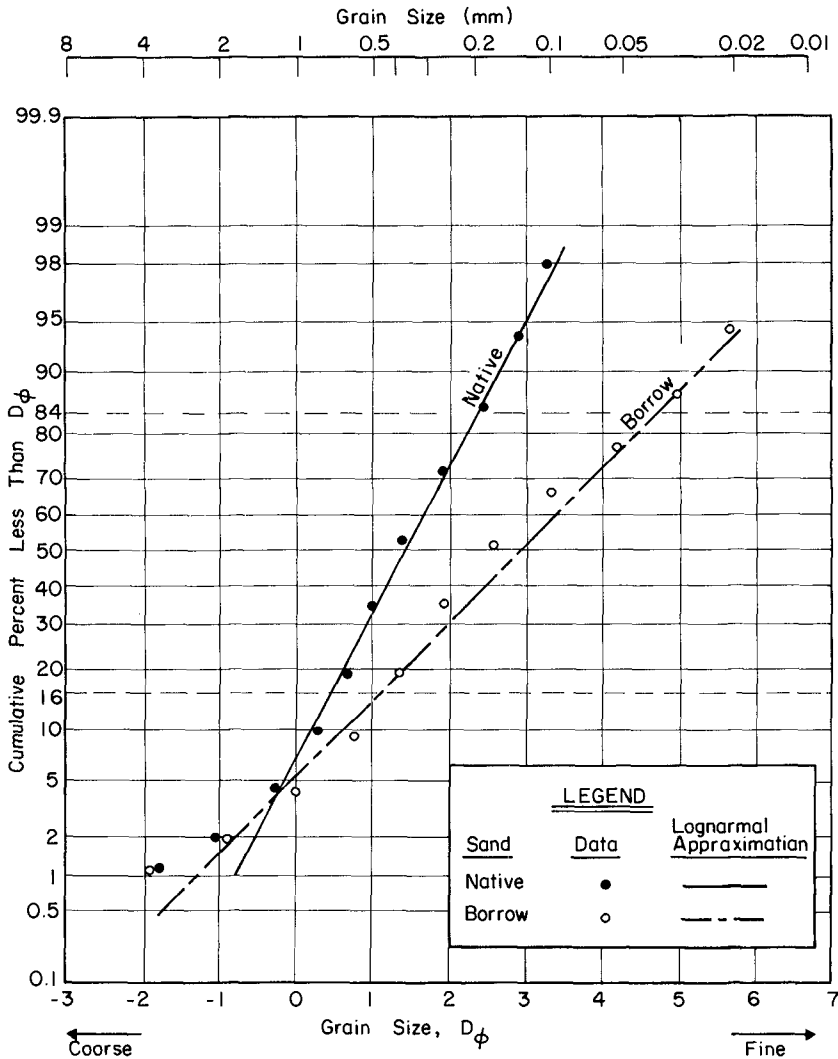


FIGURE 2 LOGNORMAL DISTRIBUTION APPROXIMATIONS TO NATIVE AND BORROW SANDS IN VIRGINIA BEACH, VIRGINIA NOURISHMENT PROJECT (FROM REFERENCE 5)

exactly the same distribution as the native material. This ratio can be shown to be

$$R_{\phi_{crit}} = \frac{\sigma_{\phi_b}}{\sigma_{\phi_n}} e^{-(\mu_{\phi_n} - \mu_{\phi_b}) / 2(\sigma_{\phi_n}^2 - \sigma_{\phi_b}^2)} \quad (3)$$

where the ϕ subscripts emphasize that μ and σ are in ϕ units. For the Virginia Beach, Virginia example presented in Figure 2, $R_{\phi_{crit}}$ is calculated to be

$$R_{\phi_{crit}} = 3.09$$

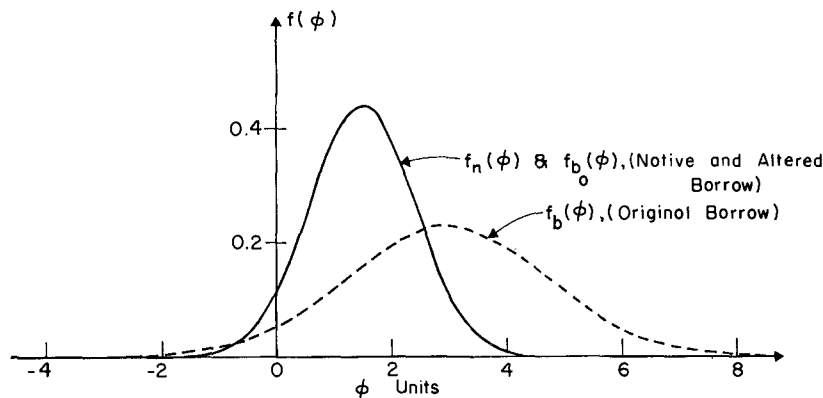
Figure 3 is a graphical presentation of the supposed effect on the borrow material to render it compatible with the native in accordance with the K-J method. It is noted that losses of the borrow material have occurred both in the coarse and fine fractions with the greater losses (for this case) in the finer components. The only diameter at which losses do not occur is at ϕ_{crit} where the original ratio of borrow to native distributions is 1:3.09. After the supposed losses occur, the ratio of retained borrow material to native material is 1:3.09 for all diameters. Of particular concern is the implied losses of the coarser fraction and this would be of greatest numerical significance in cases where the mean diameter of the borrow material (in millimeters) was greater than that of the native material. One of the objectives of the method to be described subsequently is to remove this unrealistic feature present in the K-J approach.

METHOD

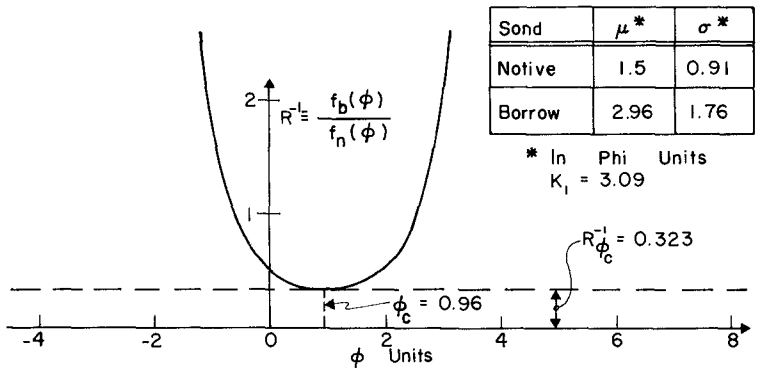
The required method must establish a realistic equivalence between the native material and the retained fraction of the borrow material. In particular, the method should allow for losing the fine fraction of the borrow that is not present in the native material; however, the coarser fraction in the borrow will be considered to be "compatible". In general, the compatibility will be based on equivalence of the mean diameter of the altered borrow and native sands. In the following a lognormal distribution of the form of Equation (2) will be considered. The reader is cautioned that the μ and σ variables are in ϕ units.

The native and original borrow size distributions will be denoted as $f_n(\phi)$ and $f_b(\phi)$ respectively and the "altered" borrow distribution as $f_{b_a}(\phi)$. The consideration that the finer fractions of the borrow material will not be "compatible", results in the altered size distribution being expressed as

$$f_{b_a}(\phi) = \begin{cases} Kf_b(\phi) & , \phi \leq \phi_* \\ 0 & , \phi > \phi_* \end{cases} \quad (4)$$



a.) Sand Size Distributions (Notive and Original and Altered Borrow)



b.) Ratio of Sand Size Distributions

← Coarse

Fine →

FIGURE 3 EXAMPLE OF KRUMBEIN-JAMES METHOD APPLIED TO THE VIRGINIA BEACH FILL ($\sigma_b > \sigma_n$)

where K and ϕ_* are constants selected such that $f_{b_a}(\phi)$ represents a normalized distribution with the same mean diameter as the native sand. The problem posed is in establishing K and ϕ_* for any given native and original borrow sand size characteristics and in interpreting the results in terms of the compatible fraction of the borrow sand.

The normalized distribution requirement is expressed as

$$\int_{-\infty}^{\infty} f_{b_a}(\phi) d\phi = K \int_{-\infty}^{\phi_*} f_b(\phi) d\phi = \frac{K}{\sigma_b \sqrt{2\pi}} \int_{-\infty}^{\phi_*} e^{-(\phi - \mu_b)^2 / 2\sigma_b^2} d\phi = 1 \quad (5)$$

and the requirement that the altered distribution mean diameter be at least as large as the native mean diameter is

$$\int_{-\infty}^{\infty} \phi f_{b_a}(\phi) d\phi \leq \mu_n$$

or

$$\frac{K}{\sigma_b \sqrt{2\pi}} \int_{-\infty}^{\phi_*} \phi e^{-(\phi - \mu_b)^2 / 2\sigma_b^2} d\phi \leq \mu_n \quad (6)$$

For a given situation of fixed borrow and native sand characteristics, Equations (5) and (6) are two relationships involving the two unknowns, K , and ϕ_* associated with the altered borrow distributions. These equations include three parameters (μ_n , μ_b , σ_b) characterizing the native and borrow sands. It is useful to reduce the number of parameters to two by introducing dimensionless quantities defined by

$$\phi' \equiv \frac{\phi}{\sigma_b}$$

$$\mu' \equiv \frac{\mu}{\sigma_b}$$

Equations (5) and (6) can be rewritten in terms of dimensionless quantities and integrated to yield

$$\frac{K}{2} [1 + \operatorname{erf}(\phi'_* - \mu'_b)] = 1 \quad (7)$$

$$\frac{K}{\sqrt{2\pi}} e^{-(\phi'_* - \mu'_b)^2 / 2} \geq \mu'_b - \mu'_n \quad (8)$$

where the error function "erf (x)" is defined as

$$\text{erf} (x) = \sqrt{\frac{2}{\pi}} \int_0^x e^{-t^2/2} dt$$

and t is a dummy variable of integration. It is noted that Equations (7) and (8) now involve only two dimensionless parameters, μ'_b and μ'_n characterizing the size distribution characteristics of the native and original borrow sands.

An iterative computer solution of Equations (7) and (8) was employed to determine K and ϕ_* for a fairly wide range of μ'_b and μ'_n . Although the parameter ϕ_* is determined in the solution, it is the quantity K that is of primary interest. It will be shown next that K represents the number of units of borrow material that must be placed in order to retain one unit of compatible fill.

Referring to Figure 4, the fraction of the original borrow material

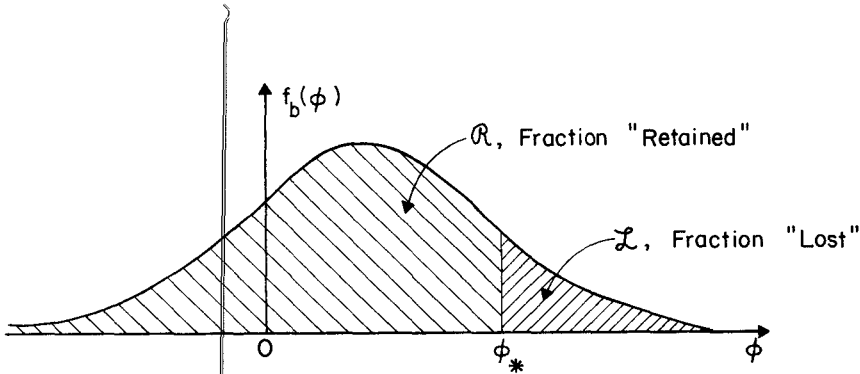


FIGURE 4 PORTIONS OF ORIGINAL BORROW MATERIAL "RETAINED" AND "LOST"

that is compatible with the native sand is defined as R , where

$$R \equiv \int_{-\infty}^{\phi_*} f_b(\phi) d\phi \quad (9)$$

but from Equation (5)

$$K \int_{-\infty}^{\phi^*} f_b(\phi) d\phi = 1 \quad (10)$$

These two equations establish the following reciprocal relationship between R and K , i.e.

$$R = \frac{1}{K} \quad (11)$$

Therefore, for a particular example in which the native and borrow sands result in a value $K = 4$, only 25% of the borrow material is compatible. Stated differently, for this example it would be necessary to place 4 units of borrow material on the beach to yield one unit of material compatible with the native sand. In general, the quantity K represents the number of units of borrow material placed on the beach that is required to yield one unit of material compatible with the native material.

Figure 5 presents isolines of K as a function of μ'_n and μ'_b . The semi-logarithmic plot was chosen as it was found that each of the isolines of K on the semi-log plot is simply a vertically-displaced form of any of the other isolines. For $\mu'_n > \mu'_b$ (i.e. the borrow material is coarser than the native), 100% of the borrow material is compatible by the criterion utilized in this paper. In the case where the borrow mean diameter is less than the native, Figure 5 provides a useful means of determining the compatibility.

EXAMPLES ILLUSTRATING APPLICATION OF THE METHOD

Example 1

Consider the case of the beach fill at Virginia Beach, Virginia. The native and borrow material characteristics have been presented by Krumbein and James(5) as presented in Figure 2; these characteristics are also given in Table I for reference. Using the Krumbein-James method,

TABLE I
SIZE CHARACTERISTICS OF THE VIRGINIA BEACH, VIRGINIA
NATIVE AND BORROW SANDS

Sand	μ^*	σ^*
Native	1.5	0.91
Borrow	2.96	1.76

* In Phi Units

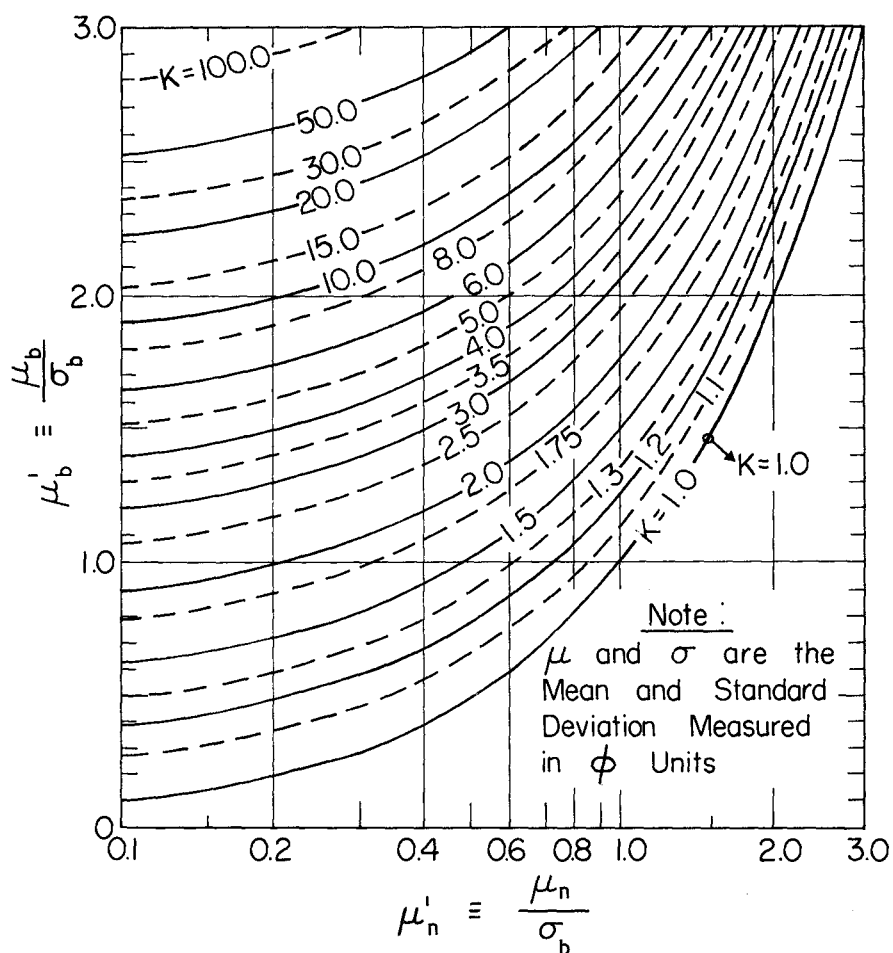


FIGURE 5 REQUIRED REPLACEMENT VOLUME, K , OF "BORROW" MATERIAL TO OBTAIN ONE UNIT OF "COMPATIBLE" BEACH MATERIAL

a required volume of 3.09 units of borrow material is indicated to retain one unit on the beach. For the method presented in this paper, a value of 2.05 is determined for K. It is recalled that the K-J method considers that portions of both the coarser and finer fractions are somehow winnowed out from the original material placed whereas the present method considers "losses" only from the finer fraction of the borrow material. These different considerations are primarily responsible for the spread from 2.05 to 3.09; differences of this magnitude could be important in evaluating the economic feasibility of a beach nourishment project.

Example 2

As a second example, consider the narrow beach north of St. Lucie Inlet, Florida (shown as the inset in Figure 6) and suppose that it is desired to consider two sand sources for possible fill purposes along the beach north of the inlet. The size characteristics of a sand sample taken from the beach face and degree of approximation by a lognormal distribution are presented in Figure 6. Figure 7 presents the lognormal distributions from two possible source areas in the inlet area. The table inset in Figure 7 presents the size characteristics of the native and borrow sands and the K values for the two borrow sands. It is seen that 1.4 units of Borrow "1" material would be required to result in one unit of compatible material; however, because the diameter of Borrow "2" material is greater (less in phi measure) than the native material, all this borrow material is compatible. If compatibility as defined in this paper were considered to be a measure of retention, these results would provide a good basis for evaluating the cost effectiveness of, for example, borrow sources which are more expensive on a unit volume basis but which possess better retention characteristics.

SUMMARY

A method has been presented for evaluating the compatibility of borrow material with the native sand on the beach. Compatibility as used here relates to that coarser fraction of the borrow material which has a mean diameter equal to or greater than the native material. The method also requires that the native and borrow sands be reasonably represented by a lognormal relationship and that the size characteristics of these sands be known. A single figure presents the number of units of borrow material required to yield one unit compatible with the native sand. Although the method does not address the important question of loss rate, it should be useful in providing a quantitative basis for evaluating various possible borrow areas for beach nourishment purposes.

ACKNOWLEDGEMENT

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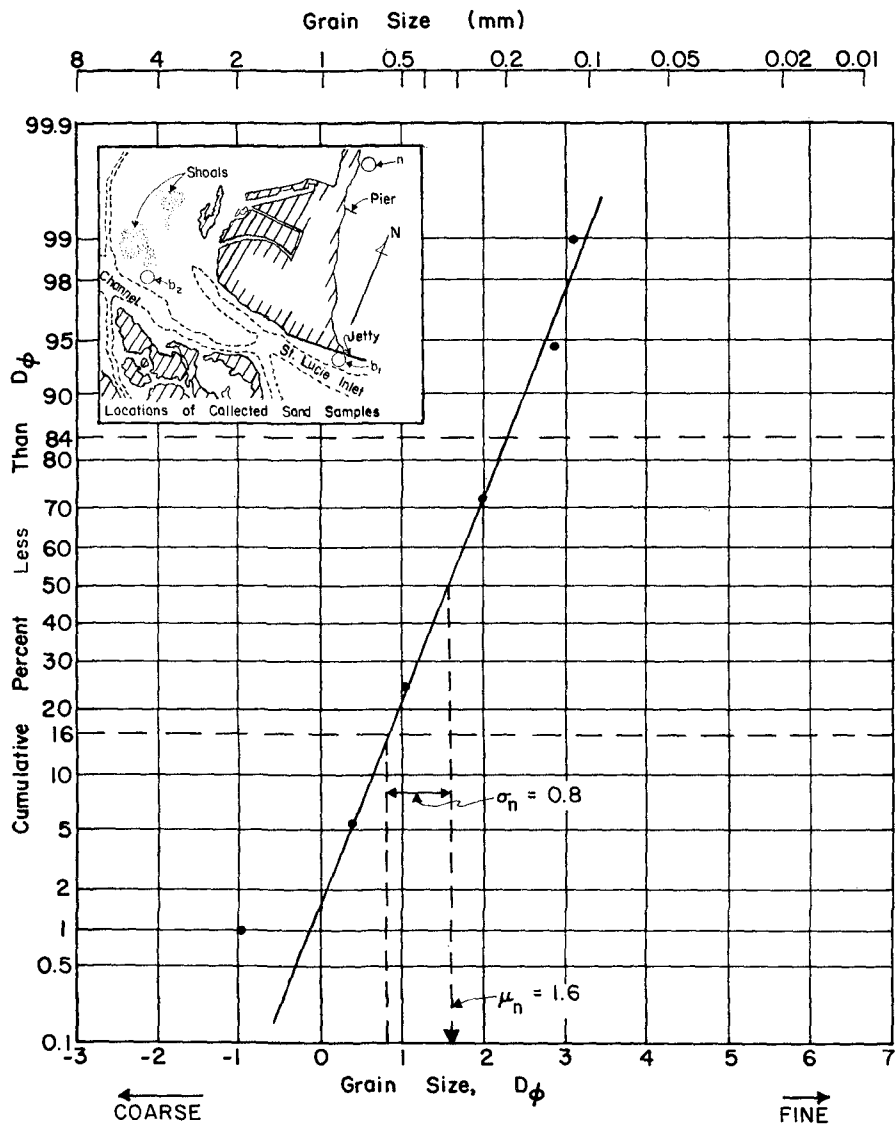


FIGURE 6 SAND SIZE DISTRIBUTION FOR "NATIVE" SAND NEAR ST. LUCIE INLET, FLORIDA

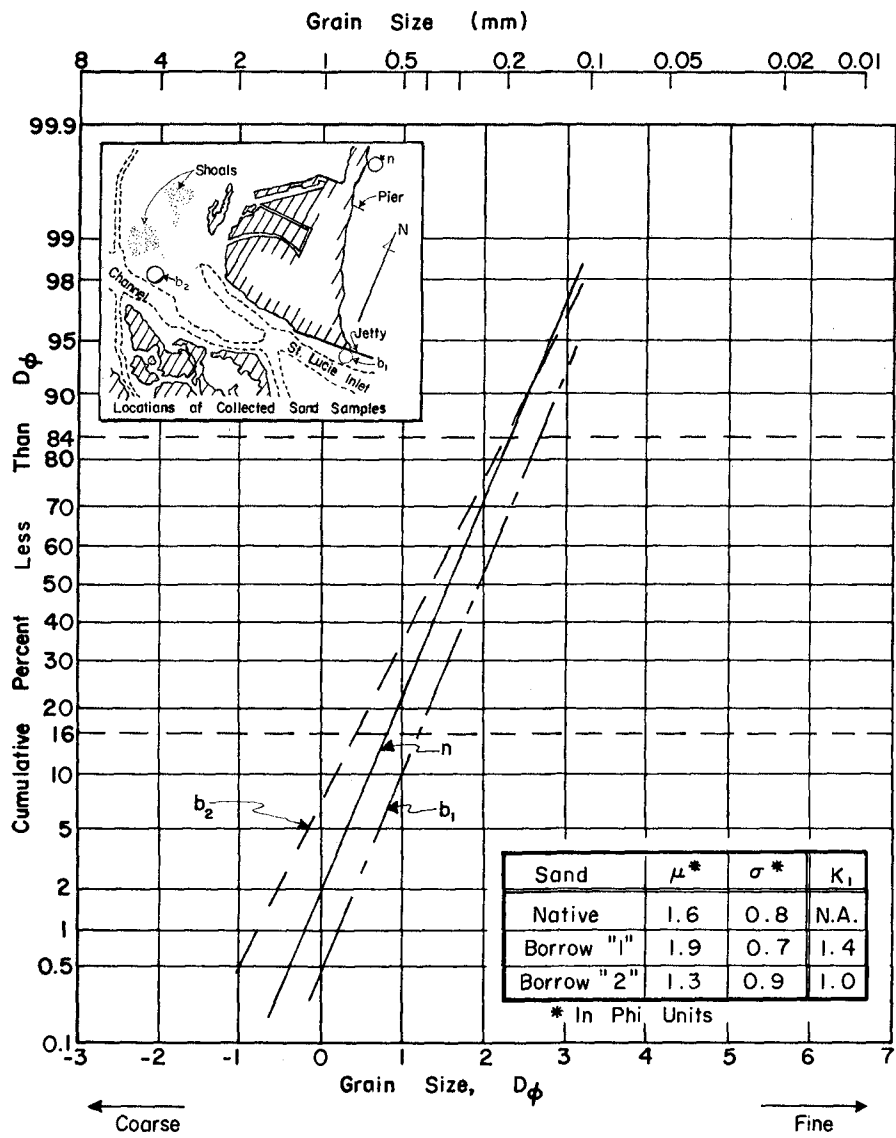


FIGURE 7 EVALUATION OF "COMPATIBILITY" OF TWO POSSIBLE BORROW MATERIALS WITH NATIVE BEACH SAND. AREA NEAR ST. LUCIE INLET, FLORIDA

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