U.S. Army Coast. Eng. Res. Ctr. TP

TP 77-6

Review of Design Elements for Beach-Fill Evaluation

by

R.D. Hobson

TECHNICAL PAPER NO. 77-6
JUNE 1977

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER TP 77-6	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REVIEW OF DESIGN ELEMENTS FOR BEACH-FILL EVALUATION		5. TYPE OF REPORT & PERIOD COVERED Technical Paper
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R.D. Hobson		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of the Army Coastal Engineering Research Center (CEREN-GE) Kingman Building, Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D31235
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army Coastal Engineering Research Center Kingman Building, Fort Belvoir, Virginia 22060		12. REPORT DATE June 1977
		13. NUMBER OF PAGES 51
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Beach fill
Beach nourishment
Erosion
Sediments
Shore protection
Waves

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Beach nourishment is one engineering alternative for combating coastal erosion and for providing shore protection against storm-produced waves and flooding. This study provides a summary and review of the following beach nourishment topics: (a) Analyzing and characterizing sediments, (b) sampling beaches and borrow sites, (c) calculating composite grain-size distributions, and (d) use of existing beach-fill schemes. State-of-the-art recommendations relating to these topics are provided at the conclusion of this report.

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PREFACE

This report is published to provide coastal engineers with a review of recent developments in and guidance for the selection of borrow material for beach restoration and periodic nourishment. The work was carried out under the coastal construction research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Dr. R.D. Hobson, under the general supervision of Dr. C.H. Everts, Chief, Geotechnical Engineering Branch, Engineering Development Division, CERC.

The author acknowledges the assistance of L. Vallianos and T. Jarrett, U.S. Army Engineer District, Wilmington, who provided the textural data incorporated in Appendix B. Dr. W.R. James, R. Rector, and S.J. Williams are also acknowledged for reviewing the draft of this report and providing many useful comments which improved both the style and technical content of the final report.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

REVIEW OF DESIGN ELEMENTS FOR BEACH-FILL EVALUATION

by
R.D. Hobson

I. INTRODUCTION

Nourishment of eroding beaches and the building of beaches for storm protection present important design problems to the coastal engineer. Over 50 percent of recent Federal shore protection projects call for beach fill and, in most cases, the fill material must be suitable for satisfying recreational demands as well as for defense against storms. The major expense of these projects is often in beach construction.

Situations calling for beach fill are neither new nor unique and historically, the coastal engineer has used his experience and intuition to select among the available fill materials. Intuition and experience cannot be discounted and it is not that intention here but during the past 20 years several "formalized" approaches to the beach-fill problem have been published (e.g., Dean, 1974; James, 1974, 1975). This study summarizes these approaches, explains their basic concepts, and shows, by example, their use and interpretation. These formalized beach-fill schemes are, by necessity, simplistic approaches to highly interactive systems in nature, and it should be emphasized that the schemes are intended to serve the engineer as additional tools rather than replacing existing tools.

A general systematic approach to a beach-fill problem might be as follows. An eroding beach requires nourishment, and to specify materials appropriate to that system, it is assumed that information must be obtained that characterizes the process-response relationships within the system; i.e., the sediment textures and geometric features (responses) of the beach reflect the waves and currents (processes) operative within that environment. Presumably, the study of one set of elements (process or response) will reveal the characteristics of the other set. However, the beach environment is highly complex and these process-response interactions are not well understood. Therefore, beach-fill schemes are generally formulated using a few response elements; namely, characteristics of the grain-size distributions of sediments found on the beach. These grain-size parameters are then used to compare beach sediments with available borrow materials to assess their beach-fill potential. The major point to be emphasized is that appropriate data must be obtained to characterize both existing beach sediments (*native composite* grain-size distributions) and potential borrow sediments (*borrow composite*) to effectively use any of the existing design methods.

This study reviews and summarizes the research in preparation and published on the following subjects: (a) Analyzing and characterizing sediments, (b) general aspects of sampling beaches and borrow sites, and (c) the calculation and use of composite grain-size distributions (gsd) within existing beach-fill schemes. The original referenced work should be consulted for broad background information.

Finally, one often confusing aspect of reading the referenced reports is the wide variety of names and symbols used for a few concepts and terms. James (1975) discusses this subject and tries to overcome the problem by arranging symbols and terminology in a table showing both previous usage and his usage in the report (Table 1 in James, 1975). This study follows James' guidelines whenever possible, and points out and documents those situations not included in his tabulation. The following listing provides a general perspective for reading the present study: (a) the phi notation (ϕ) is used to express sedimentary particle size; (b) the mean and sorting parameters used to describe particle gsd are the phi mean and phi sorting, regardless of the notation used; (c) subscripts, b and n, refer to characteristics of borrow site and native beach sediments, respectively; (d) fill factors are identified by a capital R subscripted by a letter that identifies the source of the particular factor; and (e) Greek letters identify characteristics of a "population" which are approximated, using "estimators" denoted by alphabetic symbols; e.g., the population mean, μ, is estimated by the sample mean, M; the sample sorting s, estimates the population sorting, σ.

II. DESCRIPTION OF SEDIMENTS

1. Classification.

Natural sediments are generally classified as sand, silt, etc., which indicate the dominant component of the particular sediment, and also imply an actual particle-size range as defined by one of several size classification schemes. The size schemes most commonly used by coastal engineers are the Unified Soils Classification and the Wentworth Classification (Table 1). These two classifications assign similar, but different size ranges (in millimeters) to each sediment category. For example, the total range of sand sizes is 0.074 to 4.76 millimeters for the Unified Soils scheme as opposed to 0.062 to 2 millimeters for the Wentworth. Because of these differences, communication problems can be encountered when it is not clear which classification is being used. The most useful size classification for this study is a logarithmic transformation (phi) of the Wentworth scale.

The Wentworth scale is essentially a geometric scale to the power of 2 with individual size classes defined as "twice as large or half as large" as some other class (Table 1). For example, sand ranges from 2 (2^1) to 0.062 millimeter (1/16 or 2^{-4}), boulder sizes start at 256 millimeters (2^8), and clay is finer than 0.0039 millimeter (2^{-8}). Natural beach sediments are generally composed of materials ranging downward from gravel (2 millimeters) to the silt sizes.

A common way of comparing different beach sands is to look at plots of the cumulative proportion (usually weight percent) of each sample coarser than a series of size classes. These plots tend to be fairly straight and steep in the less than 1-millimeter size classes, and then tend to "tail out" toward the coarser sizes (Fig. 1,a; Table 2). A group of plots for several beach sand samples might look similar even though there are important textural differences among the samples. This apparent similarity exists because these textural differences occur in the finer sizes

Table 1. Sediment-size classification schemes.

Unified Soils Classification			Wentworth Classification		
Size class	Class limits (mm)		Size class	Class limits (mm)	(phi)
		Gravel	Boulder		
				256.0	-8
Cobble			Cobble		
	76.0				
				64.0	-6
Coarse gravel					
			Pebble		
	19.0				
Fine gravel				4.0	-2
	4.76		Granule		
Coarse sand					
	2.0			2.0	-1
		Sand	Very coarse sand		
Medium sand				1.0	0
			Coarse sand		
				0.5	1
	0.42		Medium sand		
				0.25	2
Fine sand			Fine sand		
				0.125	3
	0.074		Very fine sand		
				0.062	4
Silt or clay			Silt		
				0.003	8
			Clay		
				0.0002	12
			Colloid		

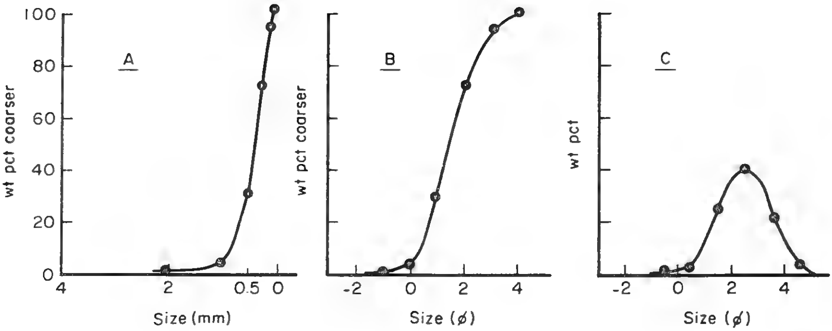


Figure 1. Size-frequency plots comparing millimeter and phi-size scales.

Table 2. Size-frequency data for Figure 1.

Millimeter range	Weight (pct)	Phi range	Cumulative (pct coarser)
1/32 to 1/16	0	5 to 4	100
1/16 to 1/8	6	4 to 3	94
1/8 to 1/4	22	3 to 2	72
1/4 to 1/2	42	2 to 1	30
1/2 to 1	26	1 to 0	4
1 to 2	3	0 to -1	1
2 to 4	1	-1 to -2	0

but actual construction of this kind of diagram tends to push these sizes together rather than accentuate them. One solution is to transform the geometric-size scale into an arithmetic scale, using logarithms to a base equal to the power (in this case 2) of the geometric scale. This is accomplished by the phi transformation introduced by Krumbein (1934, 1938) where

$$\phi = -\log_2 d(\mathrm{mm}) \quad . \tag{1}$$

See Krumbein (1957) and U.S. Army, Corps of Engineers, Coastal Engineering Research Center (1975) for tables for converting millimeters to phi. The differences in the shape of the gsd, using the phi-size scale, are shown in Figure 1(a and b). Figure 1(b) shows the ranges of finer grain sizes expanded so that their distribution is easier to see for comparison purposes. Also, a plot of the weight percent for each size class tends to be fairly symmetric about the most frequently occurring sizes when phi is used (Fig. 1,c).

The negative sign in equation (1) has the effect of giving positive phi values to finer sizes and negative phi's to the coarse sizes. This makes sense since most natural sediments do fall within the finer (positive phi) size grades but it does take some time to get used to thinking in phi terms where decreases in phi indicate increases in actual grain size. Another problem with the phi notation is that it is dimensionless and therefore inappropriate to use in certain circumstances such as the scaling of a modeling experiment; for that case, $d(\mathrm{mm}) = \mathrm{antilog}_e (\phi/ -1.4427)$. Despite these minor problems, the logarithmic phi transformation has the effect of changing many sediment-size distributions into essentially normal distributions; hence, the millimeter-size distribution is sometimes called *lognormal*. This lognormal property has several significant uses.

In this study, a phi normal curve is expressed as:

$$Y = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\left[\frac{(\phi - \mu)^2}{2\sigma^2}\right]} \quad , \tag{2}$$

where Y, the ordinate, is related to the weight percent in a size class containing phi, π and e are constants with respective approximate values of 3.1416 and 2.7183, and μ and σ are the phi mean and phi sorting (phi standard deviation) parameters of the distribution. This distribution has the familiar symmetrical "bell" shape (Figs. 1,c and 2) with a maximum frequency occurring at $\phi = \mu$ and inflection points at $\mu \pm \sigma$.

The properties of the normal curve are well known because of extensive use in statistics, and many of these properties can be adapted for describing sediments. Each combination of μ and σ values (eq. 2) defines one individual normal curve from a large family of possible normal curves. The curves in this family are similar in that all are symmetrical, and areas under each are the same for specific distances measured in σ units from

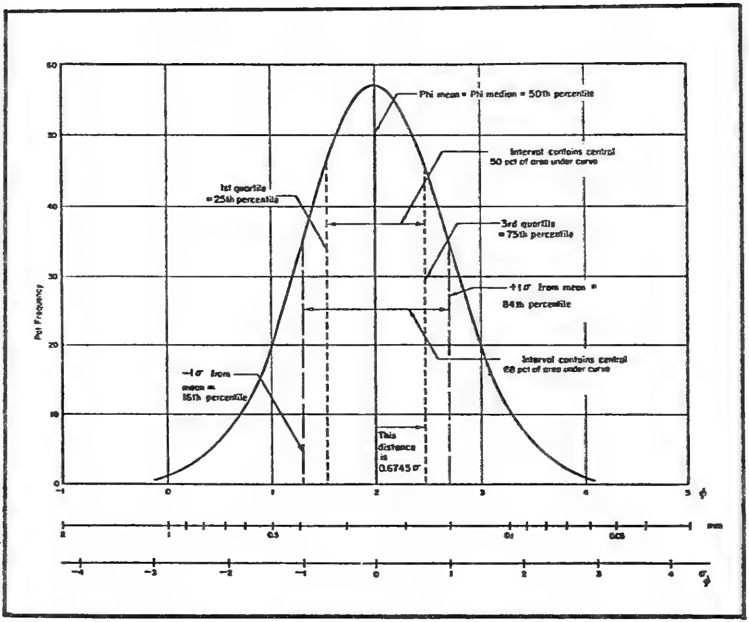


Figure 2. The normal curve (for μ = 2.0, σ = 0.70).

the mean (μ). Thus, σ can be used to measure both the spread of phi sizes under the distribution curve and the areas under the curve; e.g., 68 percent of the area under a normal curve lies between $\pm 1 \ \sigma$ from the mean, or between the 16th and 84th percentiles of the cumulative plot. These relationships can be adapted to describe sediment and one *estimate* of phi sorting (σ) commonly encountered is:

$$S = \frac{\phi_{84} - \phi_{16}}{2} \quad . \qquad (3)$$

If an actual distribution were completely symmetrical, the mean (μ) would be located at the 50th percentile phi size (ϕ_{50}) or be equal to the median size (Md). However, it is common practice to select an estimate of the mean that is statistically more efficient than the median as well as being less biased than the median for cases where the actual gsd is not completely symmetrical.

$$M = \frac{\phi_{84} + \phi_{16}}{2} \quad . \qquad (4)$$

For a symmetrical distribution, equation (4) will produce the same value as the median but for an asymmetrical distribution the mean estimate, M, is more reliable. Thus, S and M are probably the best estimates of σ and μ for describing unimodal sedimentary grain-size distributions (eqs. 3 and 4).

A common way to calculate these parameters, using a graphical technique, is shown in Figure 3. Here, the sample size data are plotted as a cumulative distribution on log (phi) probability paper in such a way that the phi and percent coordinates of a point on the curve indicate the percent of the sample coarser than that particular phi size. The sizes associated with the 84th and 16th percentiles may be interpreted directly from the plot and used to calculate M and S.

A sample that is lognormally distributed will appear as a straight line on phi probability paper. However, most sample distributions are somewhat asymmetric and their plots are not straight (Fig. 3). The degree of asymmetry, or nonnormality of the observed sample distribution, can then be determined by comparing this curve with a straight "approximation" curve which is constructed by drawing a straight line through the 84th and 16th percentile intercepts of the observed curve. The comparison can either be made qualitatively by noting the size of the "gap" between the curves along the phi size equal to the mean, or quantitatively by computing an estimate of the skewness parameter.

$$Sk = \frac{(M - Md)}{\sigma} \quad . \qquad (5)$$

In both cases, the difference between the mean and median sizes is reflected by the observed asymmetry. For example, a negative skewness exists when the observed distribution lengthens or tails out toward the coarser,

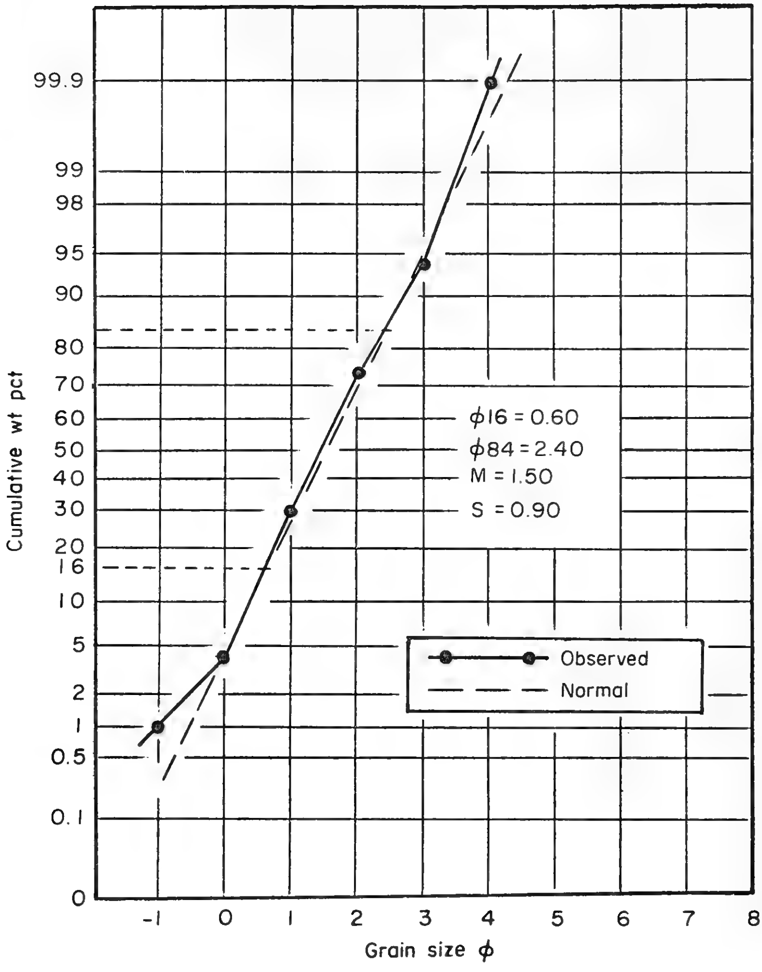


Figure 3. Cumulative size plot (data from Table 2).

negative phi sizes. In this case, the mean (center of gravity) is more affected by the long, coarse tail than by the position of the median. Positive skewness arises when the curve tails toward the finer, positive phi sizes.

Skewness differences are frequently used to compare sediment-size distributions; these comparisons can be quite effective, especially when the parameter is used within some multivariate analysis scheme. However, the skewness parameter is not as stable statistically as the mean and sorting parameters and small deviations from normality can result in fairly large skewness variations. Skewness values are not required for the calculations considered in this study. However, a value of plotting cumulative phi-size distribution curves on probability paper is that strong deviations from normality are easily spotted, preventing unwarranted use of methods to be discussed later.

2. Sieving versus Settling.

Grain-size frequency data are usually obtained using either sieving or settling techniques. For sieving, a dried sample of known weight is mechanically shaken through a nest of size-graded, wire-mesh sieves and the data obtained are the weights of sample retained on each sieve. These weights are then usually converted to weight percents for calculation purposes. For sand, the dried sample weight should not exceed 50 grams for standard 8-inch-diameter sieves and this amount of sample should be obtained by randomly splitting the original bulk sample. The sieves should be graded in equal phi intervals with a preferred interval of one-half phi (Table 3), and the shaking time should be at least 15 minutes. Weight percent loss or gain during analysis should not exceed a few percent. Weights need only be measured to the nearest tenth of a gram. Old sieves with screens that are stretched or have holes and clogged sieves are the major sources of analytical errors associated with sieving.

With settling, a small amount of sample is allowed to fall through a water column of known length and is either caught and weighed on a microbalance at the bottom of the column, or the change in pressure at the base of the column is measured as the sediment falls through the fluid. Changes in weight or pressure, with respect to time, can be converted to weight percent data using fall velocity equations for the size range of particles involved. Some common problems associated with this technique are: (a) Failure of the fall velocity equations to account for the effects of varied particle shapes and densities, interference of falling particles with each other, and water turbulence; (b) drag interference between the cylinder walls and the settling particles; (c) the divergent difficulties of accurately timing the rapid fall of larger particles and the longtime periods required to settle fine particles; and (d) various problems associated with introducing the sediment into the fluid.

Which size-analysis technique is preferable? The settling method where particles interact with a fluid is probably more analogous to real environmental conditions than sieving. Settling techniques are also

Table 3. Standard sieve nest.

Opening (mm)	Size (phi)	Mesh	Wentworth Classification
2.83	-1.5	7	
2.00	-1.0	10	Gravel
1.41	-0.5	14	
1.00	0.0	18	Very coarse sand
0.71	0.5	25	
0.50	1.0	35	Coarse sand
0.35	1.5	45	
0.25	2.0	60	Medium sand
0.177	2.5	100	
0.125	3.0	120	Fine sand
0.088	3.5	170	
0.062	4.0	230	Very fine sand

usually faster than sieving. Sieving equipment is simple and generally reliable whereas the settling tube and auxiliary electronic equipment are complex and extremely delicate. For practical beach engineering problems, sieve data are probably the most reliable and the most reproducible, especially among different laboratories. Therefore, if there is an option, sieving data are preferable over settling data. It is also important that the data from the two techniques *are not mixed* because conversion equations are not too powerful.

III. SAMPLING

1. Basic Considerations.

The basic question concerning the design of a sediment sampling plan for beach-fill purposes is "what are the composite grain-size characteristics of both the native beach and the potential borrow sites?" The sediment grain-size (textural) characteristics for the beach can be expected to vary (a) across the beach profile through the varied energy zones, (b) along the beach within any one energy zone, (c) at depth within the sediment "envelope" on the active profile, and (d) between seasons within the three-dimensional geometry of the beach. The composite gsd for the beach should be a single-size distribution that reflects these four components of textural variability; the approach would be to collect a sufficient number of samples to accurately describe the "target" native beach grain-size composite distribution. A similar approach to sampling would be taken for characterizing the target borrow site composite. Many borrow site areas are "relict" in the sense that the processes which originally developed the geological characteristics of the sedimentary body are no longer active. For example, several feet of modern fine sediments might overlie an ancient shoal area containing relict coarse sediment. In this case, the seasonal component of textural variation need not be considered in the sampling scheme.

2. Beach Sampling.

Fixed rules for beach sampling will probably never exist because each beach presents unique characteristics. General sampling guidelines can be established, however, when sufficient data are available describing the four components of textural variability. Although presently there are not enough core samples to describe the depth component, these samples are being collected. Some good data exist that describe the other three components of textural variation and the patterns from some of these data will be discussed to set up suggested temporary sampling guidelines.

Figure 4 summarizes several textural relationships common to most beach data. Individual samples and various composite samples are compared on this plot with a grand composite of 64 beach samples. Eight samples were collected from each of four ranges at Pt. Mugu, California, in November and May 1970; sample positions along the ranges were determined by elevation. November is considered here to reflect the culmination of "summer" conditions and May the "winter". The figure is constructed so

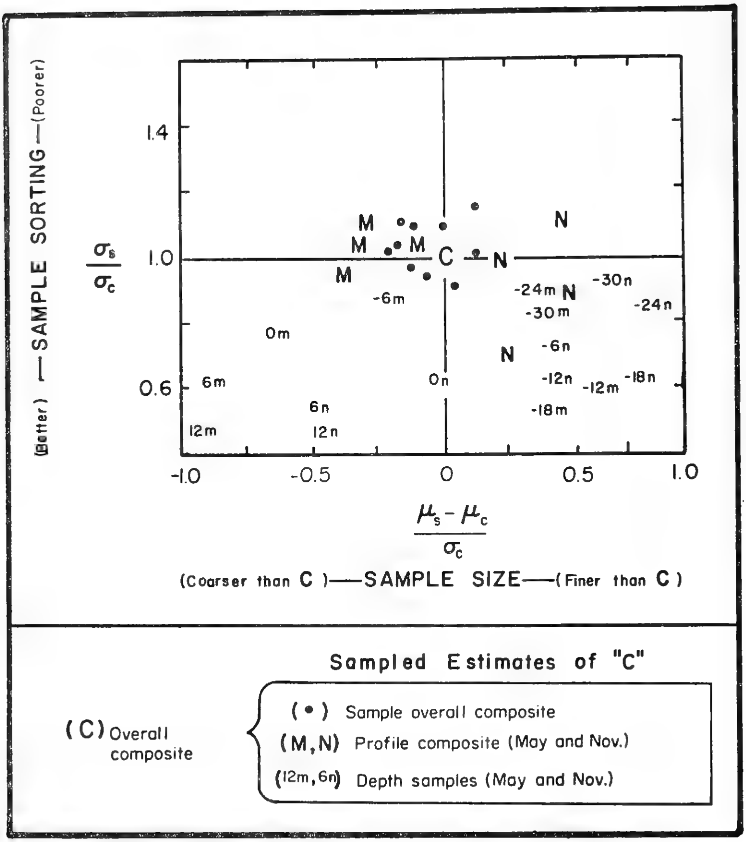


Figure 4. Comparison of overall composite (C) with seasonal profile composites (M and N), sampled composites (∘), and depth samples, Pt. Mugu, California; subscripts *s* and *c* identify samples and overall composite.

samples (subscript *s*) can be compared with the overall composite (subscript *c*) in terms of phi sorting on the ordinate and the scaled difference between phi means on the abscissa. These axes are the same as those used to plot overfill ratio curves in the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975, Fig. 5-3) and are used on several other figures in this study. A point falling in the lower right quadrant means that the sample is finer and better sorted than the grand composite; a point in the upper left quadrant shows the sample is coarser grained and more poorly sorted.

Several trends are apparent in Figure 4. First, samples taken from high on the foreshore (+12 feet) and extending offshore to -30 feet (-9.1 meters) mean sea level (MSL) become, as expected, progressively finer grained; the samples are best sorted on the high foreshore and in the moderately deep offshore regions. These relationships hold true for samples from both May and November. Secondly, the May (end of winter) samples are generally coarser on the upper foreshore and near offshore parts of the beach than the November samples, but the samples from both months are similar farther offshore. These relationships are further reflected by the plots of the four range composites where the May plots (M) are coarser and more poorly sorted than the November points (N), and thirdly, the scattering of the M's and N's show the variability between the ranges. These trends support well-known process-response relationships where coarser and more poorly sorted sediments generally indicate higher energy conditions such as those occurring in the wave-dominated nearshore, or after a stormy winter season. Although these relationships are generally known, it is important that sampling be designed to include these expected variations in texture. For example, the dots on Figure 4 represent composite estimates of C which cluster around C because they include samples selected from both May and November. The problem remaining is to determine the magnitude of textural variation contributed by these three components (across profile, along beach, and seasonal) to decide upon the optimum number of samples needed to estimate each component. Table 4 is useful in solving this problem.

Table 4 shows the phi mean values of the 64 samples from Pt. Mugu used for Figure 4, along with average mean values per profile and per elevation for both May and November, plus grand means, and standard errors of the mean for all profiles and elevations. Table 4 also shows that the greatest variation in grain size occurs at different elevations along the profiles and that little variation occurs between profiles. There is a pronounced size difference between summer (November) and winter (May). The ranges are so similar for each month sampled that probably only one or two ranges would have been sufficient to characterize this beach which is fairly consistent along its length in terms of width, slope, and offshore topography. A plan for additional sampling might call for two ranges to be sampled at eight elevations for each season, or current investigations of the depth component of textural variation may indicate that core samples obtained during one season alone will be sufficient to describe the composite character of all sediments actively affected by beach processes.

Table 4. Phi means, variances, and standard errors from four profiles at Pt. Mugu, California, 1970.

Elevation (ft)	Profile 1	Profile 2	Profile 3	Profile 4	Elevation avg. (ft)
May 1970					
12	1.21	1.49	1.61	1.55	1.46
6	1.79	1.44	1.24	1.45	1.48
0	1.31	0.89	1.29	1.27	1.19
-6	2.01	2.00	1.35	1.28	1.66
-12	2.38	2.76	2.51	2.45	2.52
-18	2.79	2.88	2.37	2.36	2.60
-24	2.26	2.35	2.58	2.78	2.49
-30	1.32	2.55	2.65	2.80	2.33
Profile avg.	1.88	2.04	1.95	1.99	$S^2 = 0.33$
	$S^2 = 0.005$		$S_x = 0.034$		$S_x = 0.20$
Grand phi mean = 1.96					
November 1970					
12	1.89	1.63	2.02	2.00	1.88
6	1.61	1.95	1.97	2.02	1.88
0	2.19	2.10	2.29	2.28	2.21
-6	2.57	2.74	2.76	1.98	2.51
-12	2.91	2.48	2.59	2.45	2.60
-18	2.74	2.95	2.78	2.75	2.80
-24	3.07	2.72	2.95	2.49	2.80
-30	2.16	2.77	3.0	2.99	2.73
Profile avg.	2.39	2.41	2.54	2.37	$S^2 = 0.15$
	$S^2 = 0.006$		$S_x = 0.038$		$S_x = 0.14$
Grand phi mean = 2.42					

Table 5 is constructed like Table 4 but for sediment samples collected in May and December 1968 at Newport Beach, California. The squares of the standard error of the mean ratios indicate that the variation in mean grain sizes is about three to six times greater along profiles than between profiles, and there is a smaller difference between seasonal means than for the Pt. Mugu example (Table 4). Data obtained either in October or November at Newport Beach would have probably been more representative of the "summer" condition, and would show greater differences with May than do the December data. The variation between profiles is much greater at Newport Beach than at Pt. Mugu.

Tables 4 and 5 indicate that more samples are needed to determine the across-profile component of variability than needed for the along-beach component but how many more? Using squared standard error ratios, the answer to this need appears to be from 3 to 35 times as many samples. The lower values could be applied to beaches of fairly regular topography with perhaps eight samples collected along each of four profiles twice a year (64 samples); a greater number of profiles would be required for beaches of more irregular topography. Until the expected magnitudes of all four components of variability have been analyzed, a conservative approach would be to use the coarser (usually winter) composite for beach-fill calculations.

3. Borrow Site Sampling.

Sediments suitable for beach nourishment have been traditionally obtained from land and estuarine sources. Offshore sources have increased in importance as land-derived materials become scarcer and because lagoonal materials are often too fine grained or unavailable due to environmental constraints. Regardless of type, the suitability of a potential borrow deposit must be determined by sampling according to a plan that reflects both geometric and genetic aspects of the deposit. These constraints often result in sampling schemes as varied as the borrow sites. Random or regular core sampling on a grid might be appropriate for characterizing a sand deposit of unknown geometry whereas a grid-sampling plan would be inadequate for evaluating a sinuous offshore deposit. The points to be made are that the composite characteristics of the borrow material must be as representative as the beach composite to predict a fill's performance and, that care must be taken to design an adequate sampling plan. Also, any additional information such as seismic reflection surveys or topographic expression of the sea floor should be used in evaluating a potential borrow deposit.

Figure 5 shows kinds of sites requiring different sampling procedures. A potential offshore region of interest (Fig. 5,a) is defined by general, shore-parallel boundaries. The position of the seaward boundary is determined by the maximum water depth (D_2) in which a modern dredge can operate, or the farthest distance offshore that pipeline pumping is feasible or sand-hauling economic. Environmental considerations or physical constraints such as wave climate or the maximum depth to which beach processes operate might determine the location of the nearshore boundary (D_1). This region of interest between D_1 and D_2 could be sampled according

Table 5. Phi means, variances, and standard errors from seven profiles at Newport Beach, California, 1968.

Elevation (ft)	Profile 1	2	3	4	5	6	7	Elevation avg. (ft)
May 1968								
12	1.93	1.47	1.33	1.36	1.46	1.25	1.68	1.49
6	2.12	1.75	1.25	1.33	1.37	1.49	2.05	1.62
0	1.81	1.41	0.81	1.02	0.83	1.35	1.88	1.30
-6	2.52	2.51	2.09	0.89	1.64	1.96	2.36	1.99
-12	2.73	2.90	1.98	2.58	2.87	3.49	2.45	2.71
-18	3.16	3.10	3.11	3.00	3.03	3.13	3.08	3.08
-24	3.21	3.95	3.50	1.72	2.96	0.97	3.09	2.77
-30	4.24	4.09	1.63	2.65	3.10	2.66	3.15	3.07
Profile avg.	2.71	2.64	1.96	1.81	2.15	2.08	2.46	$S^2 = 0.72$
		$S^2 = 0.12$		$S_{\bar{x}} = 0.13$				$S_{\bar{x}} = 0.30$
Grand phi mean = 2.25								
December 1968								
12	1.45	1.20	1.26	1.26	1.37	1.30	2.00	1.40
6	1.57	1.34	1.66	1.28	1.36	1.29	1.85	1.47
0	1.62	1.22	1.33	1.33	1.04	0.97	1.14	1.23
-6	2.04	2.26	1.81	1.78	2.34	2.18	2.59	2.10
-12	3.06	2.82	0.31	0.32	3.04	2.54	2.85	2.13
-18	3.07	3.11	1.70	1.61	1.84	3.01	3.01	2.47
-24	3.00	3.49	2.19	3.15	0.84	2.78	3.07	2.64
-30	3.00	4.16	4.16	2.27	3.35	2.13	3.12	3.17
Profile avg.	2.35	2.45	1.80	1.62	1.89	2.02	2.45	$S^2 = 0.46$
		$S^2 = 0.11$		$S_{\bar{x}} = 0.13$				$S_{\bar{x}} = 0.24$
Grand phi mean = 2.08								

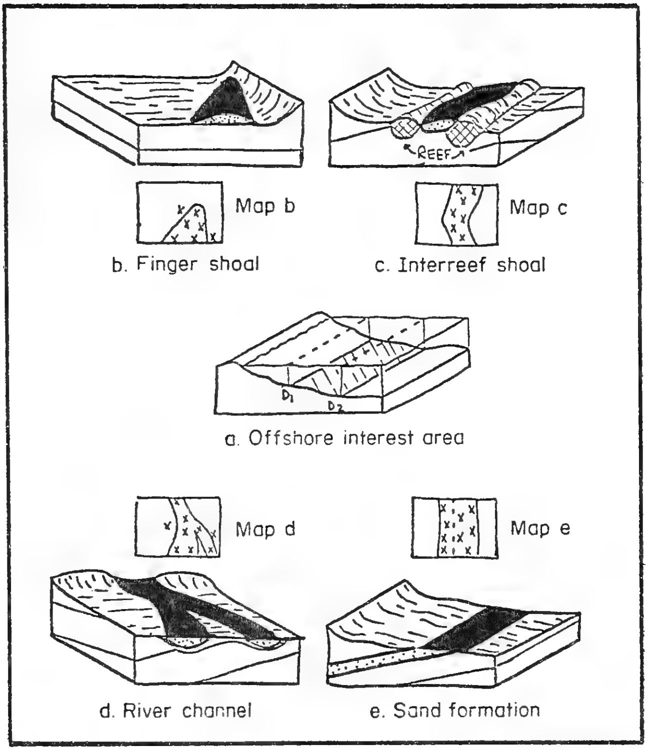


Figure 5. Four types of potential offshore borrow sites in an offshore interest area. (Solid (dark) areas in cross section show potential fill deposits.)

to a grid pattern or according to the geometry of known deposits. Examples of various sand bodies with offshore borrow potential are also shown in Figure 5(b to e). Each sand body requires a different sampling scheme as shown by the x's on the insert maps. These kinds of deposits in nature might also be covered by an overburden of modern fine-grained sediments and thus require seismic reflection or side-scan Sonar data to delineate the bodies in three dimensions.

Characterizing finger shoal sediments (Fig. 5,b) would require a lenticular sampling pattern that defines the boundaries of the body and surveys the textural variations of the shoal sediments. From an interreef shoal (Fig. 5,c) only those parts where a dredge could operate without damage to the cutter head from the reef rock should be core-sampled. The distribution of offshore ancestral river channel deposits would be controlled by the ancient drainage network (Fig. 5,d), whereas dipping sandy strata (Fig. 5,e) would only be sampled to the depth reachable by a dredge or where undesirable overburden is not excessively thick.

Cores rather than surface samples are usually collected to evaluate the composite texture of a borrow source and to estimate the potential volume of suitable sand in the body. Vibratory-type coring devices are usually used and although cores up to 40 feet (12.2 meters) in length can be recovered with this kind of equipment, the cores generally obtained range from 10 to 20 feet (3.0 to 6.1 meters) in length; thus, all dredgable parts of a sandy body might not be sampled. Seismic profiles showing sand-body thickness can be used to obtain data for calculating the volume of sediments in a body where dredge depth capability exceeds the cored limit, but the samples that are recovered must be used to estimate the textural composite for the entire body.

Once the cores have been obtained, the problem becomes the method of sampling them. Here, as in most aspects of a beach-fill problem, engineering judgment and experience become important. In a typical situation, 2 to 6 feet (0.6 to 1.8 meters) of fine silt and clay might overlie a sandy deposit that contains thin lenses of fine-grained sediment. Physical properties of the sand indicate suitability for beach fill, and it is dredged and placed by pumping onto the high foreshore of the project beach. The engineer knows that the silt and clay will not be stable in the beach environment, that much of the fine sediment will be re-suspended and lost during dredging, and that most of the remaining fines could be washed seaward beyond the active limit and lost during placement. For this case, only those parts of the cores suitable as beach fill should be sampled and analyzed. Care should be taken that the core samples are proportionally representative of the suitable materials encountered in the cores. Several sampling schemes might be chosen for this example. A composite sample could be "mixed" from: (a) samples collected at equal intervals along the core, (b) a channel or continuous sample, or (c) samples from each unique layer within the core and then "weighted" as to the thickness each represents. Perhaps, the first scheme where subsamples are collected at regular intervals would be preferable to a continuous sample because these individual samples could be easily stored and re-examined if necessary.

An engineer might be required for physical or economic reasons to select a borrow source that contains more fine sediment than is expected to be lost during dredging and placement, and a dike and fill approach might be necessary to rebuild the beach. In this case, some of the fines would still be lost during dredging but much of this material would end up as beach fill. In this case, the subsamples taken from the cores should include "reasonable" proportions of the fine-grained layers to reflect construction procedures used. A reasonable proportion would have to be determined from the engineer's experience with the equipment and techniques to be used rather than from a "cookbook" on beach fill.

4. Composite Samples.

A wide variety of size gradations across the active beach surface can be expected. Fine-grained, well-sorted sediments are typical of deepwater offshore areas, whereas coarse poorly sorted, and medium-grained well-sorted sediments are generally found near the plunge zone and backshore, respectively. A suite of samples from a densely sampled beach profile can be expected to show a nearly continuous sediment-size gradation from coarsest to finest, and the frequency plot of all samples combined would plot close to a straight line on log probability paper. These expectations have not been proven rigorously, but practical experience has shown them to be essentially true.

The beach-fill models discussed in this study indicate that beach processes will actively sort and transport the various size components of a fill into compatible environments. Thus, fill materials initially placed on the foreshore are expected to be quickly re-distributed across the entire active beach profile into a pattern as similar as possible to that of the native sediments. Sediments finer than the native sediments will probably be transported from the system; coarser sediments will remain and somewhat modify the system. Predicting the response of a particular fill involves comparing the textural properties of the native beach and fill sediments and requires accurate estimates of the overall or composite textural properties of these sediments.

The easiest and probably best method of determining the composite properties of a representative suite of beach or borrow site samples is to total the percentage of sediment in each size interval for all of the samples, then divide these totals by the number of samples. This gives an average-size distribution which can be plotted on log probability paper to determine phi mean and phi sorting. This approach is appropriate if the suites of samples are collected according to an adequately designed sampling program.

Figure 6 qualitatively shows the formation of a composite distribution from four beach sand samples collected at equal elevation intervals along a profile. The actual calculations for the composite are in Table 6. The coarsest, most poorly sorted sediments are found near the plunge zone (Table 6, sample 2) and they become finer and better sorted offshore and onshore, respectively. The composite gsd is represented by the dashed curve (C in Fig. 6) which is more poorly sorted than any of the individual sample

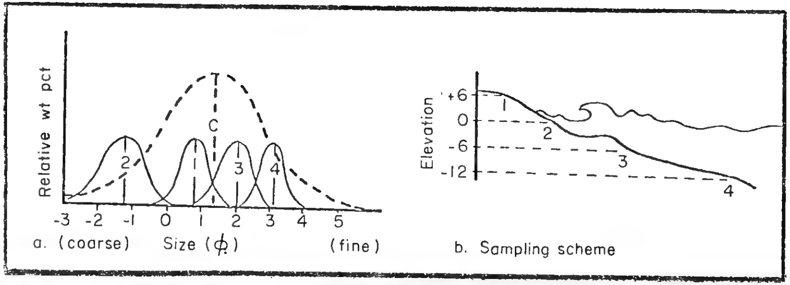


Figure 6. Diagrammatic relationships between sample-size distribution and computed composite distribution (a), and elevation-controlled sampling plan along profile (b).

Table 6. Cumulative weight percents (coarser than phi size) for the four samples from Figure 6(b) and the computed composite distribution.

			Phi sizes														
Sample	Mean	Sorting	-2.0	-1.5	-1.0	-0.5	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
1	0.80	0.40				0.1	3.5	27.0	73.0	96.5	99.9						
2	-0.25	0.65	0.4	2.5	12.0	34.0	64.0	87.0	97.5	99.6	99.9						
3	2.00	0.50						0.1	2.0	16.0	50.0	86.0	98.2	99.9			
4	3.10	0.4									0.3	8.0	44.0	86.0	99.0	99.9	
Averaged composite	1.40	1.50	0.1	0.6	3.0	8.5	16.9	28.5	43.1	53.0	62.5	73.5	85.6	96.5	99.8	99.9	

distributions. This is an important property of composites often misunderstood. These distributions must encompass the entire range of sizes encountered, and their sorting *is not* simply the average sorting of the samples. The graphical composite mean is about equal to the averaged sample mean (1.41 versus 1.40 for the composite), but the graphical composite sorting is much greater than the averaged sample sorting (0.49 averaged versus 1.50 for the composite). Figure 4 also reflects this relationship where the sorting of each individual sample is less than for the overall and sampled composites.

In general, a composite of 20 or more beach samples will tend to plot as a relatively straight line on log probability paper. The degree of log normality can be quickly checked by comparing the fit of the plotted curve with a straight line drawn through the 16th and 84th percentile intersections. Often, a composite curve will tend to straighten out when more samples per profile or more profiles are added, and when a smaller phi interval is used during analysis. It is best to *use a constant phi interval*; for most purposes, *an interval of one-half phi is usually adequate* (Table 3).

An alternative method for obtaining a *computed composite* is presented by Krumbein (1957). He assumes that the samples are nearly equally sorted and vary in phi mean grain size with coarse and fine extremes labeled M_b and M_a, respectively. In this approach, the composite phi mean, M_c, and variance, σ_c^2, are computed as follows:

$$M_c = \frac{M_a + M_b}{2} \quad , \tag{6}$$

$$\sigma_c^2 = \sigma_a^2 + \frac{(M_b - M_a)^2}{12} \quad , \tag{7}$$

where σ_a^2 is the average squared sample sorting. For the data in Table 6, σ_a^2 is 0.25, M_c is 1.43, and σ_c is 1.18. This approach might be followed in cases where the original size percentage data are unavailable or where a beach has been lost by erosion and the "native beach" data consist of mean sizes and sortings that seem most probable, considering the processes present. However, *a composite distribution obtained by averaging is preferable to a computed composite*. The averaging approach is less affected by extreme values and with its use, no assumption is made regarding the equal sorting of the samples.

The same techniques are used for calculating the composite-size distribution for both borrow site and native beach sediments. The sampling plan should be tailored to the characteristics of each borrow area but the concept of the composite remains the same. The quality of any beach-fill calculations is at best, only as good as the native beach and borrow site composites.

Finally, in concept, the averaging of individual sample size frequencies is equivalent to mixing parts of the actual samples and then doing a single-size analysis of the mixture. Care must be taken in the laboratory to obtain random splits of appropriate size from the samples. These splits must be mixed completely to eliminate bias in obtaining the final sample of the mixture to be analyzed. Sample splits of equal weight are generally mixed if the samples are collected to represent equal parts of the beach or borrow site. Splits of unequal size would be appropriate when a sampling plan requires a weighting factor. The major benefit of mixing samples is the reduction of laboratory time and expense for analysis. For example, two independent mixings of the 8 samples over each of five profiles would require the sieving of 10 samples instead of 40 and would allow evaluation of laboratory errors associated with the mixing process. There are important drawbacks to this approach as well. Perhaps, for engineering reasons it might seem reasonable to omit all samples collected at the -30-foot (-9.1 meters) depth or to ignore samples obtained in a particular part of a borrow area. In these cases and many others, the initial sample mixtures might be inappropriate for later requirements. Foresight and planning can avoid such problems or, at worst, splits from the original samples can be remixed and analyzed to suit future needs. The potential savings in sediment analysis that may result from mixing samples warrant the consideration of this procedure in most situations.

Appendix A provides an additional discussion of mixing sand samples for composite analysis and an example of the different procedures for obtaining the composite. The results of the experiment in the appendix show that similar composite characteristics are obtained using either mixing or nonmixing methods.

IV. BEACH-FILL MODELS

1. Basic Types.

Two basic types of mathematical models have been proposed to handle beach-fill problems. The first model enables calculation of a *fill factor* which is an estimate of the volume of a specific fill material needed to create a unit volume of native beach material. In most cases, fill factors exceed one, indicating that the particular borrow material is less than ideal and that winnowing processes will selectively remove unsuitable parts from the fill until it becomes compatible with existing beach sediments. The second model enables calculation of a *renourishment factor* which is used to estimate how often placement of a particular fill will be required to maintain specific beach dimensions. In all, three "fill factor" and one "renourishment factor" approaches have been published (Krumbein and James, 1965; Dean, 1974; James, 1974, 1975). James (1975) provides a more detailed and formalized discussion of the four methods.

These methods are based on simplistic models of the extremely complex, interactive littoral zone system. Each uses composite mean and sorting values of the native and borrow materials as basic input. Thus, at best their predictions can only be as good as the basic composite data used. Fill factors and renourishment factors can be useful and revealing calculations, and powerful tools when considered within the entire engineering framework of a problem.

2. Fill Factors.

Krumbein and James (1965) proposed the fill factor approach discussed in Chapter 5 of the SPM (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975); the other two methods were proposed by Dean (1974) and James (1975). The mathematical models underlying the three methods are similar, and although the ratios are not the same, each approach uses many of the same assumptions:

(a) Native sedimentary materials found on a beach are considered to be the most stable for the environment.

(b) The entire volume of fill materials placed on a beach is sorted by local processes to achieve a gsd similar to the native material.

(c) Sorting processes change the fill materials into native-like sediments by winnowing out a *minimum* amount of the original fill.

(d) For calculation purposes, the native and borrow grain-size composites are assumed to be normally distributed.

These common assumptions may be questioned at times; e.g., does the native composite from an eroding beach reflect the stable condition for that environment? This composite usually indicates what materials are being selected by the processes distinctive to that environment. However, if erosion dominates in a system because not enough sediments are being supplied by littoral processes, then perhaps a renourishment approach would be more appropriate than using a fill factor approach. Another challenge to the assumptions could be that the composite distribution for many borrow sites, e.g., a finger shoal, can be expected to be normal. Often this assumption is justified, considering that the composite distributions for many well-sampled deposits do tend to be normal. If a site is sampled, its composite characteristics can be used with these methods, and significant departures from normality (e.g., some bimodal glacial deposits) should be considered in the evaluation of the actual calculated values. Another challenge might be, why assume that all of the fill placed will be sorted? This challenge may be justified for some situations, but using the conservative approach is probably best if no contrary information exists. In conclusion, although the assumptions seem to be legitimate and realistic working postulates for many situations, they should be questioned and evaluated for each problem considered.

The three fill factor methods are also similar in that the shape of the borrow gsd is mathematically altered to a shape compatible with the native gsd, and the degree of difference between the original and altered borrow distributions is used to calculate the volume of fill required. The methods are dissimilar in the criteria used for the alterations. Fill factors can be directly calculated using all three methods, but in general, graphical solutions are adequate and easier.

a. The SPM Method (R_S). With this approach, the ratios of weight percents of the native to borrow composites are compared across the range of observed grain sizes to determine the phi grain size at which the ratio is a maximum (*critical phi size*). The SPM fill factor (R_S) is the value of the ratio at this size and represents the minimum amount of borrow material which, when selectively winnowed from *all* size fractions, will produce a unit volume of material with a size distribution identical to the composite native sediments. In process-response terms, this approach assumes that both fine- and coarse-grained sediments will be lost in situations where the borrow material is more poorly sorted than the native material.

Figure 7 shows isolines of R_S plotted against the reference axes used for Figure 4 in this study. One problem with this method is that it only applies directly to textural conditions defined in quadrant 1 where the borrow composite is finer grained and more poorly sorted than the native composite. Again, an important shortcoming of the method may be the assumption that natural sorting conditions would actually remove coarse, seemingly "stable" sediments from the active beach system to achieve a compatible size distribution for the fill.

b. The Dean Method (R_D). Dean (1974) proposed a second fill factor method aimed at overcoming the problem in the SPM of assuming that a part of the coarse, stable sediments are lost by selective sorting. Dean found this concept incompatible with what is commonly observed in nature. His approach assumes that all fill material coarser than the native phi mean reflects stability within the beach environment. Mathematically, a minimal amount of the finest sizes is systematically removed from the borrow gsd until the mean size equals the native mean size. From a process standpoint, this approach is equivalent to assuming that winnowing processes progressively wash out the finest sediments from a fill until its average size is equal to that observed for the beach before restoration. The variables required to obtain a graphical estimate of R_D (Fig. 8) are the phi mean sizes of the native and borrow composites and the phi sorting value of the borrow material. The fill factor values obtained for any particular set of the composite parameters are lower for R_D than for R_S. Dean's factor is probably a more reasonable approach than that of the SPM in terms of reflecting conditions observed in nature. However, the approach does have drawbacks. First, by ignoring the natural sorting of native sediments, a modified borrow distribution can be created that is quite dissimilar to that for the sediments assumed to be in environmental equilibrium. A second shortcoming is that the approach is somewhat unreasonable in situations where the borrow materials are coarser but more poorly sorted than native sediments. Here, the mathematical model predicts stability for all fill placed although the finer grain sizes will surely be removed by winnowing.

(c) Adjusted SPM Method (R_A). Shortcomings of the Dean and SPM methods prompted James (1975) to propose a third fill factor method. The

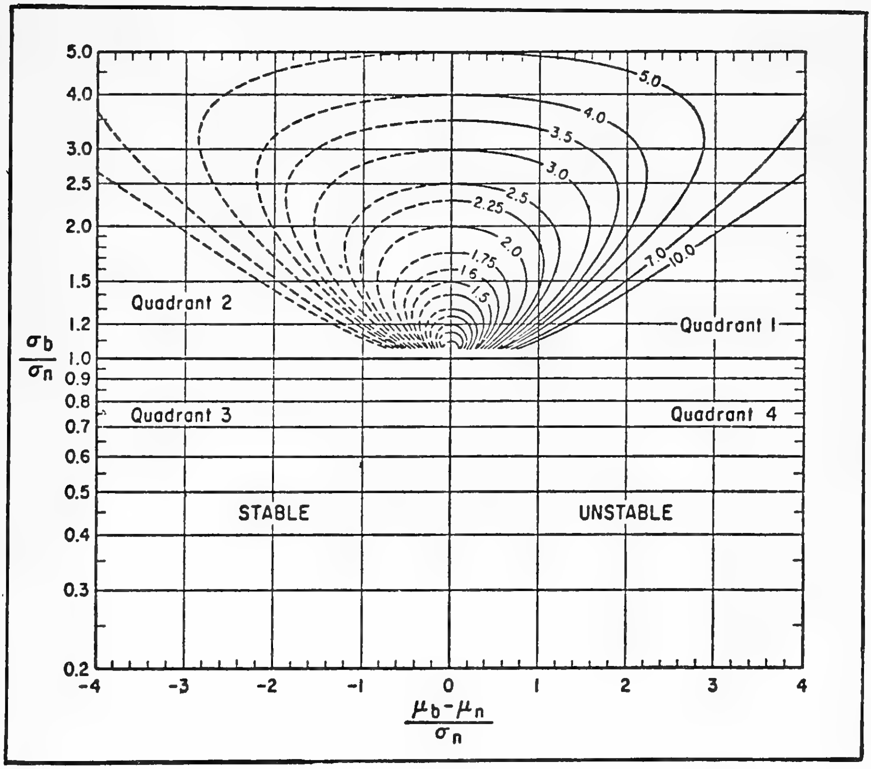


Figure 7. Isolines of SPM fill factor (R_S) versus phi mean difference and phi sorting ratio (from James, 1975).

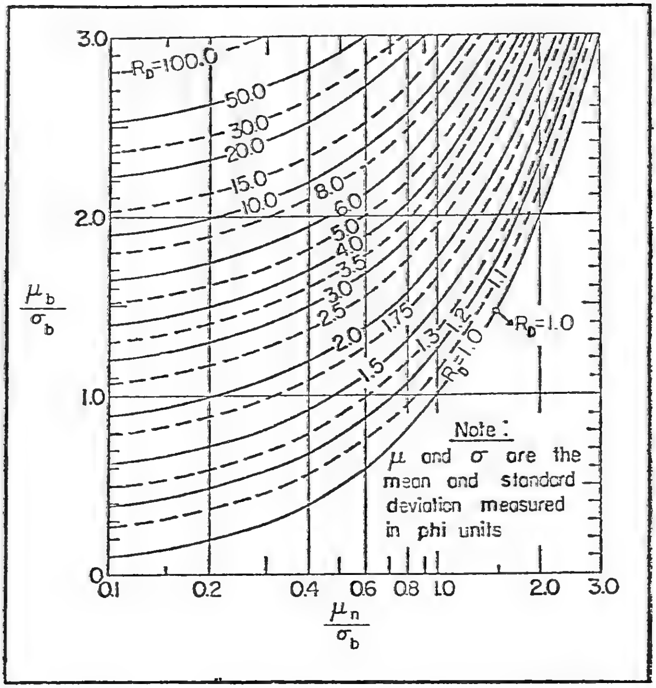


Figure 8. Isolines of the Dean fill factor (R_D) (modified from Dean, 1974).

problems were basically the selection of the critical or stable grain size for a borrow distribution, and the quantitative methods by which that distribution was to be modified to resemble native sediments. The adjusted SPM approach assumes the critical grain size to be equal to that chosen by the SPM approach (ϕ critical), except in situations where the borrow is coarser than the native. Then, the stable size is allowed to increase toward a maximum of $\mu - \sigma$. Although this maximum is somewhat arbitrary and may not directly relate to processes, it allows for the "retention" of coarser sediments that can play the important role of "armoring" a beach during periods of rapid erosion. As with Dean's approach, this method also assumes that losses to the fill will be from the sizes finer than the critical size, but unlike Dean, the losses are from *all* sizes finer. The result is a modified fill distribution which is as close as possible to the proportions of the native distribution in the finer size classes, but retains the borrow material characteristics in the coarser size classes. Actual calculations of R_A involve fairly complicated mathematics but accurate graphical estimates can be obtained using the curves in Figure 9. Again, the basic information required is the phi mean and phi sorting values for both native and borrow composites.

d. Comparison of Fill Factor Methods. The easiest comparisons can be made using the four quadrants defined in Figure 7, where the vertical axis is the log of the ratio of the borrow to native sorting values and the horizontal axis shows the difference between borrow and native means as scaled by the native sorting. In the first quadrant, where the borrow is finer and more poorly sorted than the native, the adjusted SPM value (R_A) is between a low Dean factor (R_D) and a higher SPM value (R_S). The borrow is coarser but more poorly sorted in quadrant 2 and here the SPM factor is an upper bound, while the adjusted SPM and Dean factors are close to one, except where the borrow is much more poorly sorted and then the adjusted SPM factor is increased while the Dean value remains one. In quadrant 3, the borrow is coarser and better sorted than the native and all three methods predict values of one except where the borrow is much better sorted than the native material (Fig. 7). This situation is unlikely to be encountered but still R_A values are conservatively high as compared with values of unity for R_S and R_D. Borrow sediments are finer and more poorly sorted in quadrant 4 and generally unsuitable as fill. Here, an SPM value cannot be calculated, and the R_A and R_D factors are usually high.

3. Renourishment Factor (R_J).

The renourishment factor (R_J) (James, 1974) is a dynamic approach to answering how beach processes can be expected to modify specific fill sediments. It attempts to predict how often renourishment will be needed and to evaluate the long-term performance of different fill materials with regard to suitability, maintenance, and expense. In general, the conceptual approach is that the active beach system can be viewed as a compartment which receives sediments through longshore transport and from gradual erosion of the inactive "reservoir" of sediments that form the backshore. The compartment loses sediments by longshore and offshore transport beyond its

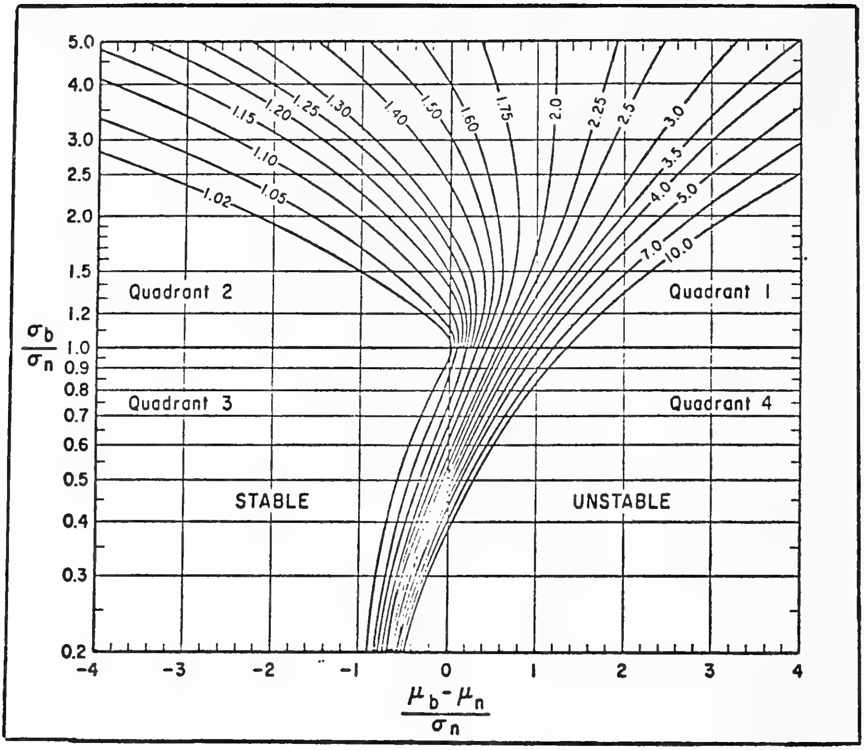


Figure 9. Isolines of the adjusted SPM fill factor (R_A) versus phi mean difference and phi sorting ratio (modified from James, 1975).

boundaries. In this scheme, a fill is viewed essentially as an increase to the backshore reservoir. Sediment particle residence time in the compartment is longer for coarse-grained sediments than for fine; thus, a comparison between composite-size distributions of native and borrow sediments can be used to predict the lifetime of a fill. The scheme thus becomes a "bookkeeping" problem of monitoring material going in and out of the system by using mass-balance equations that are similar to the more familiar sediment-budget calculations.

Various simplifications are made to the basic mass-balance equation which result in this *relative retreat-rate* equation:

$$\text{Log}\ (R_J) = \Delta \left[\frac{(\mu_b - \mu_n)}{\sigma_n} \right] - \frac{\Delta^2}{2} \left[\frac{\sigma_n^2}{\sigma_b^2} - 1 \right] \tag{8}$$

where

R_J = the relative retreat rate (renourishment factor) which is a ratio of the borrow to native retreat rates

μ and σ = the phi mean and phi sorting

b and n = subscripts referring to borrow and native composites, respectively

Δ = a dimensionless parameter related to selective sorting (winnowing) in the environment.

The value of the delta parameter, Δ, is estimated to be between 0.5 and 1.5, but to date appropriate fill data have not been collected to obtain more accurate values. Renourishment factors can therefore vary depending upon the Δ value used. Using a Δ of unity, Figure 10 shows R_J contours plotted against the "standard reference axes" that compare the textural parameters for the native and borrow composites. A renourishment factor of one-third means that the borrow material is three times as stable as the native, or that renourishment with this borrow material would be required one-third as often as renourishment with nativelike sediments. However, an R_J of 3 indicates the borrow is one-third as stable, and if used as beach fill, would require renourishment three times as often as the nativelike sediments. Probably, the most obvious shortcoming of this model is the lack of real values for the "winnowing parameter, Δ," but the kinds of predictions obtained are nevertheless consistent with general beach-fill guidelines. It is concluded that this model, as is, can be used profitably to solve actual beach-fill problems, and that this kind of approach must be considered in cases where periodic renourishment is anticipated.

4. Comparison Example.

Figure 11 shows size-frequency histograms for native and borrow composites and phi mean and sorting values from Virginia Beach, Virginia. The

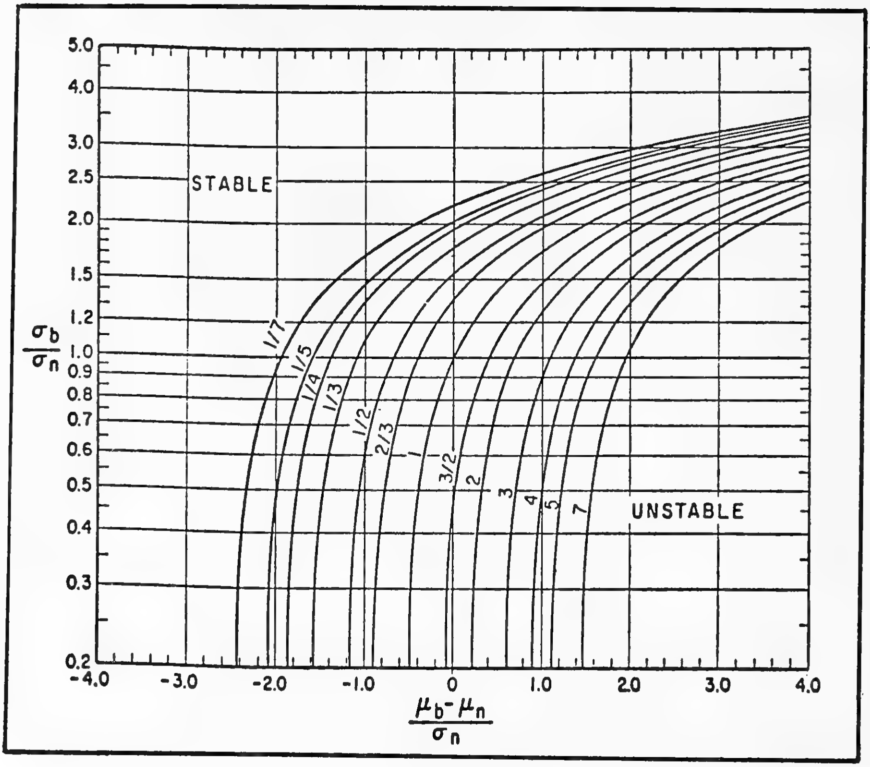


Figure 10. Isolines of renourishment factor (R_J) versus phi mean difference and phi sorting ratio (modified from James, 1975).

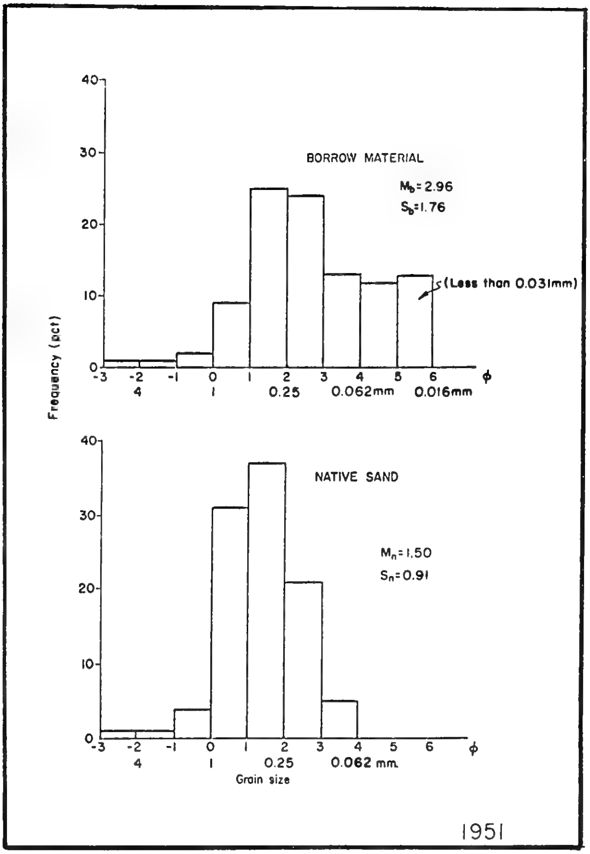


Figure 11. Grain-size histograms for borrow and native sand composite distributions, Virginia Beach, Virginia (modified from Krumbein and James, 1965).

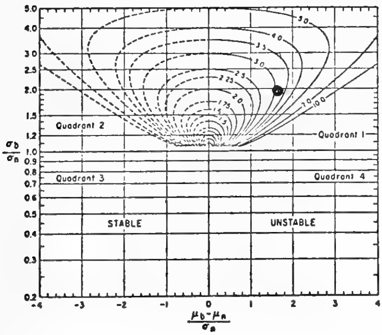
borrow is finer and more poorly sorted, and the fill factors and renourishment factor for these data are shown in Figure 12. All four beach-fill models are plotted against the standard reference axes for comparison purposes; therefore, the pattern of the Dean ratios (R_D) is different than in Figure 8. (Figure 8 is better for accuracy.) The points plot in the first quadrant, and as expected for the overfill ratios, the adjusted SPM value (R_A = 2.80) lies between a high SPM (R_S = 3.09) and a lower Dean value (R_D = 2.12). The renourishment factor is 1.71 and is consistent with the overfill values, showing the borrow to be less desirable for nourishment than native sediments.

The question to be asked now is which technique is best? Although any of the fill factors might be best suited to some particular problem, the adjusted SPM method is a compromise approach that clearly attempts to overcome inadequacies of the SPM and Dean methods and thus it is generally recommended. *If the question is how much overage may be required, use the adjusted SPM method* (R_A) *whereas the renourishment factor* (R_J) *should be applied to attempt to answer how often renourishment may be required.* Appendix B contains an example of using both methods for evaluating a problem where beach fill is required.

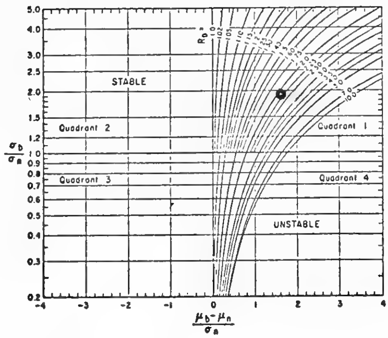
Most engineers have been familiar with only the fill factor-type approach to solving beach-fill problems. However, the renourishment approach is probably better suited to those common situations where beach erosion is a continuing process that must be considered in any plans for long-term shore protection. Undoubtedly, the use and popularity of the renourishment approach will increase as data accumulate from field experiments and from monitoring the performance of nourished projects.

V. CONCLUSION

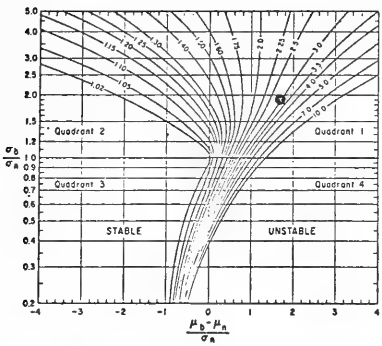
This study considers the current "state-of-the-art" with regard to two topics. The first is to show the importance of composite gsd for characterizing native beach and borrow site sediments, and the uses of composites for beach-fill evaluation. The second topic is to set up general sampling and computational guidelines to ensure that composites accurately represent the characteristics of the sedimentary bodies sampled. Other topics, such as describing beach-fill models and sediment properties, have also been included to provide a framework for considering the major subjects. Several important topics have not been considered here because they can be found elsewhere; e.g., James' (1975) discussion of the uses and interpretations of the renourishment and fill factors. Topics involving unsolved problems or for which adequate data are unavailable were also omitted. A great number of these subjects deserve attention, and the fact that they are so numerous attests to the dynamic and changing nature of the broad subject of beach fill. Topics that are in particular need of further thought and investigation are the practical, economic, and responsibility aspects of beach fill. These topics were chosen arbitrarily for organizational purposes but each contains a number of elements (often common elements) that are mentioned, in part, in the concluding paragraphs.



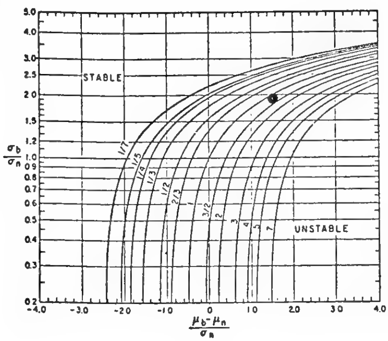
A. SPM Fill Factor (R_S = 3.09)



B. Dean Fill Factor (R_D = 2.12)



C. Adjusted SPM Fill Factor(R_A=2.80)



D. Renourishment Factor (R_J=1.25)

Figure 12. Comparison of fill factor techniques and renourishment method for example data from Virginia Beach, Virginia.

Although simplistic in nature, the beach-fill models must be used in the practical environment of real and unique engineering problems. Some of these problems are: Should a fill factor apply to all of the fill placed? Which sedimentary data should be selected to compute a specific composite? Would the placement of fill on different parts of a beach require different fill factor calculations to assure project specifications? How should a borrow site composite distribution be modified to reflect the effects of different kinds of equipment and techniques? Each of these questions is project specific, but the compilation of information regarding actual decisions made and the performance of completed projects will eventually provide the kinds of data needed to establish guidelines for future projects.

Economic considerations for a project must, in part, reflect practical aspects such as the equipment available for use, or practices of local contractors. Project expenses should also be based on the engineer's decisions to use solutions that seem most suited to a problem. For example, a volume of fill sediments could be determined by the size of the "hole" dredged, the number of barges hauled, or perhaps the amount of sediment actually ending up on an active beach as determined by prefill and postfill surveys. Payment should be made for that volume estimate which best reflects the original calculations or models used to set up the project. In a situation where periodic renourishment is appropriate, renourishment factors calculated for several potential fill materials should be used to select the cheapest material for the life of the project. Perhaps, a standard for fill should be used to assure, through rigorous sampling during placement, that the materials paid for were of the expected quality. The point made here is that many aspects of the topics discussed can be used to help define and control expenses.

Many of these comments suggest that the models and methods discussed can serve the engineer as tools to help solve beach-fill problems as well as provide the criteria to evaluate the progress and success of a project. This second appraisal capacity can give the engineer additional control over a project. For example, he can be more active in specifying how and what sample data should be collected, the best placement method to be used for a specific fill, and how payment for a fill should be determined. All of these aspects place more responsibility for a project on the engineer. This is probably reasonable, but if he is more responsible, he should include in his designs the collection of enough information to adequately monitor the performance of each project. Thus, the final recommendation is that *long-term monitoring should be one aspect of all beach-fill projects*, and that data obtained from such monitoring will improve existing beach-fill schemes and also provide the basis for predicting the success of future works.

VI. SUMMARY AND RECOMMENDATIONS

1. Two beach-fill models are recommended.

a. The adjusted SPM method (R_A) enables calculation of a fill factor to determine how much overage may be required when the textures of borrow and native beach sediments are dissimilar.

b. The renourishment factor (R_J) compares the stability of borrow sediments relative to native beach sediments by estimating how often renourishment may be required.

2. Both beach-fill models use the mean and sorting values of the composite grain-size distributions of native and borrow sediments as basic input.

3. A composite distribution describes the overall, or averaged grain-size characteristics of sediments sampled from a particular beach or borrow site deposit.

a. For a beach, surface samples should be collected from the active profile surface in accordance with a sampling plan designed to adequately assess the along-beach, across-beach, and seasonal components of textural variability.

b. Sediment samples obtained from cores rather than surface samples are usually used to evaluate the composite texture of a borrow source and to estimate the potential volume of suitable sand in the body.

c. The best composite distributions are obtained by either averaging the percentage of sediment in each size class interval for all samples collected, or by analyzing the gsd of a sample obtained by mixing equal amounts of the individual samples. Both methods should provide identical results.

d. Careful attention should be paid to the design of sediment sampling plans since the quality of any beach-fill calculations is, at best, only as good as the native beach and borrow composites.

4. Sediment analysis considerations.

a. For beach-fill purposes, particle size is expressed in phi units and the phi mean and phi sorting are used to describe sedimentary gsd.

b. It is best to use a constant phi interval for describing particle-size distributions and for most purposes, an interval of one-half phi is adequate.

c. Sediment-size analyses can be obtained using either sieving or settling techniques; however, sieving data are probably more reliable.

d. It is important not to mix sieving and settling data because each method reflects different properties of the sedimentary particle and conversion equations are not too powerful.

e. If the mixing method is used to obtain a single composite sample, care must be taken in the laboratory to obtain random splits of appropriate size from individual samples and then to mix these splits completely to eliminate bias in selecting the final sample of the mixture to be analyzed.

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APPENDIX A

MIXING SAMPLES FOR COMPOSITE ANALYSIS

It was suggested in Section III that essentially the same composite frequency-size distribution could be obtained either by averaging the frequencies per size class for each sample from a set or by analyzing a single mixture of all samples. The two approaches are identical from a mathematical standpoint, but can similar laboratory results be expected using the two approaches? The following experiment was conducted to look into this practical problem.

Eight test samples were prepared by blending predetermined weights of 1/4-phi-sized sands. Each test sample was normally distributed with mean and sorting values like those typically observed across a profile, on an east coast beach, and at elevation spacings of 4 feet (1.2 meters) from +4 feet MSL (test sample 1) to -24 feet (-7.3 meters) MSL (test sample 8). Six random splits were then obtained from each test sample using Jones Sample Splitter. Each test split contained approximately the same amount of sand as determined by visual comparison of their relative volumes. This semiaccurate procedure was selected as being fairly consistent with what could be expected with normal sample preparation procedures. Three analysis procedures were then followed.

First, two sets of samples containing one split of each test sample were analyzed at CERC using settling techniques. The size data from each set were averaged and their calculated composite distributions are the two samples labeled "No mixing" in Table A-1. Secondly, splits from test samples 1 to 4 (onshore and nearshore) and samples 5 to 8 (offshore) were physically mixed to create two samples representative of the test set. This procedure was followed twice and the samples were analyzed; these calculated composites are shown as the "Mixture 2" in Table A-1. The third procedure was to physically mix all eight splits and then analyze only one sample from the mixture. Again, the procedure was repeated twice (Mixture 1, Table A-1). Finally, the column labeled "Test composite" shows the composite-size distribution for the test samples as computed from the weight proportions used to initially make up the samples.

Comparison of the calculated composites with the test composite shows fairly high variation in actual percentages of sediment observed in the various size fractions. These variations probably are caused more by the technique used to obtain the "equal" splits than by analysis error. Still, there is little variation of the phi mean and phi sorting values from the test composite parameters and these results do not seem to favor a particular analysis procedure.

Recommendations resulting from this small experiment are: (a) Mixed samples can be used to obtain accurate composite data; (b) care should be taken to obtain random splits of appropriate size from samples and to thoroughly homogenize the mixtures; (c) it is probably best to combine samples into related mixtures such as onshore, nearshore, and offshore samples, or

Table A-1. Comparison of computed composite estimates of a test composite frequency-size distribution of known characteristics.

Phi size	Test composite	Calculated composite distributions					
		No mixing (8 analyses each)		Mixture 2 (2 analyses each)		Mixture 1 (1 analysis each)	
		A	B	A	B	A	B
-0.5	0.7	0.1	1.7	----	0.2	----	0.4
0.0	2.2	0.5	2.4	----	0.8	----	0.4
0.5	5.8	6.5	2.5	5.8	5.0	3.1	3.8
1.0	12.6	18.5	21.2	19.2	23.3	20.9	15.9
1.5	19.1	17.6	17.5	15.1	15.6	17.9	13.6
2.0	17.3	11.0	12.8	15.7	13.5	9.2	17.6
2.5	13.8	15.2	14.0	12.2	12.3	15.7	14.9
3.0	11.7	12.9	12.4	13.2	12.4	12.1	12.6
3.5	10.2	12.7	11.1	12.0	10.3	14.0	14.1
4.0	6.6	5.0	4.4	6.8	6.6	7.1	6.5
Curve data							
Phi 16	0.84	0.75	0.78	0.80	0.78	0.85	0.90
Phi 84	3.02	3.02	2.95	3.10	3.02	3.12	3.10
Mean	1.93	1.89	1.87	1.95	1.90	1.99	2.00
Sorting	1.09	1.14	1.09	1.15	1.12	1.14	1.10

to arrange them by elevation groups, in order to have the data in a form useful to project considerations; (d) when mixed samples are used, analysis of duplicates from the mixtures can provide a way to evaluate variability in the results due to analysis procedure; and (e) the original unmixed samples should be retained should additional size analysis be required because of errors or because the original mixtures chosen do not provide the appropriate information needed to solve problems later in the investigation.

APPENDIX B

COMPARISON OF EXISTING BEACH AND POTENTIAL BORROW MATERIALS AT OAK ISLAND, NORTH CAROLINA

This example of using beach-fill models for hurricane-wave protection and beach erosion control was reported in a General Design Memorandum (GDM) for Yaupon Beach and Long Beach, Brunswick County, North Carolina (U.S. Army Engineer District, Wilmington, 1973). These beaches extend east for approximately 9 miles (14.5 kilometers) along Oak Island from Lockwood's Folly Inlet (Fig. B-1, heavy line extending to profile 180). Long-term erosion rates range from 5.7 feet (1.7 meters) per year at Yaupon Beach at the western end of the project area to 3.6 feet (1.1 meters) at Long Beach.

1. Project Description.

The GDM considered 19 plans of action for the area. Optimization procedures were used to consider factors of shoreline and hurricane history, wind and wave climate, shore processes, environmental impact, and recreation and economic aspects of the area. In addition, 170 sand samples were collected from along 10 beach profiles (Fig. B-1) and 750 samples were obtained from 79 cores to describe native beach sediments and to evaluate potential borrow materials for beach renourishment. Plan BTG in the GDM was selected as the most cost effective to provide the needed protection from hurricanes and beach erosion as well as being acceptable to State and local interests.

Briefly, this plan consisted of an initial placement of 11,931,400 cubic yards (9,122,748 cubic meters) of fill plus additional fills of 1,055,400 cubic yards (806,959 cubic meters) placed every third year at two feeder beach localities. The initial fill would be used to construct a 25-foot-wide (7.6 meters) dune at +15 feet (4.0 meters) MSL, a 50-foot-wide (15.2 meters) storm berm at +12 feet (3.7 meters) MSL, and a sloped beach to close out with the existing bottom at approxiamtely -27 feet (-8.2 meters) MSL. In addition to the beach fill, plan BTG called for construction of a timber bulkhead at Yaupon Beach, a 900-foot (274 meters) rock revetment at Long Beach, and groin fields at the east and west margins of the project. The initial cost for plan BTG was estimated to be $11.6 million plus $1.2 million in annual maintenance costs.

Nine potential borrow areas were considered and of these, sediments from Lockwood's Folly Inlet and from the Yellow Banks area of the mainland (Fig. B-1, area A) were determined most suitable. The criteria used to select suitable borrow material were their similarity to native beach sediments as determined by the SPM fill factor method, the environmental impact of removing the materials, the cost per yard of material, and the expense of mobilization and demobilization. Materials found in Middle Ground shoal at the mouth of the Cape Fear River (Fig. B-1, area B) were of the best quality for renourishment purposes but expensive in terms of mobilization-demobilization expense estimates. Nevertheless, for this example Middle Ground shoal and Yellow Banks sediments are evaluated as

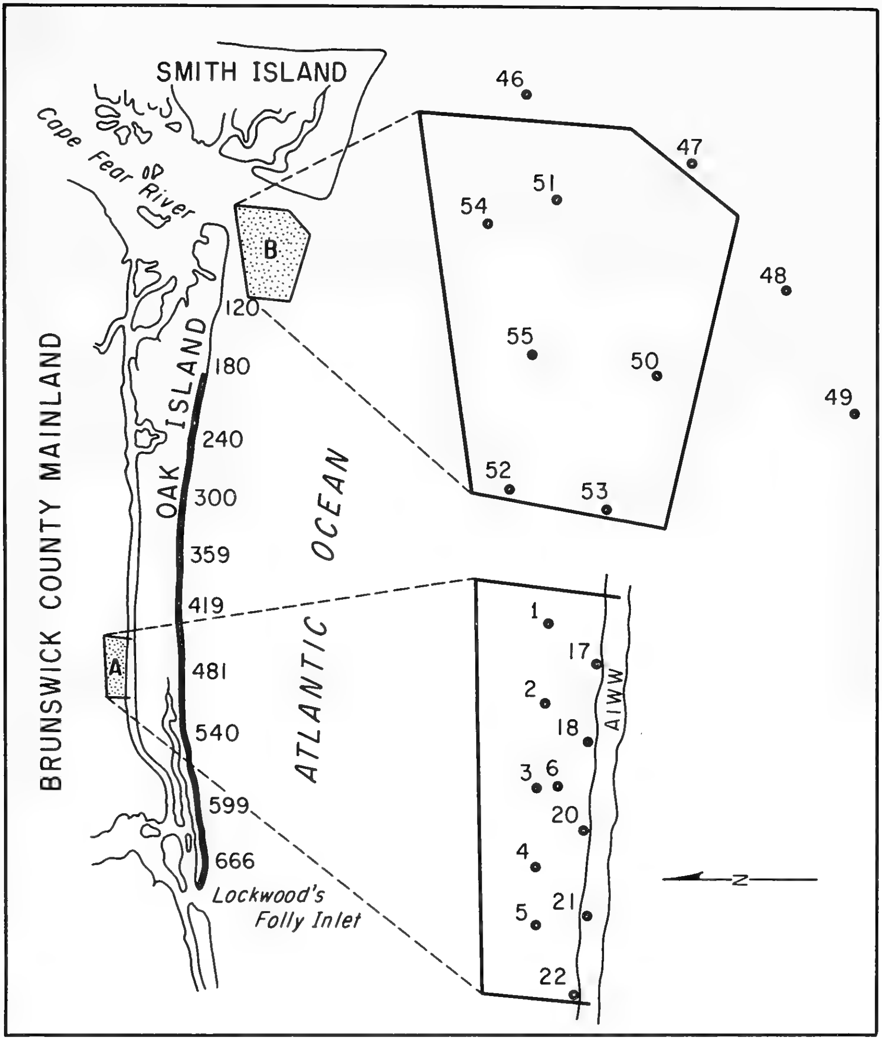

Figure B-1. Oak Island Beach restoration project area (heavy line). Yaupon Beach lies between profile ranges 240 and 180 and Long Beach extends to Lockwood's Folly Inlet. Inserts show locations for the cores in the Yellow Banks (A) and Middle Ground shoal (B) borrow sites.

potential beach fill. The Lockwood's Folly Inlet sediments are not included here because of the small volume available.

2. Composite Distributions.

The procedure for obtaining the composite gsd for sediments from the native beach and for the two potential borrow sites consisted of: (a) obtaining averaged frequency distributions for the set of samples from each profile or core (Table B-1); (b) calculating the three composite distributions by averaging the distributions from Table B-1(a, b, and c, respectively); (c) plotting these composite averages as cumulative frequencies on phi probability paper (Fig. B-2); and (d) using equations (3) and (4) from the text for calculating the phi mean and phi sorting values and using percentile data obtained directly from the plots.

a. Native Beach. Seventeen surface samples were collected from across each of 10 profiles spaced at approximately 6,000-foot (1,829 meters) intervals along the study beach (Fig. B-1). Profiles 120 and 180 were located west of the project area in order to include sediments being introduced into the area from updrift sources. Samples were collected at specific elevations across the profiles starting from the berm out to an offshore depth of -32 feet (-9.8 meters) MSL. For this example, the -24-foot (-7.3 meters) depth is used to define the margin of the active profile; thus, 130 sample-size distributions were averaged to obtain the native beach composite distribution (Table B-1,a).

b. Middle Ground Shoal. This area contains the coarsest materials of all potential borrow sites investigated. Six cores from within the area plus four cores obtained nearby (Fig. B-1) were used to collect 98 samples to determine the composite-size distribution (Table B-1,b).

c. Yellow Banks. This area (Fig. B-1, area A) has high topographic relief (+30 to 50 feet MSL) and consists of ancient beach deposits and spoil material dredged from the Atlantic Intracoastal Waterway (AIWW). The composite distribution (Fig. B-2) was calculated by averaging the sized data from 108 samples (Tables B-1,c) taken from 11 cores.

3. Beach-Fill Calculations and Discussion.

Table B-2 summarizes the comparison of native beach sediments with the composite grain-size characteristics of the two potential borrow sites, using the adjusted SPM fill factor (R_A) and the renourishment (R_J) models as determined graphically from Figures 9 and 10. A third factor, G, is also given where,

$$G = \frac{100\%}{\%\ \text{Sand}} \times R_A \quad . \qquad \text{(B-1)}$$

This factor is used in the original GDM to adjust for the proportion of clay contained in the sediments at each borrow site. These fine sediments were judged dynamically unstable in the beach environment and would be lost during dredging and placement or soon after placement.

Table B-1. Composite grain-size distributions for the native beach (a), Middle Ground shoal (b), and Yellow Banks (c).

Profile-Core (No.)	No. of samples	Phi-size class								
		3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.0	-0.5
Profile		a. Native beach								
120	13	3.6	11.5	21.8	19.6	24.5	14.6	3.6	0.8	---
180	13	5.8	12.0	19.8	20.3	24.1	14.5	3.0	0.4	---
240	13	7.1	14.1	20.7	19.8	23.7	13.2	0.9	0.5	---
300	13	4.1	12.8	18.0	15.4	19.8	14.9	12.4	2.6	---
359	13	5.7	17.2	22.0	17.4	17.8	10.8	7.2	1.6	0.3
419	13	4.8	13.4	23.6	21.5	21.4	13.9	1.2	0.2	---
481	13	7.1	23.2	27.9	20.5	15.3	5.8	0.2	---	---
540	13	6.7	21.3	31.1	18.7	16.7	5.0	0.5	---	---
599	13	4.3	11.4	21.5	18.6	23.4	18.2	2.4	0.2	---
664	13	4.1	16.1	26.6	32.2	20.7	7.1	0.2	---	---
Average		5.3	15.3	23.3	19.6	20.8	11.8	3.2	0.7	---
Core		b. Middle Ground shoal								
46	9	1.3	8.2	16.0	16.0	28.4	25.9	4.2	---	---
47	8	0.5	1.9	4.4	11.3	27.8	47.1	16.4	0.6	---
48	11	0.7	8.1	18.3	20.6	19.1	16.7	9.5	6.3	0.7
49	10	2.7	13.7	26.4	21.9	15.8	8.5	8.2	2.8	---
50	11	3.4	16.6	18.6	16.3	16.8	18.4	12.9	2.6	0.2
51	11	1.5	5.4	11.9	12.3	17.2	22.6	24.2	4.9	---
52	6	7.0	22.0	25.8	16.3	15.8	6.1	3.9	3.1	---
53	11	1.9	9.9	19.2	20.3	24.5	14.9	5.2	2.6	1.5
54	11	2.7	5.7	15.5	17.2	18.4	22.3	14.5	3.4	0.3
55	10	2.7	10.2	18.8	18.9	19.5	12.6	12.8	4.2	0.3
Average		2.2	9.6	17.5	17.2	20.3	19.6	10.2	3.1	0.3
Core		c. Yellow Banks area								
1	7	0.7	6.5	22.5	24.7	23.7	18.4	3.5	---	---
2	12	3.9	10.2	30.1	33.8	20.1	1.7	0.2	---	---
3	8	4.1	10.8	28.1	29.4	22.1	4.8	0.7	---	---
4	10	9.7	10.2	26.4	26.2	22.2	4.0	1.0	0.3	---
5	9	3.3	8.4	27.6	28.1	22.0	8.5	2.1	---	---
6	11	3.4	8.5	26.9	25.8	22.4	7.7	2.3	1.7	1.3
7	12	3.4	11.9	29.9	25.9	26.3	2.6	----	---	---
15	5	7.9	30.1	30.6	13.8	9.4	5.4	2.8	---	---
16	7	10.6	27.3	27.3	16.5	13.3	3.0	0.5	1.6	---
17	5	10.7	29.3	31.3	16.1	8.8	3.4	0.4	---	---
18	7	10.2	25.0	28.0	12.4	7.8	4.6	5.7	6.3	---
20	6	9.6	20.8	27.3	17.4	8.8	7.4	6.2	1.7	0.8
21	5	4.9	13.2	29.6	15.3	17.3	10.2	3.7	3.7	2.1
22	4	11.0	25.1	31.5	15.6	13.3	2.2	1.3	---	---
Average		6.7	17.0	28.4	21.3	17.0	6.0	2.2	1.1	0.3

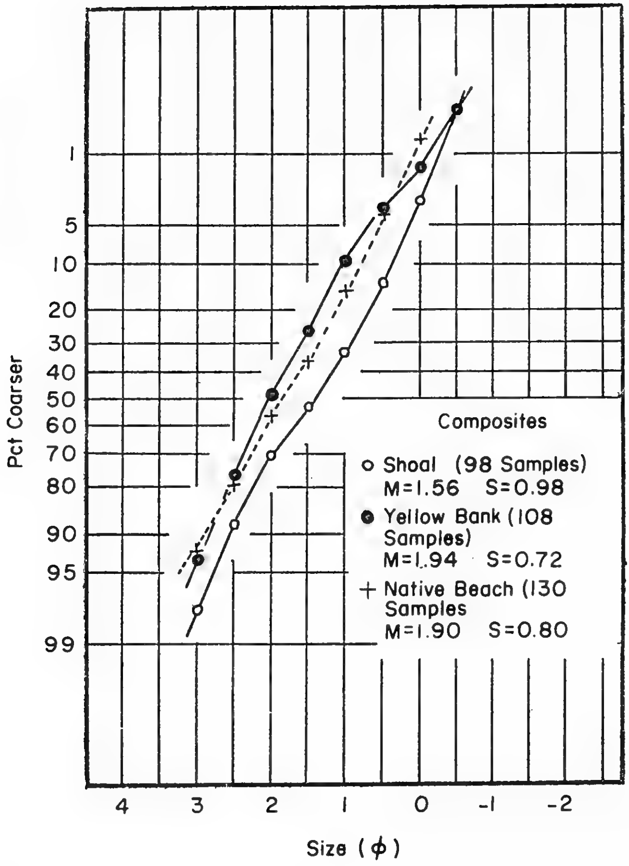

Figure B-2. Cumulative size-frequency plots for the native beach, Middle Ground shoal, and Yellow Banks composite-size distributions.

Table B-2. Composite grain-size distribution parameters and beach-fill comparisons.

	Native beach	Middle Ground	Yellow Banks
Phi mean	1.90	1.56	1.94
Phi sorting	0.80	0.98	0.72
S_b/S_n	------	1.22	0.90
$M_b - M_n/S_n$	------	-0.42	0.05
Pct sand	100	89	95
R_A	------	1.00	1.20
G	------	1.12	1.26
R_J	------	0.61	1.07

Even with adjustments, the Middle Ground sediments clearly have the greatest potential as fill but as discussed earlier, other cost considerations prevented their selection. However, the renourishment calculations (R_J) predict that a fill consisting of Middle Ground sediments would last nearly twice as long as Yellow Banks sediments. Thus, although a similar volume of material would initially be needed from either source to obtain project dimensions, the yearly renourishment requirements using the shoal sediments would be significantly less (Table B-3). These relationships show how the use of Middle Ground shoal sediments might become more economical when renourishment considerations are included in project planning.

Table B-3. Comparison of initial fill and renourishment requirements using different borrow sources, Oak Island Project, North Carolina.

Source	Initial fill (yd^3)	Nourishment per year (yd^3)
Middle Ground	10,618,946	200,558
Yellow Banks	11,931,400	351,800

For this particular project, the estimated mobilization-demobilization expenses and cost per cubic yard of fill estimates used in the original GDM favor the Yellow Banks area even when renourishment is considered. However, as the use of offshore borrow sites becomes more commonplace and the techniques of their exploitation better understood, the costs of offshore sediments should become more economically favorable when compared with conventional sources.

Hobson, R.D.
Review of design elements for beach-fill evaluation / by R.D. Hobson. – Fort Belvoir, Va., : U.S. Coastal Engineering Research Center, 1977.
51 p. : ill. (Technical paper – U.S. Coastal Engineering Research Center ; no. 77-6)
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TC203 .U581tp no. 77-6 627

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