CHAPTER 370

THE EFFECT OF GRAIN SORTING ON PROFILE STABILITY OF NOURISHED BEACHES

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Abstract

Dean's (1983) model is often used to predict the profile shape and berm width after nourishment. Ideally, if the borrow sediment is identical to native sediment, the adjusted profile will take on the same shape as the existing profile. But, if the borrow sediment is coarser than native, the nourished profile will adjust to a steeper configuration, producing a wider dry beach. If borrow sediments are finer, the fill will adjust to a gentler slope, producing a narrow dry beach. A conceptual model of the effect of grain sorting on nourished profile stability is presented in this paper and verified by comparison with actual beach measurements. The results indicate that the post-nourishment performance can be improved measurably by minor variations in grain size distribution, specifically where a coarse fraction is present (i.e., negative skewness). Fill placement technique and other environmental factors, of course, also impact performance.

Introduction

Numerous researchers have developed empirical models for beach profile stability and equilibrium slopes (Brunn, 1954; Dean, 1983 and 1991; Hands, 1981; and Krumbein and James, 1965). However, these models relate primarily to environmental factors such as wave steepness, wave energy, tide levels, and sea-level changes. Historical data from numerous beaches indicate a trend of increasing slope with grain size and decreasing slope with increasing wave energy (Wiegel, 1964). The general relationship of wave energy, grain size, and beach face slope on sand beaches is illustrated in Figure 1. Empirical data from numerous beaches confirm the trend of increasing slope with grain size and decreasing slope with

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increasing wave energy (Wiegel, 1964). Larger grain sizes allow increased percolation of wave uprush and a corresponding decrease in backrush volumes (Waddell, 1973). This results in steeper beach face slopes with increasing grain size.

Intense mixing under breaking waves will further affect the distribution of grain sizes over the shore face. Coarsest material is common at the breakpoint ("step" at the toe of the beach face), and fining will occur in either direction: toward the foredunes and back shore (Mason and Folk, 1958; Fox el al., 1966) and toward the lower foreshore (Swift et al., 1971). Multimodal size distributions across the beach occur in some areas [e.g., Duck, North Carolina (Kana et al., 1980)], but more commonly, a single mode distribution occurs. Data from Swift et al. (1971) revised by Swift (1976) show variations in the modal grain size from the berm to the lower shoreface (Figure 2). Sediment coarsening near the breaker line is reflected in the size distribution in Swift's transect B, as well as by coarse-skewed distributions for this zone of profile in transects A and C. As Swift's data show, sorting is generally good across the shoreface. Dean (1983; 1991) performed extensive work in modeling equilibrium profiles, assuming a uniform grain size distribution across the active profile.

Work and Dean (1991) suggest that varying the grain size across the profile within limited size ranges typical for beaches does not significantly improve the simpler, and often used, profile model (Brunn, 1954; Dean, 1983):

$$h(y) = Ay^{0.667}$$

where h is the water depth at a distance y offshore of the mean water line and A is a scale parameter dependent on sediment characteristics.

Dean's model (Dean, 1983; 1991) has been used to predict the resulting profile shape and berm width (dry beach width) after nourishment. In simple terms, if borrow sediment is identical to the native size distribution, the adjusted profile will take on the same shape as the existing profile. But if the borrow sediment is coarser than native, the nourishment profile will adjust to a steeper configuration, leaving more sand along the back shore (and producing a wider dry beach). If borrow sediments are finer, the fill will adjust to a gentler slope with more material shifting offshore (producing a narrow dry beach) as shown in Figure 3. As a result of these important relationships, the Shore Protection Manual (USACE, 1984) and common practice recommends use of the same or slightly coarser size distribution for nourishment purposes. The authors followed these guidelines for selecting the borrow area for the 1991 Hunting Island nourishment project (CSE, 1991). The borrow area sediments for this project contained slightly coarser sands and the grain size distributions confirmed the negative skewness of the samples produced by the presence of broken shells. Overfill ratios for this project were favorable in the range 1.10 to 1.20 and the percentage mud was relatively low at 5 percent. Based on these results and the findings of other investigators just outlined, some changes in the profile shape and slope after nourishment would be expected. This change would be due to a general coarsening of the beach sediment, or due to a change in the grain size distributions across the shoreface after nourishment.

A conceptual model of the grain size distribution shift for hydraulic nourishment projects will be presented in this paper and verified by comparison with actual beach measurements taken after the fifth Hunting Island beach nourishment project.

Effect of Method of Placement on Profile Stability

Given a different size distribution of borrow sediments compared to the native sediments, the method of placement would affect the size distribution across the profile. Fill by trucks along intertidal and dry beach is likely to produce uniform admixtures which are gradually eroded along the seaward margin. Back shore fill in this case may initially contain the same distribution of fines as the borrow area. In fact, a legitimate concern with such projects is the possibility of creating hard pan because of the binding effect of muddy sediment in the mixture (Siah et al., 1985; Kana and Jones, 1988). These fines may not erode until large storms occur or more seaward material has shifted downslope through profile adjustment.

For projects built by pipeline dredge, the response will be different. Studies on dredged material disposal (Montgomery, 1978; Palermo et al., 1978) show that coarse material settles closest to the discharge point, whereas the fine material moves further away in the slurry. If the pipeline is placed along the back shore, this leads to sorting down-profile, with coarse material concentrating along the berm and finer material settling downslope. The result will be a systematic shift in the grain size distributions from the back shore to the lower foreshore.

Conceptual Model of Nourished Beach Profile Stability

A conceptual model of the grain size distribution shift for hydraulic nourishment projects is presented in Figure 4. As the material is discharged onto the beach, the coarser fraction settles in the upper beach face. This modifies the prenourished grain size frequency curve by shifting it to the left, thereby indicating that the coarser fraction has increased (Figure 4a). The mid-sized fraction moves further down the beach profile and settles along the beach face. Since the grain size distribution of this section of the beach is very similar to the modal size fraction, the prenourished grain size frequency curve retains its shape more or less (Figure 4b). The finer fraction moves further down the profile and eventually settles at the lower foreshore. This modifies the prenourished grain size frequency curve by shifting it right, thereby indicating that the finer fraction has increased (Figure 4c).

An important consequence of this is that the upper beach face and berm becomes more stable and wider than would occur if the borrow area sediments matched the native beach. This means that the recreational life may be longer as well because dry-beach width often defines recreational benefits. A negative consequence of such a shift in the grain size distributions is the possibility of accelerated erosion of the lower shoreface.

Comparison with Actual Beach Observations

Comparison of prenourished (1990) and postnourished (1993) grain size distribution curves for the fifth Hunting Island beach nourishment project (Figure 5) show a clear trend of the sediments at the berm becoming coarser after nourishment while those along the beach face becoming finer after nourishment. The 1993 beach samples retained a coarse tail but the proportion of coarse material decreases with distance offshore. The bulk of the sample population is seen to shift toward finer sized down profile and has a smaller modal size than native in the lower shoreface.

Two schemes of statistical analysis were used to compare the native beach (1990) and nourished beach (1993) sediments (Krishna Mohan et al., 1993). In the first method (Method A), coarse sand, very coarse sand and gravel were grouped together to form percent coarse material (ie., <1.0 Phi). Similarly, very fine sand, silt, and clay were grouped together to form percent fine material (ie., >3.0 Phi). According to this scheme, the total sediment volume of the borrow area (757,644 cy) consisted of 15.35 percent (116,298 cy) coarse material and 19.17 percent (145,240 cy) fines. While the results of this analysis (see Table 1) show the expected trend of increased coarsening in the berm and increased fines in the lower beach, they do not include a large portion of the fill represented by size classes 1.0 Phi to 3.0 Phi. Therefore, the authors prepared a second analysis whereby the entire sediment grain size range was divided into two broad subdivisions comprising of coarse and fine groups.

In the second method of analysis (Method B), materials with grain sizes less than 2.5 Phi were classified as coarse and those with grain sizes greater than 2.5 Phi were classified as fines. Accordingly, most fine sands, medium sands, coarse sands, very coarse sands and gravel fall into the "coarse" category. Similarly, some fine sands, very fine sands, silts and clays fall into the "fine" category. According to this scheme, the total sediment volume of the borrow area (757,644 cy) is comprised of about 51.44 percent (389,732 cy) coarse material and about 48.56 percent (367,912 cy) fines. Table 2 summarizes the results obtained by this method which clearly supports the propositions of the conceptual model. A close examination of Table 2 indicates that coarse sediments in the berm increased from 36 percent to about 78 percent of the sample population after nourishment, whereas those at the beach face decreased from 56 percent to about 42 percent of the sample population. These trends correspond to the leftward shift of the upper beach sediments and the rightward shift of the lower beach sediments as predicted by the conceptual model. The grain size statistics in Tables 1 and 2 confirm these trends but also show that two years after nourishment the fill retains a coarse tail and is more graded. Sorting decreased significantly between 1990 prefill and 1993 postfill conditions (about 0.4 Phi to 1.0 Phi, respectively); and skewness became more negative in the 1993 samples. Skewness after nourishment was higher on the beach face than on the berm or lower foreshore.

Table 1. Comparison of native beach (1990) versus nourished beach (1993) composite samples. [Coarse <1.0ϕ; fine >3.0ϕ]

Location	Mean Grain Size		%Coarse		%Fine	
	[1990]	[1993]	[1990]	[1993]	[1990]	[1993]
Berm	2.73	1.57	0.20	32.52	26.70	4.35
UBF	--	1.93	--	23.05	--	11.39
LBF	2.49	2.41	0.80	8.66	9.15	17.01
LSF	--	2.56	--	0.31	--	12.83

Note:UBF=Upper Beach Face; LBF=Lower Beach Face; LSF=Lower Shore Face.

Kana and Andrassy (1993) conducted a volume change analysis for the postnourished beach profile which showed that there has been a rapid loss of sand in the project area. By April 1993, north beach had lost 50 percent of the fill, and south beach had lost almost 80 percent of its fill. The central project area compartment lost about 45 percent of the fill by April 1993. Figure 6 (lower) illustrates the average unit volume beach change since nourishment (February 1991) as a function of contour interval within the project area. The dry beach to MHW (+10 ft to +3.2 ft NGVD) within the project area retained 70 percent of the fill through April 1993. The intertidal beach (MHW to MLW; ie., +3.2 ft to -2.2 ft NGVD) retained about 45 percent of the fill two years later. In contrast, the underwater lenses (-2.2 ft to -12.0 ft NGVD) retained only 27 percent of the fill by April 1993. A close review of these results reveals an interesting factor: the loss rate for the upper beach lenses was much lower. These results support the predictions of the conceptual model that more fill is retained at the berm than on the lower beach.

Table 2. Comparison of native beach (1990) versus nourished beach (1993) composite samples. [Coarse <2.5ϕ; fine >2.5ϕ]

Location	Mean Grain Size		%Coarse		%Fine	
	[1990]	[1993]	[1990]	[1993]	[1990]	[1993]
Berm	2.73	1.57	35.98	78.04	64.02	21.96
UBF	--	1.93	--	60.71	--	39.29
LBF	2.49	2.41	56.02	43.25	43.98	56.75
LSF	--	2.56	--	46.28	--	53.72
	Sorting (ϕ)					
Berm	0.42	1.13				
UBF	--	1.14				
LBF	0.41	0.82				
LSF	--	0.41				
	Skewness					
Berm	0.02	-0.29				
UBF	--	-0.48				
LBF	-0.58	-0.91				
LSF	--	-0.13				

Note:UBF=Upper Beach Face; LBF=Lower Beach Face; LSF=Lower Shore Face.

Comparison with Previous Projects

Unpublished profile data following the December 1968 and December 1971 federal projects at Hunting Island were used to develop an estimate of the average fill volumes remaining (Figure 6 top and middle). The reported mean grain sizes prior to nourishment are given in Tabel 3.

Table 3. Mean Grain Size of Native Beach and Borrow Area Sediments.

Project Year	Native Beach Grain Size (mm)	Borrow Area Grain Size (mm)
1968	0.16	0.18
1971	0.16-0.21	0.18
1975	--	--
1980	0.14-0.20	--
1991	0.20	0.20-0.23

A review of Figure 6 indicates that fill losses have been exceedingly rapid after all projects. However, the proportion of fill remaining above low water has been many times higher following the 1991 nourishment. In fact, upwards of 75% of the fill remaining following the 1991 project has been situated above the low water contour. In contrast, most of the fill above low water was lost soon after the 1968 and 1971 projects.

Conclusions

A conceptual model of profile stability for beach nourishment projects was presented in this paper. The model predicts a trend of sediments in the upper beach becoming coarser by means of selective sorting at the discharge point (hydraulic nourishment) along the back shore, while those at the lower beach become finer after nourishment. While the conceptual model of nourished profile stability is not quantitative, it can be used as a basis for predicting trends and formulating alternatives. Comparison with actual beach observations support this prediction since the actual (observed) data showed the berm sediments becoming measurably coarser in both mean grain size and degree of grading (ie., poor sorting). Comparative profiles and a detailed volume change analysis revealed that the dry beach retained 70 percent of its fill whereas the underwater lenses retained only 27 percent of their fill after two years. This further supports the idea that use of coarser borrow material will improve longevity of the upper beach. Profiles, in this case, became steeper after nourishment. In conclusion, three factors become important in controlling the postnourishment grain size distribution and profile stability (in order): *(i) Grain size distribution:* This fundamentally controls the overall slope and distribution as predicted by equilibrium profile theory. Basic engineering logic suggests increasing coarse material tends to improve beach profile stability. The finer fraction washes out faster, thereby decreasing longevity and, hence, should be kept to a bare minimum whenever possible; *(ii) Placement of fill material:* The most common method of placement of fill material in a nourishment project is by the use of pipelines. If discharge is along the back shore, coarse material will settle near the berm and fines will shift downslope with the slurry. This type of placement improves berm longevity. If the discharge point is along the lower foreshore (ie., profile nourishment, Brunn, 1988), coarse material will have less chance of concentrating on the berm; and, *(iii) Environmental factors:* These include the magnitude and interrelationship of the following variables: background erosion rates, shoreline morphology, waves, currents, tides, and storm frequency. These factors produce site-specific responses and are independent variables in nourishment design.

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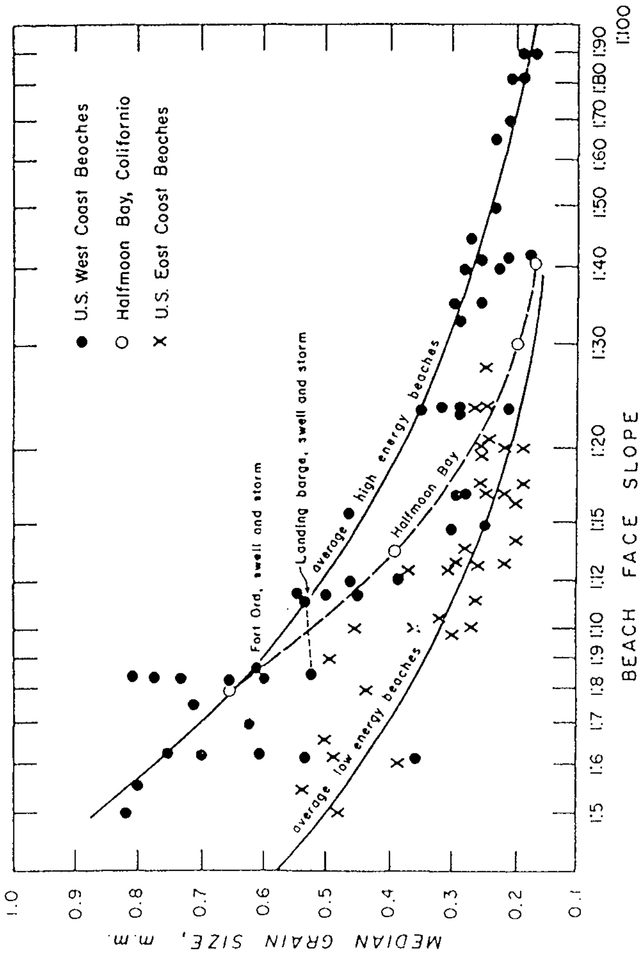

Figure 1. Relationship of grain size, wave energy, and beach face slope [from Komar, 1976]

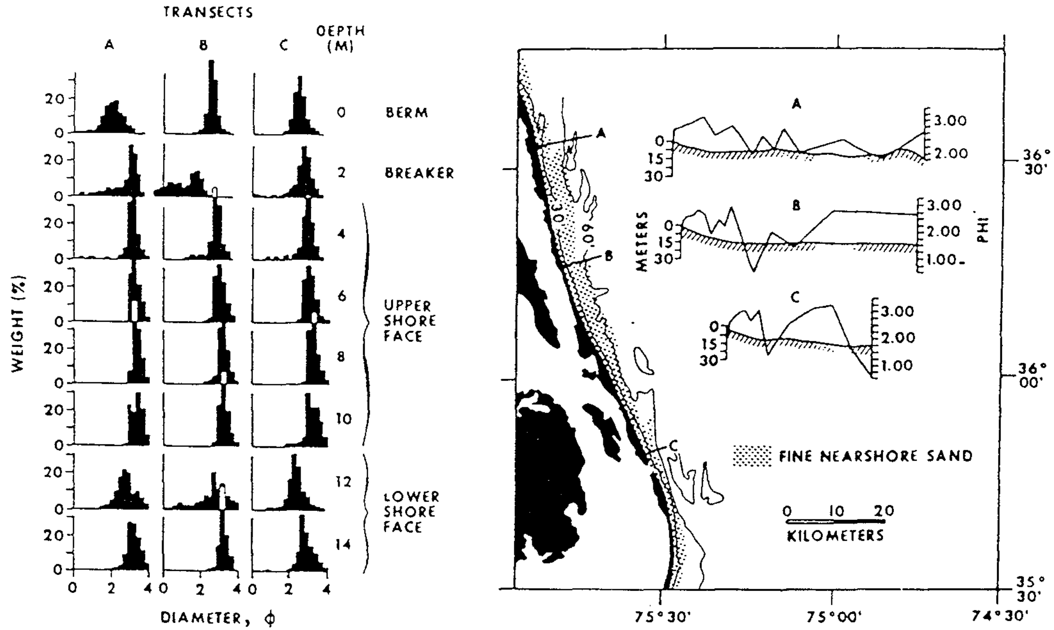

Figure 2. Distribution of grain sizes (in Phi units) along three shoreface transects of Virginia-North Carolina coast [from USACE, 1984, after Swift et al, 1971]

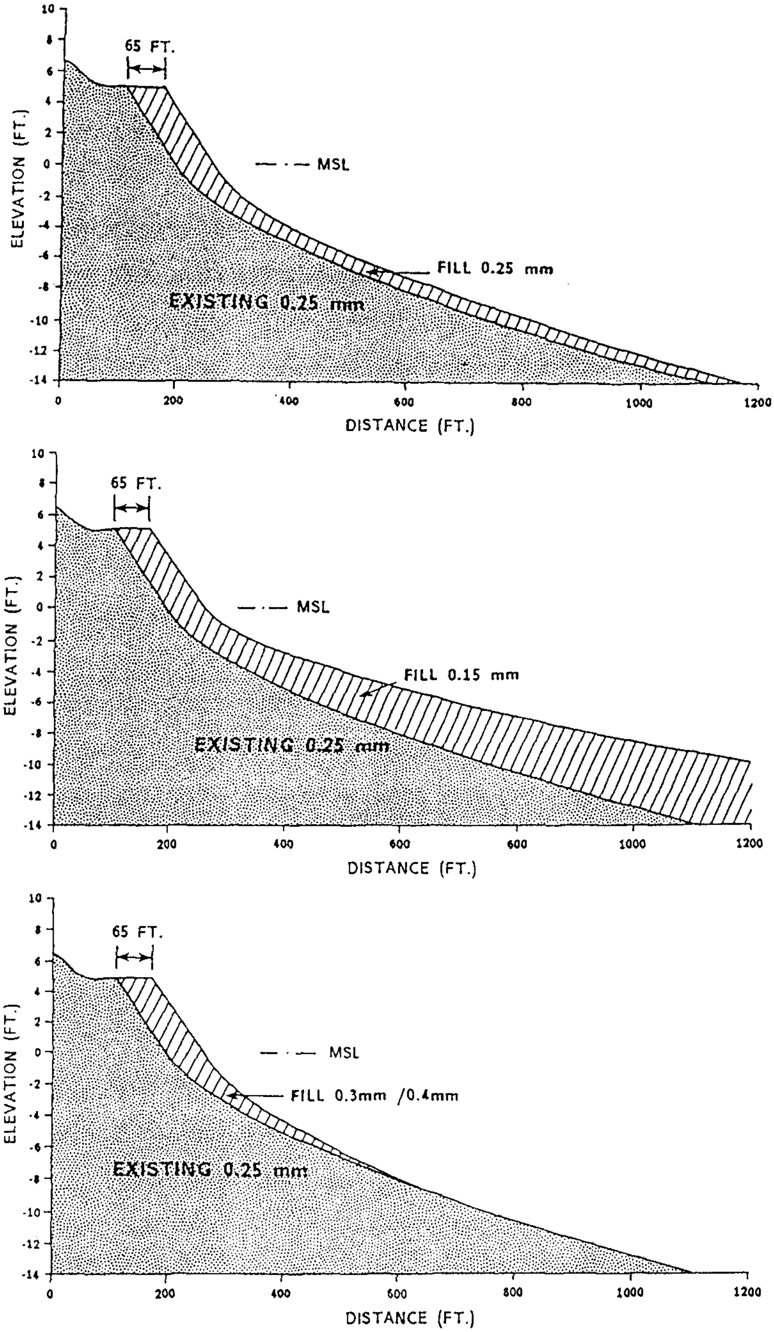

Figure 3. Theoretical equilibrium profiles to produce a uniform berm width using borrow sediments that: matches native sediment (top), is finer than native sediment (middle), and, is coarser than native sediment (bottom) [from Siah et al., 1985, after Dean, 1983]

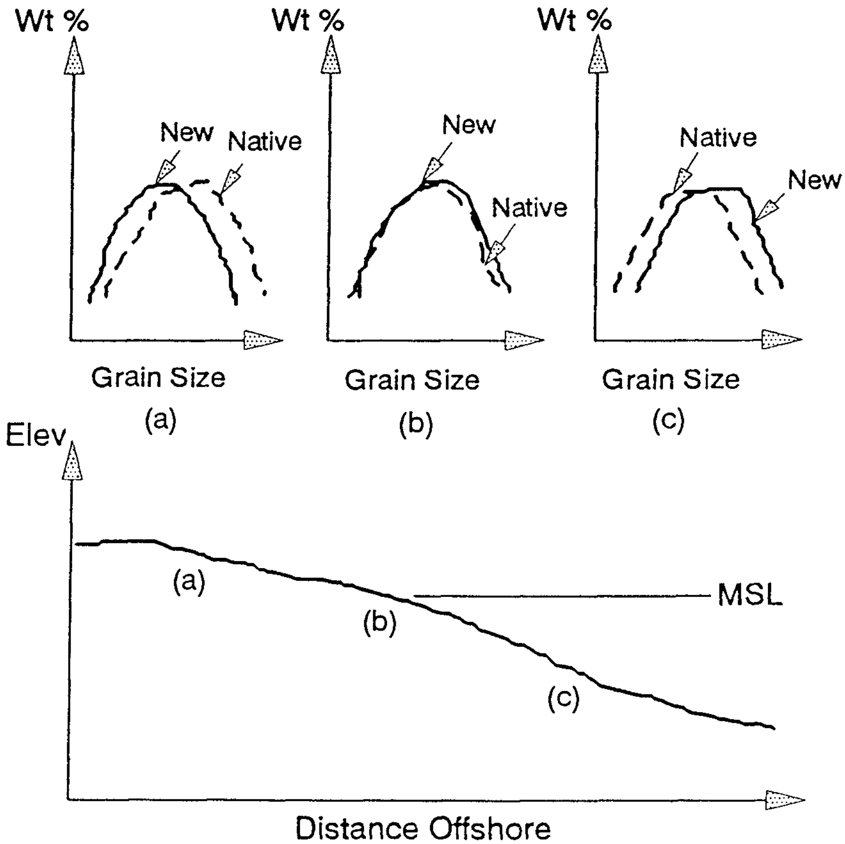

Figure 4. Schematic of the conceptual model relating to a shift in grain size distribution under a hydraulic fill with discharge along the back shore. [This assumes that the borrow source contains some fraction of sediment which is coarser than the native sediment]

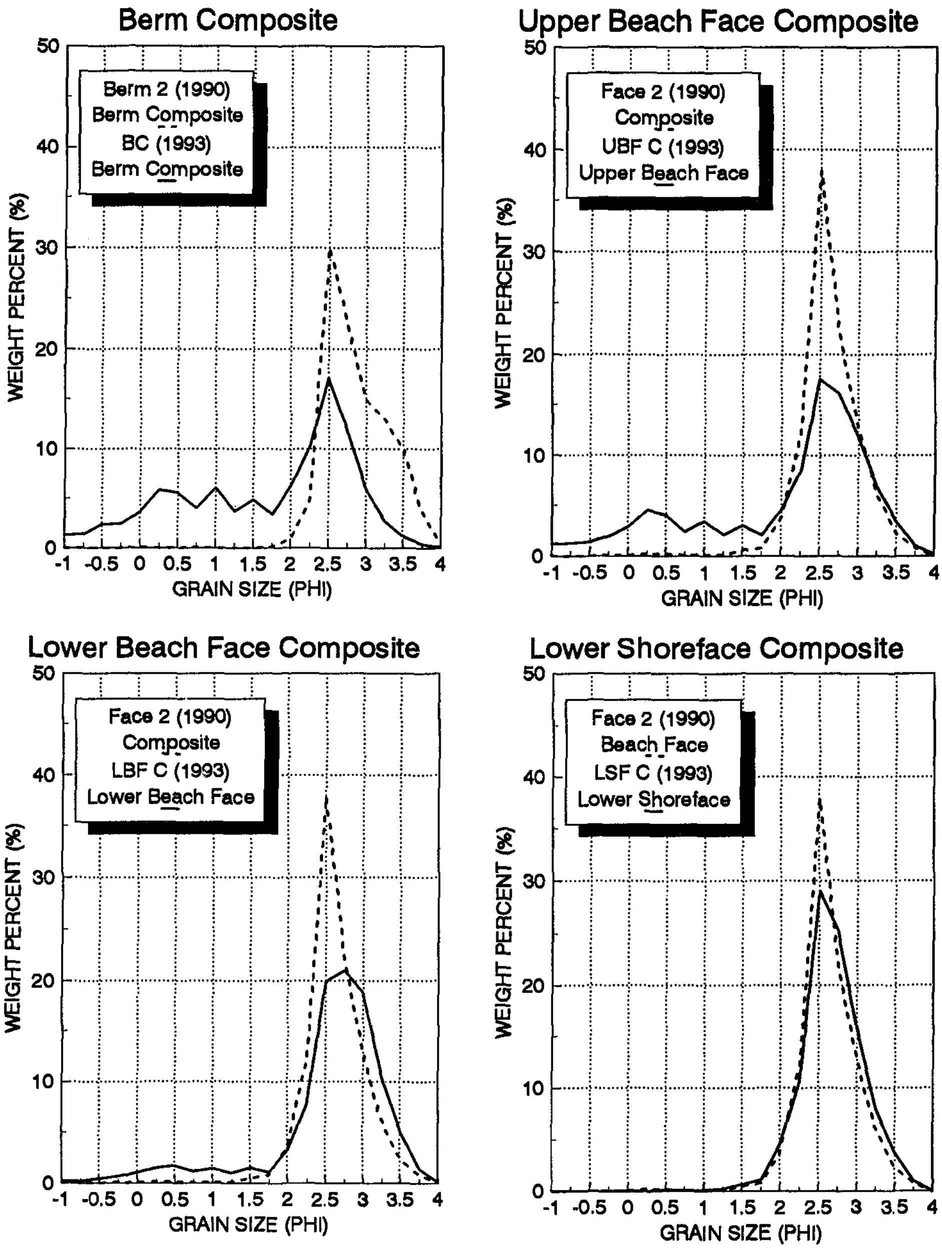

Figure 5. Grain-size comparison plots of 1990 versus 1993 beach composites for the Hunting Island beach nourishment project.

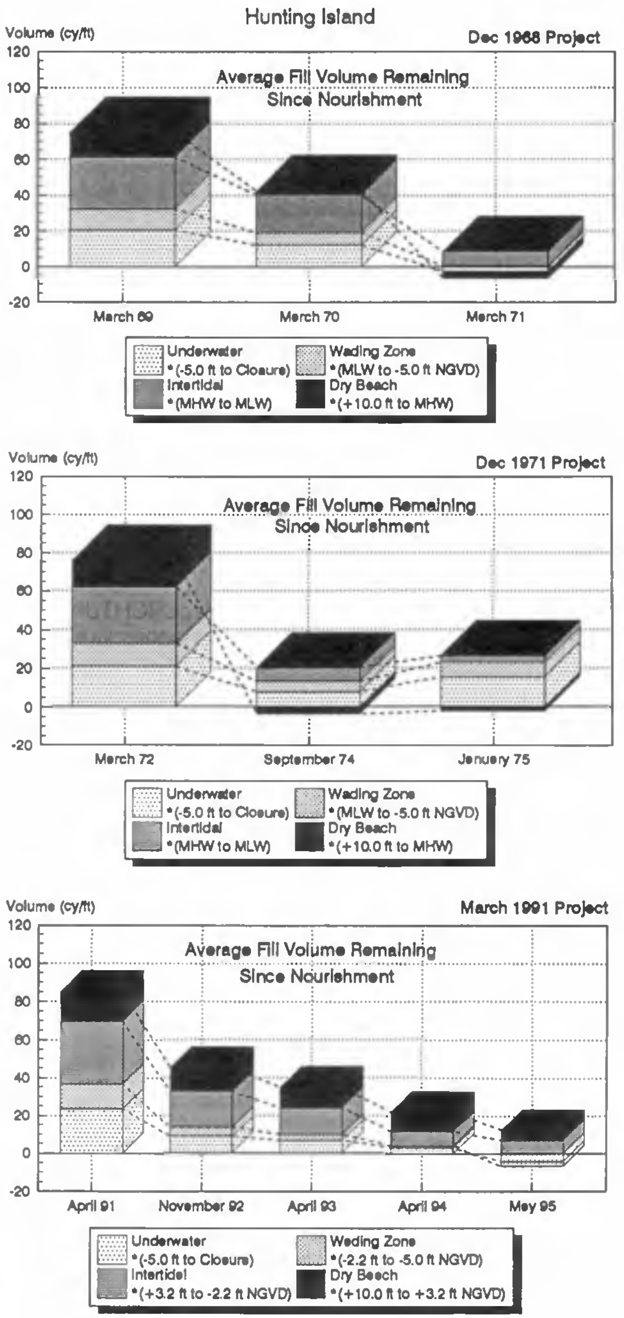

Figure 6. Estimated average unit volume fill remaining after the December 1968, December 1971, and March 1991 nourishment projects as a function of contour interval* within the Hunting Island project limits (based on surveys by USACE and CSE).