CONSTRUCTION SLOPES FOR BEACH NOURISHMENT PROJECTS

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ABSTRACT: The correlation between sediment grain size, tide fluctuations, and constructed beach fill slopes is investigated using as-built survey data from 18 beach nourishment projects in the southeastern United States. An engineering relationship is identified between median grain size and lower construction slope, where the latter is defined as the slope below an elevation related to the local mean tide level and tide range. A concise relationship between the upper construction slope and the beach-fill sediment characteristics was not evident in the data; instead, the as-built upper slope is more a function of the mechanical manipulation undertaken to meet the slope's specified value.

INTRODUCTION

Construction of beach nourishment projects requires the specification of a "construction template," which the contractor must fill with sand. The template is defined by the elevation and width of the berm, and one or more seaward slopes. Presently, there is little or no design guidance regarding specification of the appropriate slope(s), though it is known from experience that attainable slopes are a function, in part, of the beach fill's sediment characteristics and placement technique. Previous studies have correlated *natural* beach slopes, sediment grain size, and wave energy (Shepard 1963; Wiegel 1964; Christiansen 1977; Dette 1984; *Shore* 1984). E.A.K. (1981, as cited in Dette 1983) comments upon the grain size and initial slope of hydraulically placed beach fill; and Delft (*Manual* 1987) provides general comments on beach fill construction slopes. While of interest, these observations are generally broad and for the purposes of specific engineering guidance.

The present investigation examines the relationship between construction techniques, water level variations, sediment characteristics, and the as-built construction slopes of prototype beach fill projects. Its objective is to determine correlations that may exist between these terms in order to aid engineering specification of the seaward slope(s) of beach fill construction templates.

BACKGROUND

In a beach nourishment project, the engineer must typically specify the elevation, width, and seaward slope to which the fill material shall be placed upon the beach (Fig. 1). These dimensions describe the "construction profile" or "construction template." In turn, the contractor must place a sufficient volume of sand (or other specified material) to completely fill this construction template. The constructed shape of the sand berm is termed the "as-built," "after-fill," or "afterdredge" profile. The interest of the present paper concerns the seaward slope(s) that characterize this "as-built" profile. This slope is thought to be principally dependent upon the construction technique used to place the fill material, the local tide and wave climate, and the characteristics of the fill material.

Two construction techniques are commonly available for beach fill construction: hydraulic dredging and truck haul. The hydraulic dredging method entails excavating material from a submerged borrow area and pumping a slurry of suspended sediments and water through a pipeline to the fill site. Because the slurry typically is about 70–80% water, the discharged material tends to run, resulting in a mild residual beach slope. Along the upper portions of the profile, the slope can be manipulated by bulldozers to construct a desired shape. Below the mean water level, however, the discharged material is unconstrained and reposes to a slope that may be representative of the textural characteristics of the sediments (and wave climate). A truck haul fill is constructed by dumping individual truck loads of sand along the upper portions of the beach profile. Because truck-haul material is usually dry and deposited above the water line, the residual slope of the material tends to be steeper than that for the hydraulic dredging technique. From casual observation, coarser-grained sediments tend to stack more steeply than finer grained sediments, regardless of the construction technique.

Determining a correlation between construction beach slopes and beach-fill material sediment characteristics may provide guidance in specifying design template slopes for beach fills. This would ensure that the design template is filled, the pay volume is optimized, and the project is physically constructable. The template can then be upheld as an attainable goal based upon prior, known project performance. That is, the seaward slope(s) of the construction template must be specified so that a competent contractor is physically able to fill the template with sand in a profile that does not require significantly greater, or lesser, volume that the project's total design volume. If the template is not properly specified, the contractor may have basis for claims or the project's design objective may not be met. Simply put, this paper attempts to address the following problem: Given a sand borrow source

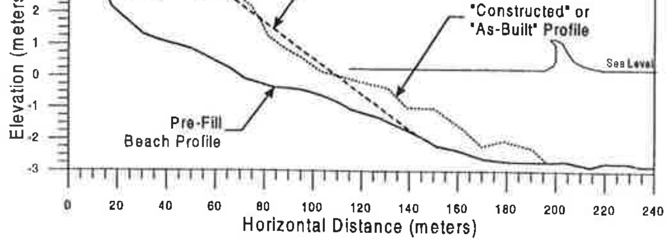

FIG. 1. Definition Sketch of Typical Beach Fill Construction Template

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for which typically available sediment grain-size data are known, to what approximate slope(s) will the sand repose during the process of beach fill construction?

DATA

General

The database for this investigation includes information from 18 beach fill projects constructed in Florida, South Carolina, and North Carolina. The general locations of these projects are shown in Fig. 2. The project data of interest include

- Beach fill placement method (i.e., hydraulic or truck, haul)
- "As-built" beach profile surveys
- Specified construction slope
- Sediment grain-size characteristics

For each individual beach fill project, the "as-built" beach profiles and the available sediment data were examined and divided into self-similar groups—based upon profile slope and sediment grain size, respectively. In most cases, entire beaches could be averaged to create composite representations of the constructed slope and the sediment characteristics for a given project. Some beaches, though, had distinguishing alongshore characteristics due to varying grain size or dissimilar construction slopes, thus requiring numerous composite averages to represent one project, e.g., "HHI-1," "HHI-2," etc.

For purposes of this investigation, the data were classified into three categories: (1) "high confidence" hydraulically placed fills; (2) "low confidence" hydraulically placed fills; and (3) truck-haul fills. High-confidence data points include those project data sets that inculde beach profiles representing the immediate post-construction shape of the fill berm, and sediment grain-size data from the construction berm. Low-confidence data points are those for which the postconstruction beach profiles may not have been surveyed immediately after placement of the beach fill, or for which the sediment data were collected from the general borrow area rather than from the in-place fill. In the figures, bold dots indicate the high-confidence data points. In instances where a "best-fit" curve of the data was developed, only the high-confidence data points were used. The "T" suffix in a project's identifying label designates a truck-haul beach fill.

Beach Profile Data

The physical characteristics of postconstruction beach profiles were determined from "as-built" surveys of the constructed berm collected immediately after placement of the fill material. Where immediate postplacement profiles were unavailable, the earliest available postconstruction profiles were used. These were typically surveyed several weeks or months after construction. Because some berm equilibrium and sorting of the fill material can occur within this period, these cases were generally included among the low-confidence data points, noted above.

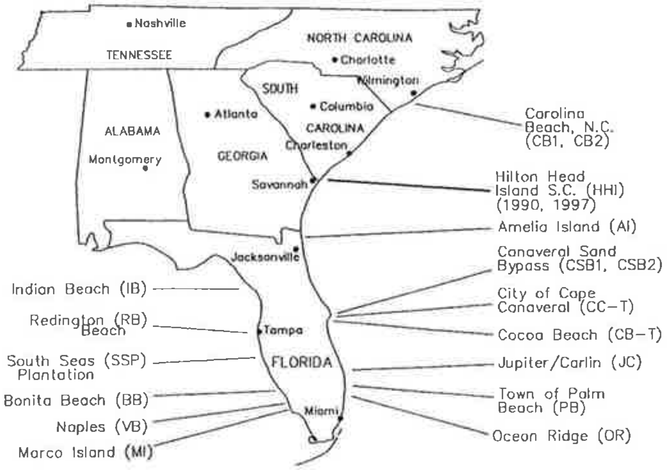

FIG. 2. General Locations of Projects from Which Data Were Obtained

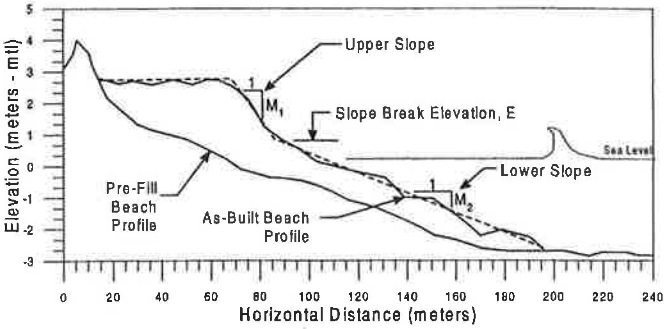

FIG. 3. Concept of Upper and Lower Constructed Beach Fill Slopes

The representative constructed slope of the fill berm was defined as that slope which described the general trend of the seaward face of the berm. Inspection of the data set revealed that most of the profiles were best represented with a two-slope shape: an upper slope, M_1, and lower slope, M_2. The elevation at which the two slopes intersect was defined at the slope break elevation, E (Fig. 3).

Generally, the upper slope was uniform from the top of the berm to the slope break elevation. Accurately representing this upper slope was generally straightforward. The slope of the lower portion of the profile, however, tended to vary significantly from the slope break elevation to the closure point with the native profile. Here, the constructed lower slope was defined by a line passing through the lower profile shape that would conserve the fill volume along the lower portion of the profile. This concept is depicted in Fig. 3.

Sediment Data

Sediment characteristics for each project (or representative reach of a particular project) were determined from samples collected along the constructed beach berm or from composite borrow area samples. Sediment sample data collected from the berm, above the wave zone, were presumed to best represent the placed fill material, i.e., prior to sorting by waves or the introduction of native sand. In the absence of sediment data from the constructed berm, sediment characteristics of the borrow area were assumed to represent the placed fill material. It is noted, however, that portions of the fine-sediment fraction are often lost between the borrow and beach fill areas during the hydraulic dredging process.

Sediment grain-size parameters of interest included the median grain size, d_{50}, the coarse fraction, d_{84}, and the fine fraction, d_{16}, based on a percent finer scale. Other statistical characteristics of interest included the mean grain size, sorting, and skewness (Folk and Ward 1957). The mean sediment size was computed using a 3-point average defined as

$$d_{\text{mean}} = \frac{d_{84} + d_{50} + d_{16}}{3} \tag{1}$$

The sorting parameter, which quantifies the variations in sediment sizes within a sample, is defined as

$$\sigma = \frac{d_{84} - d_{16}}{2} \tag{2}$$

Well-sorted sediments are those for which the individual grain sizes are mostly similar and exhibit a low sorting parameter value. A poorly sorted sample, in which there is a greater diversity in the sediment grain sizes, has a high sorting parameter value.

The skewness of a sediment describes the degree to which the grain size distribution departs from symmetry:

$$\alpha = \frac{d_{\text{mean}} - d_{50}}{\sigma} \tag{3}$$

Sediment with a high percentage of large grain sizes would be negatively skewed, whereas sediment with a high percentage of smaller grain sizes would be positively skewed.

During the construction of a beach nourishment project, the fill material will generally stack at a slope considerably gentler than the sediment's maximum angle of repose, especially for projects that are constructed hydraulically. It is noted that the natural angle of repose for typical beach sands is about 1:1.3 to 1:1.7, or, slope M = 0.77 to 0.59 (Bascom 1959, among others). Additionally, the fill material is generally placed at a slope steeper than the natural beach profile, for reasons of construction practicality. Only after equilibration with wind and wave forces will the beach sediments adjust to the native beach slope, although construction placement techniques and sediment characteristics are influential in this process.

Tidal Datum Data

Values of the tide range for the project sites were taken as the mean range, as published in "Tide Tables of the East Coast of North and South America" (1984).

ANALYSIS

Hypothetical "models" were developed to describe the expected physical relationship between (1) the tide range and slope break elevation, and (2) the constructed beach slopes and sediment grain-size characteristics. For the former, it is hypothesized that the elevation of the break in the beach fill's profile slope, E, may correspond to the high tide limit of wave uprush; i.e.,

$$E = \frac{1}{2}\ \text{tide range} + \text{wave runup} \tag{4}$$

where wave runup is expected to be on the order of about 0.6 to 1.0 m for the sites considered in this study. For the latter, the construction beach slope is hypothesized to be related principally to sediment grain-size characteristics, where the most *fundamental* characteristic is the median or mean grain size. Larger-grained, noncohesive sediments tend to stack steeper than finer-grain sediments. Therefore, it is proposed that the beach slope that can be constructed is related in a lognormal manner to the median and mean sediment grain size. Fig. 4 depicts this proposed "model" wherein the upper asymptote represents the maximum natural angle of repose of sand and the lower limit represents a flat horizontal slope.

The expected relationship between sediment sorting and skewness and the expected slope of the construction profile was also considered. A poorly sorted sediment has a diverse assortment of grain sizes, which may tend to better interlock and result in potentially steeper slopes than a well-sorted sediment. It is therefore expected that the construction slope might be steeper for a poorly sorted sediment (i.e., high sorting parameter). Similarly, sediments with negatively skewed grain size distribution reflect a high percentage of coarser grains and may result in beach fills that repose more steeply than do sediments with normal or positively skewed distributions. Accordingly, it is expected that the construction slope might be steeper for sediments with negative skewness.

RESULTS

The "models" described above were compared with the prototype beach fill data. The results of these comparisons are presented below.

Slope Break Elevation

Fig. 5 depicts the comparison between tide range and slope break elevation, E. All data points are included; some overlap. For those project sites where the mean tide range is greater than about 0.7 m, the break in slope is approximately related to the high water level plus an allowance for wave runup of about 0.43 m. For tide ranges smaller than about 0.7 m, there

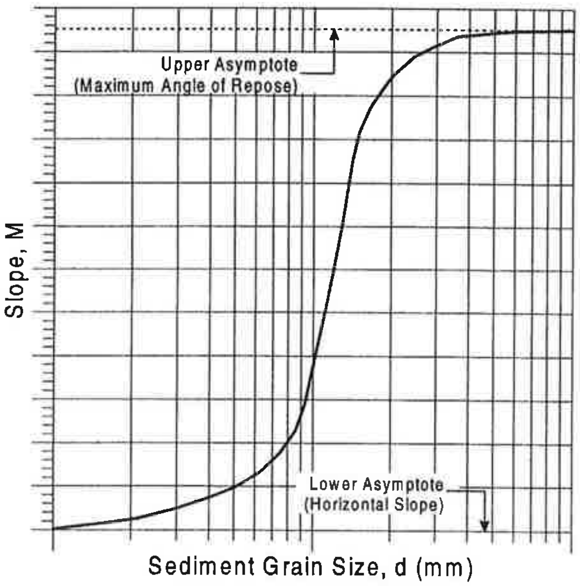

FIG. 4. Hypothetical Relationship between Median (or Mean) Sediment Grain Size and Construction Slope

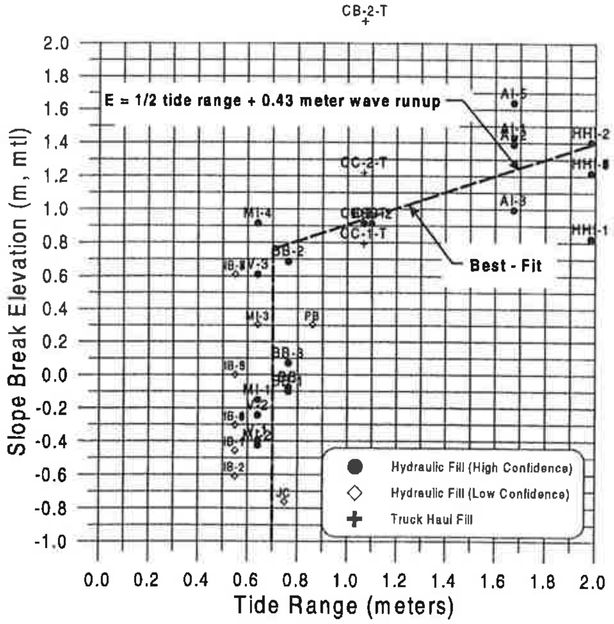

FIG. 5. Relationship between Tide Range and Slope Break Elevation

does not appear to be a correlation between tidal range and break in elevation for beach slopes. That is,

$$E < 0.75 \quad \text{for} \quad T_R < 0.7 \text{ m} \tag{5}$$

$$E = \frac{1}{2} T_R + 0.43 \quad \text{for} \quad T_R \geq 0.7 \text{ m} \tag{6}$$

where T_R = mean tide range (in meters), and E = elevation, relative to the approximate mean tide level (in meters) that defines the break between the upper slope, M_1, and the lower slope, M_2. Of course, higher wave heights and associated run-up at a given site would be expected to increase the slope break elevation, E; however, these variations were not evaluated in the present investigation.

Lower Slope

Fig. 6 is a comparison of the lower beach fill slope, M_2, and the *median* grain size, d_{50}, of the beach fill sediments. The high-confidence data reveal a general trend of increasing slope with increasing median grain size, as expected. A lognormal best fit represents the high-confidence data fairly well, and emulates the hypothetical "model" between grain size and construction slope (Fig. 4). A similar trend is also evident in a comparison of the *mean* grain size to lower slope (Fig. 7), although the correlation with a best-fit curve is poorer for the *mean* grain size ($r = 0.35$) than for the *median* grain size ($r = 0.69$). The results compare reasonably well those of E.A.K. (1981) for the case of hydraulically placed beach fill slopes measured below the still water level in moderate to strong seas, viz., slopes of 0.036 to 0.1 for 0.1–0.6 mm sand, and 0.1 to 0.25 for 0.6–2.0 mm sand.

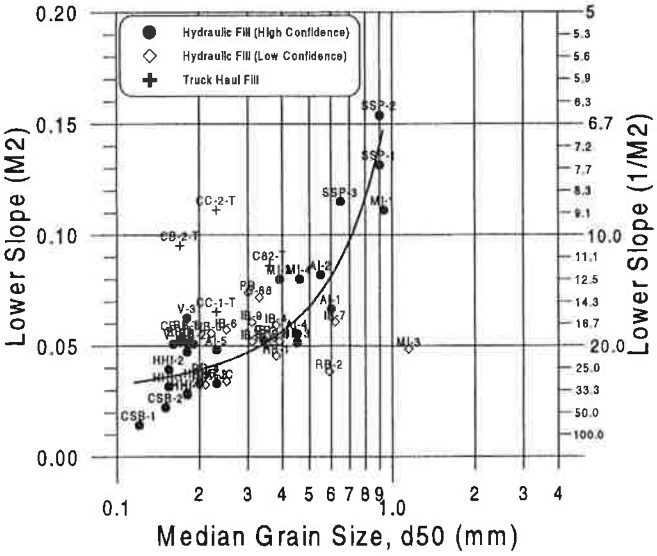

FIG. 6. Relationship between Median Grain Size and Lower Construction Slope

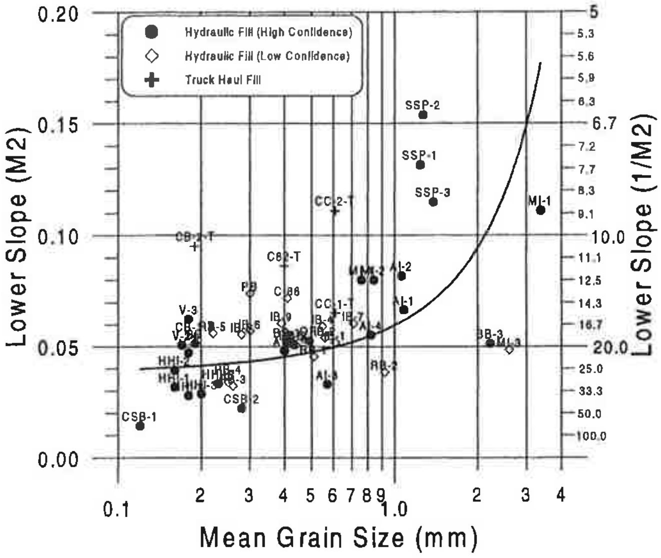

FIG. 7. Relationship between Mean Grain Size and Lower Construction Slope

Correlations of lower construction slope with other sediment grain-size parameters were also considered. These parameters included the coarse fraction, d_{84}, fine fraction, d_{16}, sorting parameter, σ, and skewness, α. As expected, the lower slope revealed a trend of increasing steepness with increasing coarse- and fine-fracton grain size; however, best fits of these data are poorer than those for the median and mean parameters. The lower slope also revealed an expected trend of increasing steepness with increasing sorting parameter value; however, no discernable relationship between lower slope and skewness is evident. To this end, these comparisons suggest that the lower construction profile slope is most strongly related to the *median* grain-size parameter, at least for the purposes of developing an engineering model.

Upper Slope

Unlike the lower slope, no clear relationship was apparent between the *upper* construction slope and sediment characteristics. Fig. 8 compares the upper slope and the *median* grain size of the beach fill sediments, and illustrates a weak trend, but with considerable scatter. Likewise, comparison of the *mean* grain size and upper slope (Fig. 9) as well as the *coarse fraction* and the upper slope (Fig. 10) did not reveal a concise relationship. The latter was surprising, as it was suspected, from experience, that coarser sediments in the fill (particularly shell hash) would result in steeper upper slopes. For completeness, correlations of construction slope with the fine fraction, d_{16}, sorting parameter, σ, and skewness, α, were also made.

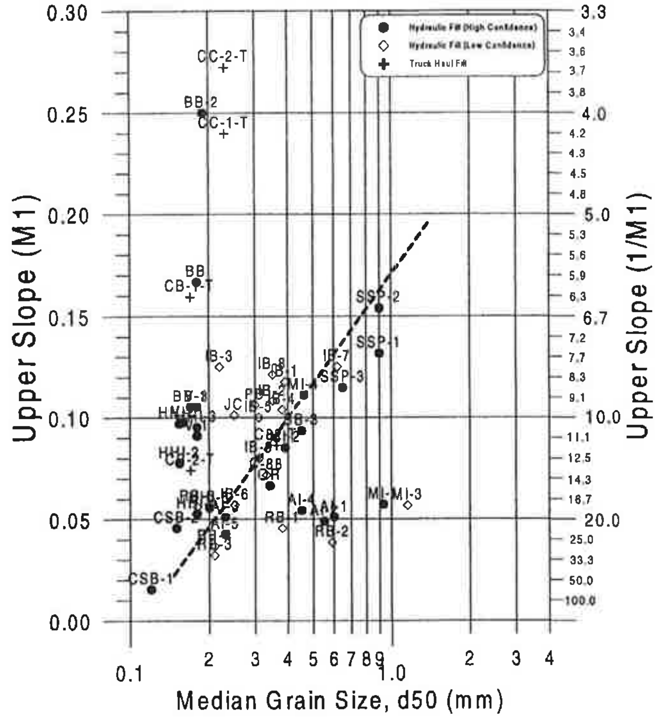

FIG. 8. Relationship between Median Grain Size and Upper Construction Slope

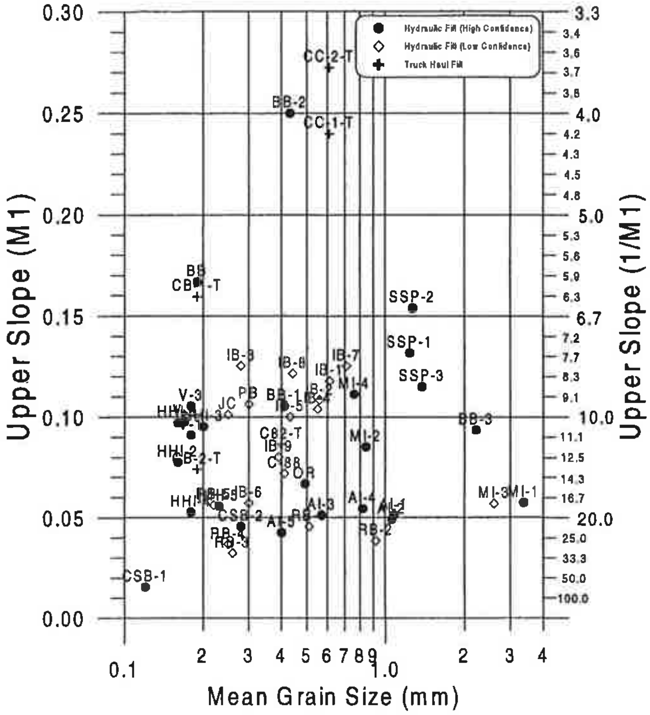

FIG. 9. Relationship between Mean Grain Size and Upper Construction Slope

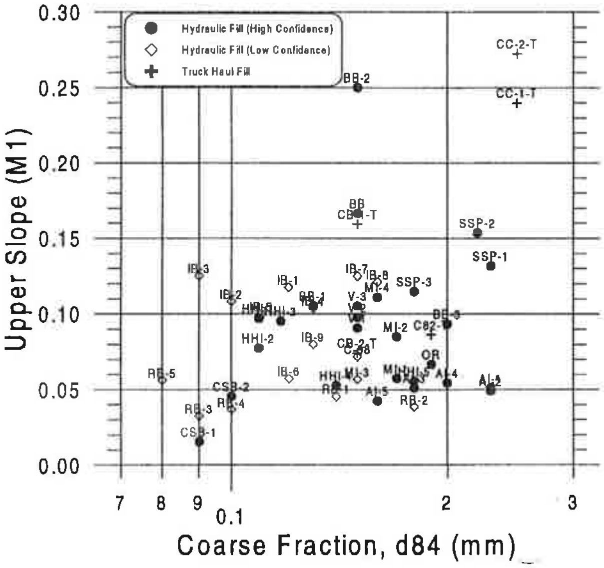

FIG. 10. Relationship between Coarse Fraction, d_{84}, and Upper Construction Slope

However, no discernable relationship resulted from these comparisons.

From the lack of an apparent relationship between the upper slope of the construction fill and sediment parameters, it is suspected that the upper slope may be primarily related to factors other than the fill sediment. Because most of the upper portion of the fill is constructed above the mean water level, the contractor has more control over the discharged sediment and the ultimate shape of the construction slope. This argument is supported by a comparison of the specified slope and that which was actually constructed. For the high-confidence data points, the measured difference between the *specified* construction slope and the *as-built upper* slope is plotted against sediment grain size in Fig. 11(a). In the figure, it is clear that for numerous projects with a wide range of grain size characteristics, the upper slope was built essentially as specified. Therefore, it may be appropriate to assume that regardless of the beach-fill material characteristics, any reasonable slope above the slope break elevation can be constructed. Prudent design, however, typically dictates that the upper slope is at least as steep as that of the natural beach, or steep enough that the design (postequilibrated) berm width is not greater than the specified construction berm width. In contrast, there is greater general difference between the specified construction slope and the as-built *lower* slope [Fig. 11(b)].

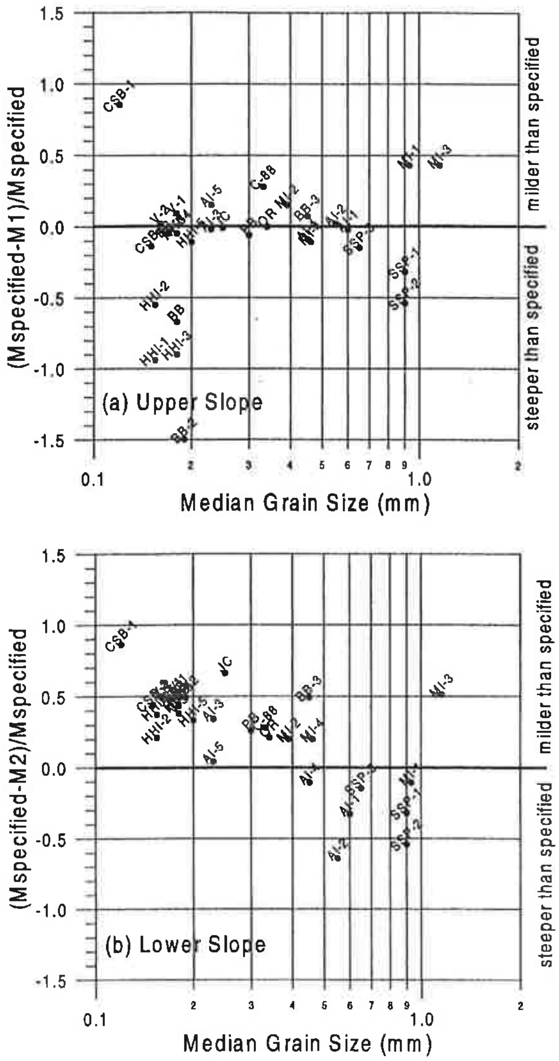

FIG. 11. Difference between "Specified" and "As-Built" Beach Fill Slope: (a) Upper Slope M_1; (b) Lower Slope M_2

Hydraulic versus Truck Haul Placement

No distinguishable difference between the slopes constructed by hydraulic fill and those constructed by truck haul fill, for a given grain size, was detected in the data. This may be due, in part, to the limited size of the database and the small number of truck haul fills included therein. It is expected, however, that the constructible slope for truck haul fills might be less sensitive to variations in sediment grain-size characteristics than those of hydraulic fills because the sediments are typically dry, placed above the mean high-water line, and shaped mechanically.

EXAMPLE APPLICATION

The results from this investigation may be useful in selecting construction slope(s) for a given beach-fill sediment source. As an example, assume that the median grain size, d_{50},

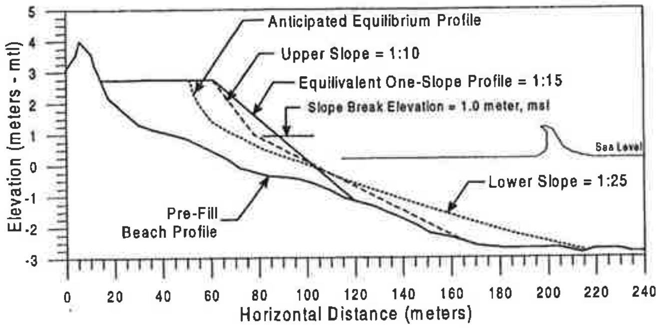

FIG. 12. Two-Slope and Equivalent One-Slope Construction Template Profile

of fill material for a proposed beach nourishment project is given as 0.21 mm and the local mean tide range is about 1.2 m. The project design calls for a sectional fill volume of 150 m^3/m. The predicted berm width after initial fill equilibrium, based upon examination of "healthy" equilibrium profiles in the area with similar grain size, is 35 m.

From Fig. 5 or equation (5), the slope break elevation would be at approximately 1.0 m above mean tide level. From Fig. 6, for $d_{50} = 0.21$ mm, the lower slope is expected to be approximately $M_2 = 0.04$ (1:25). Likewise, from Fig. 8, an upper construction slope of $M_1 = 0.055$ (1:18) would be consistent with other projects in the database, although any upper slope between $M_1 = 0.04$ (1:25) and, say, $M_1 = 0.11$ (1:9) may be reasonable. It is advantageous to specify the upper slope at a value equal to (or slightly steeper than) that of the predicted equilibrium profile—which, in this example, is about 1:11. A reasonable upper slope value is therefore specified as, say, 1:10. In the present example, specifying the upper slope equal to the lower slope (1:25) is not advisable, as this would result in a construction berm that is narrower than the predicted equilibrium berm. The resulting two-slope construction template is shown in Fig. 12.

The figure also depicts the equivalent one-slope construction template that best represents the two-slope profile, and which yields the equivalent sectional volume as the two-slope profile. In this application, it is seen that the two-slope profile, developed using the method described above, provides a foundation, or useful guidance, in specifying the one-slope construction template.

CONCLUSIONS

Based upon data collected from 18 beach fill projects in the southeastern United States, a correlation was developed between the constructed beach slope and the median (or mean) grain size of the fill material, below a specific slope-break elevation (Figs. 6 and 7). The data suggest that this slope-break elevation is related to the tide range plus a 0.43 m allowance for wave run-up for sites with tide ranges greater than about 0.7 m. For tide ranges smaller that about 0.7 m, there does not appear to be a correlation between tide range and the elevation of the break in constructed beach slopes. The slope of the construction berm above the slope-break elevation does not appear to be strongly related to sediment characteristics, but rather than be constructed at any reasonable specified slope. The results provided herein may provide design guidance in specifying beach profile construction templates for various borrow materials.

The present study did not consider variation in wave climate between project sites, though it is acknowledged that waves can significantly influence the slope of the placed beach fill, or at least the rate at which the slope of the placed fill resposes. It is reasonably assumed that the wave conditions during construction of the projects considered herein were mostly mild (i.e., wave heights on the order of 0.5–1.0 m), because dredging is typically suspended during larger wave events. The degree to which the correlations observed in this study may apply to other areas with significantly greater wave heights and/or tide ranges is uncertain. Accordingly, the addition of new data points to those presented herein will be of potential value and interest.

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APPENDIX I. REFERENCES

Bascom, W. N. (1959). "The relationship between sand grain size and beach-face slope." *Am. Geophys. Union Trans.*, 32(6), 866–874.

Christiansen, H. (1977). "Economic profiling of beach fills." *Proc., Coastal Sediments '77*, American Society of Civil Engineers, New York.

Dette, H. H. (1983). "Technique of small scale beach fills." *Conf. on Coast. and Port Engrg. in Devel. Countries*, Colombo, Sri Lanka.

E. A. K. (1981). *Emfehlungen fur die Ausfuhrug von Kustenschutzwerken (Recommendations for the performance of coastal works)*, Die Kueste, Heft 36, F.R. Germany.

Folk, R. L., and Ward, W. C. (1957). "Brazos River Bar: A study in significance of grain-size parameters." *J. Sedimentary Petrology*, 27, 3–26.

"*Manual on artificial beach nourishment*." (1987). Center for Civil Engineering Research, Codes and Specifications (CUR), Rijkswaterstaat, Delft Hydraulics, Delft, The Netherlands.

Shepard, F. P. (1963). *Submarine geology*. Harper and Row, New York.

Shore protection manual. (1984). U.S. Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, Miss.

"Tide tables of the East Coast of North and South America." (1984). U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, Md.

Wiegel, R. L. (1964). *Oceanographic engineering*. Prentice-Hall, Englewood Cliffs, N.J.

APPENDIX II. NOTATION

The following symbols are used in this paper:

d_{16} = beach-fill sediment grain size for which 16% of sample is finer;
d_{84} = beach-fill sediment grain size for which 84% of sample is coarser;
d_{mean} = mean grain size of beach fill material (mm);
d_{50} = median grain size of beach fill material (mm);
M_1 = as-built construction slope (rise/run) of beach fill above elevation, E;
M_2 = as-built construction slope (rise/run) of beach fill below elevation, E;
E = elevation of break-in-slope, relative to mean tide level (m);
T_R = mean tide range (m);
mtl = mean tide level;
σ = sorting parameter of beach fill material (mm); and
α = skewness of beach fill material.