A REVIEW OF THE ROLE OF GRAIN SIZE IN BEACH NOURISHMENT PROJECTS

Donald K. Stauble, PhD, PG
U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

ABSTRACT

This paper will provide a review of guidance on the various methods now in use to identify suitable material for beach nourishment and how to determine the volume of fill material required to provide a stable fill. Recommendations are provided to assess the relative compatibility of alternative borrow sources for beach nourishment and procedures for estimating fill volume requirements to provide the desired beach width. Two basic approaches are commonly used that apply grain size parameters to characterize the native (pre-nourished beach) and borrow area sediment in calculation of the overfill ratio and to apply the concepts of the equilibrium beach profiles in determining needed fill volumes. A newer approach of Q-mode analysis is suggested for a possible tool to assess suitability. Case Studies are used to examine actual project sediment behavior. Fill density is also examined as a measure of how the sediment suitability calculations measured up to actual fill behavior on these projects.

INTRODUCTION

Ideally, for any given beach nourishment project, the borrow material should be similar in grain size distributions to the native beach. Often the composition of fill material in available borrow areas is not the same. The correct analysis of sediment data is important to the design engineer and regulatory official in obtaining the following information about the project:

1) The suitability of borrow area sand for erosion control projects,
2) The volume of sand needed to obtain a level of storm protection desired,
3) Assessment of long-term sediment characteristics, fill stability and the need for renourishment.

Several techniques have been developed to identify suitable sand sources for beach fill material and predict the volume of this material needed to make a stable beach fill. No clear guidance exists on which of several approaches will provide a satisfactory method to predict fill behavior. Coastal engineers are required to predict the performance of the fill from the available borrow sources and to provide adequate fill material to meet the design criteria. Swart (1991) stated that the most reliable prediction of fill behavior is obtained when using sediment grain size parameters of native and borrow area, fill geometry and some measure of wave climate. Beach fill projects can be costly to construct and maintain. It is important to provide design guidance to optimize fill suitability and reduce operations and maintenance costs.

SEDIMENT SAMPLING

In order to estimate the performance of candidate borrow sources for beach nourishment, one must be able to obtain representative native beach and borrow sediment samples. ***The Native Beach:*** is a dynamic 3-dimensional feature that varies in form and sediment composition both temporally and spatially. Spatial variations may be present due to variations in the underlying geology of the area, transient morphology (such as beach cusps and bar features) and influences of shore protection structures (such as groins or inlet jetties). Characterization of the native beach can be divided into two interrelated tasks: collection and analysis of the native beach grain size distribution, and the beach profile (Stauble 1991a, 1991b). Beaches are made up of a variety of mineral components and contain a wide range of grain sizes that vary in both the cross-shore and long-shore directions. On a regional basis, the mean grain size influences the generalized beach slope, with coarser grain sizes associated with steeper beach slopes and flatter beach slopes having finer grain sizes (Bascom, 1959). While the main component of most beach nourishment project sediment is well-rounded quartz sand, many beaches may contain a few percent to almost 100 percent of components such as carbonate material (i.e. shell, coral fragments, aragonite), rock fragments (i.e. volcanic basalts, plagioclase, chert), and heavy minerals. The grain size distribution at any given point on the beach is a function of the energy of the cumulative coastal processes (i.e. wind, waves and currents) and mineralogy of the available sediment. In addition, color, shape and roundness, and sediment bulk density also play a roll in the choice of borrow sediment makeup and aesthetics of beach fill material.

There are noticeable differences in the grain size distribution as one proceeds from the dune base, across the beach and continues offshore as described by Bascom (1959). The coarsest grains are usually found in an area just seaward of the backwash/surf interaction zone, at the shore break plunge point, an area of high turbulence (Bascom, 1959, Zarillo, et al, 1985, Stauble, 1992). The berm crest area also contains significant coarse material due to runup sediment transport dynamics. Finer, better-sorted material is found in the dune area owing predominantly to wind transport processes. Seaward of mean low water, sediments become finer and better sorted at least out to depth of closure. Examples of this distribution are found at the Field Research Facility (FRF) beach at Duck, NC, where a long-term sediment study (Stauble 1992) found slight variations in seasonal sand distributions but this basic cross-shore sediment distribution persisted. A long-term sediment study of the Ocean City, MD beach fill project (Stauble and Bass 1999) also exhibited this cross-shore sediment distribution (in the native pre-fill beach sediment distributions, after fill placement and in the long-term fill resorting). Figure 1 shows an example cross-shore sample scheme at two of the profile locations and a plot of mean grain size versus cross-shore location over the entire study showing the coarsest sediment in the low tide/trough area, with fining in the inshore and offshore direction.

Several types of composite samples were examined (Stauble and Hoel, 1986) to determine which combination of beach samples eliminated spatial variability and provided the best comparison of actual behavior over time from various beach fill projects. The grain size distribution of these composite samples will vary depending on the location of the included samples. Two basic types of composites were chosen after an examination of various combinations of samples available from each project:

1) The *intertidal composite* consists of samples from within the intertidal zone, between mean high tide to mean low tide. This composite gave the best representation of the beach-fill behavior over time since this is the location of main fill placement and of subsequent fill reworking on most projects. The intertidal composite (high tide, mid tide and low tide samples) was usually coarser and resulted in a higher overfill ratio (requiring more fill to be placed to provide a stable fill due to coarser native composites relative to borrow), but long-term project performance was more favorable.
2) The *profile composite* consists of intertidal samples plus samples collected seaward of the swash zone to approximately the depth of closure (around 6 m (20 ft) depth on the east coast of the U.S.). This is a common type of composite used on most past projects. This composite was usually skewed to the finer grain sizes of the nearshore samples, which often was a good match to finer borrow material but over time more fill loss was measured on these projects.

Based on the composite samples and subsequent fill behavior over at least one year, the intertidal composite is recommended to better represent the native beach and provide a more accurate measure of the overfill ratio. The resulting higher overfill ratio required more fill to be placed but the project retained more fill volume within the first year than projects that used the profile composite.

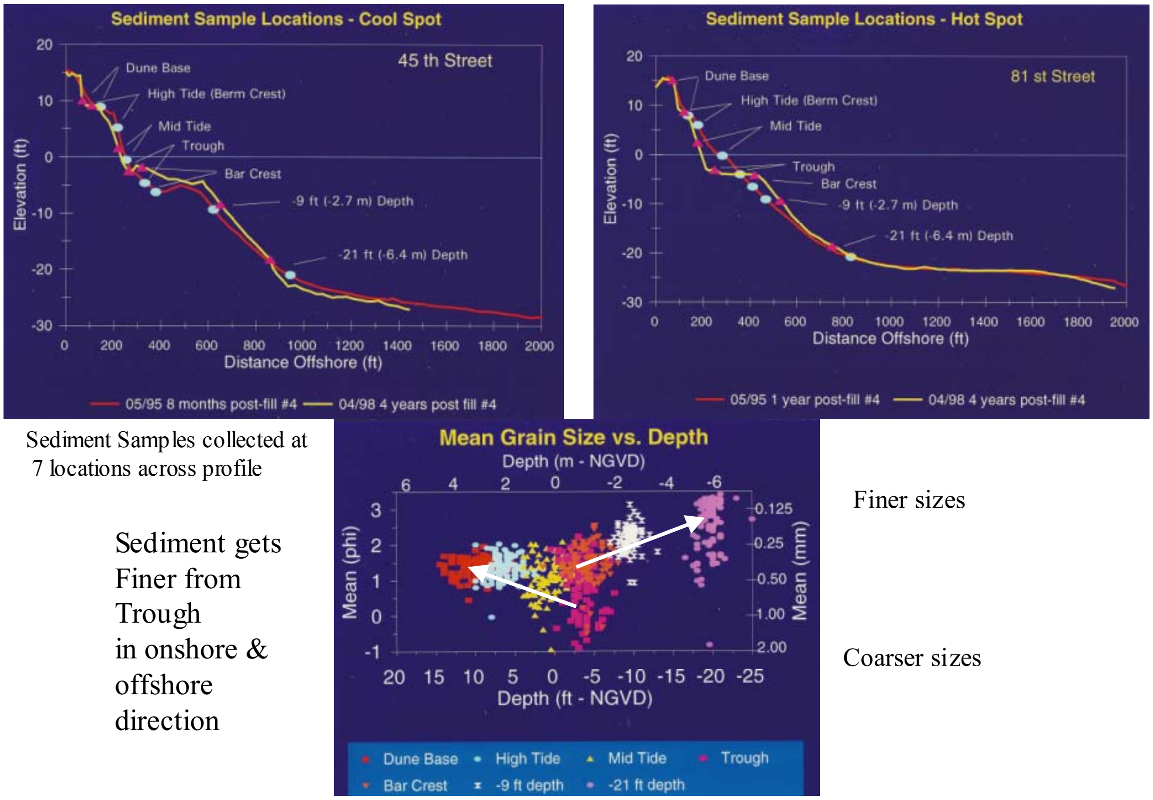

Figure 1. Sediment sampling at Ocean City, MD Beach fill project and sediment grain size cross-shore distribution (after Stauble and Bass 1999).

The Borrow Area: Fill material for beach nourishment can come from a variety of sources (Stauble and Hoel, 1986). Sand from *upland sources* such as dredge disposal areas or quarries has been trucked to a beach site. Sand from *inlet ebb and flood shoal mining*, *navigation channel dredging*, *sand trap mining* or *sand bypassing* has typically been placed on downdrift eroding beaches adjacent to inlets. *Estuarine or bay sand* deposits have been pumped across barrier islands and placed on the beach. *Nearshore shelf sand* sources (ridges and shoals) have been dredged by hopper or cutterhead dredges and pumped out onto the beach. Because the environment of deposition of a borrow area can be different from the beach to be nourished, the sediment distribution of the borrow area can vary from that of the beach on which it is placed. Variations in the distribution of borrow sands cause design challenges for determining what is stable fill material and what is environmentally suitable to be placed on the beach.

To characterize the variation in sediment distribution in the borrow area, several representative surface samples and cores are needed to adequately describe the three-dimensional nature of most borrow sources. Sediment samples are collected from representative sediment layers within each core. Core composite samples are made by combining sample data from within each core and borrow area composite samples are made by combining sample data from each core.

FILL FACTOR and FILL SUITABILITY METHODS

The grain size distribution of the borrow material will effect the slope of the nourished beach, the rate that the fill material will erode and how the fill will respond to storms (CEM, 2003). One technique utilized to predict borrow material performance is the overfill factor method (sometimes referred to as the fill factor). The technique uses the analysis of sediment grain size distribution data from the native beach and borrow area sediment to predict the volume of borrow material needed to produce a unit volume of stable fill material with the same general grain size as the native beach. Overfill models estimate the proportion of fill that will be retained after losses that occur following placement of fill. This method is based on the premise that the sediment distribution of the pre-nourished native beach is in equilibrium with the environmental forcing functions and that the fill sediment distribution is assumed to return to the pre-nourished native beach sediment distribution over time. The method provides a multiplier for the amount of borrow material needed to produce a stable unit volume of compatible native beach material (CEM, 2003). The multiplier is based on both the native beach and borrow sediment grain size statistics of mean and sorting, and is referred to as the overfill ratio. Currently three overfill factor methods exist, and use a graphical technique to calculate the overfill factor. Overfill factor calculations require the use of the phi scale in calculating the grain size parameters.

The first model developed was the Shore Protection Manual (SPM) Method by Krumbein and James (1965). This SPM Method compares the ratios of weight percentages of the native to borrow composites across the range of observed grain sizes to determine the grain size at which the ratio is at a maximum (which is identified as the critical grain size). One major weakness with this method is the assumption that a portion of the coarse stable fraction of the borrow material will be winnowed out along with the fine material to create a theoretical compatible grain size distribution that will remain on the beach after placement as shown in the area colored in green on Figure 2d. In the example shown, borrow material is finer and more poorly sorted than the native material (a common occurrence in many beach nourishment projects). The SPM method implies a selective sorting will occur in both the fine and coarse size fractions. Due to complicated mathematical equations all of the overfill methods use a graphical approach. The graphical technique requires that the mean and sorting of the native and borrow sediment be calculated and plotted. The x-axis is the ratio of the mean of the borrow sediment minus the mean of the native sediment ($\therefore_b$ - $\therefore_n$) over the sorting of the native sediment (F_n). The y-axis is the ratio of the sorting of the borrow material (F_b) over the sorting of the native material (F_n). Each model's plot (Figure 2a-c) is divided into four quadrants with Quadrant 1 (upper right portion) containing finer, more poorly sorted borrow sediment than native creating an unstable match (James, 1975). Quadrant 2 (upper left portion) contains sample comparisons where the borrow material is coarser and more poorly sorted than the native sand resulting in stable fill material. Quadrant 3 (lower left portion) has a coarser, better sorted borrow than the native. The overfill factor distributions in this quadrant usually do not occur but should be stable. Quadrant 4 (lower right portion) has finer, better sorted borrow material. Overfill factors usually do not occur in this quadrant but should be unstable with an expected high loss of finer fill material if they are encountered. Figure 2a shows the SPM method plot; with possible overfill values only in Quadrants 1 and 2.

Dean (1974) developed a second method to overcome the problems with the SPM method not accounting for the stability of the coarser material. Dean's method assumes that only the finer material will be removed until the mean of the modified fill equals the native mean. This model predicts stability of all grain sizes when the borrow material is coarser and more poorly sorted than the native material, even though the finer material will be removed. The blue area on Figure 2d shows the stable portion of the grain size distribution based on the Dean method. Dean's

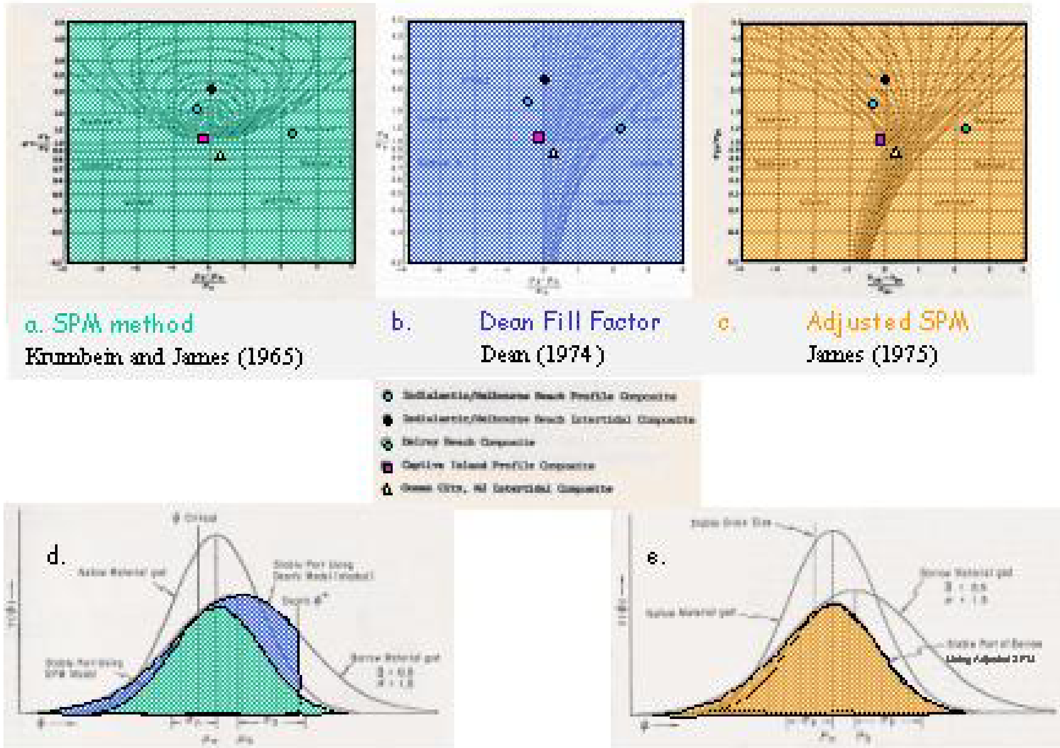

Figure 2. Fill Factor method graphs and plots (after James 1975 and Stauble and Hoel 1986).

method plotted using the same graphical technique is shown in Figure 2b, with the lines indicating the volume of borrow material needed to be placed on the beach to obtain one unit of compatible beach sediment are all in the unstable right side of the graph. Dean's method requires that the stable part of the borrow sediment have a mean coarser than or equal to the native mean, and that near total loss will occur in the fine fraction below some size (N^*). This value is determined by equating the means of the native and the stable part of the borrow material distribution.

The SPM method cannot be applied where the native material is more poorly sorted than the borrow material (Quadrant 4) and also provides unrealistic values when the borrow material is coarser than the native material (Quadrant 3) (James, 1975). The SPM method predicts higher overfill factors and may overestimate fill volume needed and should be considered an upper bound of fill volume required. The Dean method predicts lower overfill factors and may underestimate fill volumes needed and should be considered a lower bound on volume required.

The Adjusted Shore Protection Manual method developed by James (1975), corrects certain limitations of the first two methods. The SPM model assumes that the overfill factor will be equal to the "critical ratio" which represents the grain size for which the ratio of native to borrow material grain size distribution is a maximum. The Adjusted SPM assumes no sorting losses at this grain size or any coarser sizes. This results in a modified grain size distribution which is as close as possible to the proportions of the native distribution in the finer size classes (which allow for some fine grain material similar to the native beach), but retains the borrow characteristics of the coarser size classes (orange in Figure 2e). This adjustment solves the problem of loss of coarse material in the SPM method and allows some retention of finer material not accounted for in the Dean method. James (1975) presented a new graph (Figure 2c) of the Adjusted SPM plot that differs from the SPM plot in Quadrant 2. It allows for stable fill calculations in Quadrant 3 which can be above unity and in Quadrant 4 the Adjusted SPM plot allows for solutions where the fill and borrow are similar. Typically, the Adjusted SPM method produces fill factors less than the SPM method, but greater than the Dean method (Hobson, 1977).

CASE STUDIES

To provide a technique to evaluate how well the fill factor models predict the behavior of borrow material a review of several projects was done to evaluate the redistribution of fill sand post-placement (Stauble and Hoel, 1986). The overfill factor is defined as the volume of borrow material required to produce a unit volume of stable fill material. Thus a overfill factor of 2 means that ½ of the borrow material is unstable and twice the design volume of borrow area sediment would have to be placed on the beach to provide the desired protection. To assess how well the predictions work on actual projects, several projects were evaluated (Stauble and Hoel 1986). Three examples of change in sediment distributions from one year post-placement on two projects and eight years post-placement on one project are presented here that compared the native beach with the borrow and post-fill sediment. The percentage of fill volume lost in the first year was measured by profile change. The post-fill calculation is a variation of the pre-fill overfill factor calculation substituting the long-term mean and sorting in place of the borrow and then comparing the ratio of native beach to longer-term fill material grain size distribution data. A comparison of what actually happened to the fill with what the model predicted provided an idea of how the models actually worked.

Sediment samples from the 1982 Ocean City, NJ fill project consisted of intertidal samples only. The native-borrow comparison (Figure 3a), shows that both the native (green curve) and borrow (blue curve) had very well sorted samples with the borrow material having a lower percentage in the 0.177 to 0.125 mm (2.5 to 3.0 phi) range and excess sand in the 0.105 to 0.044 mm (3.25 to 4.5 phi) range. The excess fine material in this borrow distribution is due to its Great Egg Harbor Inlet flood shoal origin. The native mean was 0.171 mm (2.55 phi) and a sorting of 0.58 phi as compared to the borrow mean of 0.149 mm (2.75 phi) and sorting of 0.50 phi. Some of this excess fine material was immediately transported offshore during placement by hydraulic dredge. The fill factor was calculated at 1.75. One year later the fill material had returned to a native like grain size distribution as shown by the magenta curve in Figure 3b.

The borrow material for the 1981 Indialantic/Melbourne Beach, FL fill contained excess coarse shell material (4.0 to 0.5 mm, -2.0 to 1.0 phi), excess fine-grained material (0.18 to 0.04 mm, 2.5 to 4.5 phi) but was significantly deficient in the 0.5 to 0.18 mm (1.0 to 2.5 phi) medium sand range due to its origin as upland stockpiled material from dredging of the Port Canaveral navigation channel and turning basin. This sand was trucked to the placement site. Figure 4a compares the intertidal composite (green curve) with the borrow material (blue curve). The native mean was 0.32 mm (1.62 phi) and exhibited a sorting of 0.72 phi, while the borrow mean was 0.33 mm (1.59 phi) with a sorting of 1.61 phi. Though the mean grain-size was similar, the borrow material was more poorly sorted and significantly bi-modal with a fill factor of 1.10. This emphasizes the importance of looking at the entire grain size distribution when determining the suitability of a borrow material for a beach, and not just using the mean and sorting values alone. One year later, the fill had resorted itself back to close to the native distribution (magenta curve) with a loss of the fine material (Figure 4b).

The Delray Beach, FL fill project of 1974 was an interesting placement of much finer borrow material (blue curve) on a relatively coarse native beach (green curve). The offshore borrow source area sediment contained a large excess of fine-grained material 0.25 to 0.044 mm (2.0 to 4.5 phi) and is deficient in the larger sand-sized fractions 2.0 to 0.25 mm (-1.0 to 2.0 phi). The native beach (profile composite only data available) had a mean and sorting of 0.49 mm (1.02 phi) and 0.57 phi respectively. The borrow material had a mean and sorting of 0.21 mm (2.27 phi) and 0.67 phi respectively. This is an extremely large difference in mean grain-size, but the sorting was similar (Figure 5a). The fill factor was greater than 10. Large losses of the fine-grained sediments were seen initially and eight years later the sediment was still finer than the native beach (magenta curve in Figure 5b). This project is an example of the borrow area sediment distribution permanently changing the distribution of the beach after placement.

PROFILE EQULIBRIUM METHOD

Another approach to estimating overfill quantities (and more directly the volume of fill material required to provide a given design beach width) are based on the equilibrium beach profile concept. Each profile is the result of past and present forces that have acted to shape the profile and a wealth of information is contained within its form and sediment texture (Dean et al, 1993). This method was originally developed by Dean (1991) to determine the volume of fill material needed to produce a desired width of subaerial beach. This method includes the effects of coastal processes that shape the native and filled beach profile along with grain size information. The equilibrium beach profile concept assumes that most beach profiles are similar in that 1) they are generally concave upwards, 2) the coarser sediment beaches have steeper profile shapes and finer grain beaches have a flatter slope and 3) storm waves tend to transport sand seaward, reducing the beach slope and result in beach recession (Dean, 2002).

The equation to calculate an equilibrium profile was proposed by Bruun (1954) as:

$$h = Ay^{2/3} \quad\text{……………..(1)}$$

where h is the water depth, A is the so-called "profile scale parameter" (Dean, 2002) and y is the distance seaward from the shoreline.

The A parameter has been correlated with sediment grain size (D) by Moore (1982). The relationship is shown in Figure 6a. The A value is a single value for the entire beach profile. As has been shown, the mean grain size changes along a typical profile. For initial discussion, a single "representative" mean grain size will be used to determine the profile A value. It is not stated in the literature how to choose a single representative grain size to use to determine the A value. Most of the literature on this type of analysis uses a single value to characterize the grain size of the profile, which is either the median (D_{50}) or mean of possibly a composite of all samples along that profile.

The equilibrium profile model provides more information on the processes that are at work on the beach to be nourished. The choice of the sediment scale parameter A value is important in matching the equilibrium profile to the native beach and to the proposed fill profile once the project is constructed. An accurate measure of volume needed to provide storm protection will depend on the choice of grain size distributions of the native and borrow sediment and how they are applied in the model. Finer grain sizes produce a flatter sloping beach profile and coarser grain sizes produce a steeper sloping beach profile. Different available borrow grain sizes can form different design profiles (Figure 6b). The volume of fill required to provide a given level of protection will be a function of the fill profile slope that can be achieved with a given grain size.

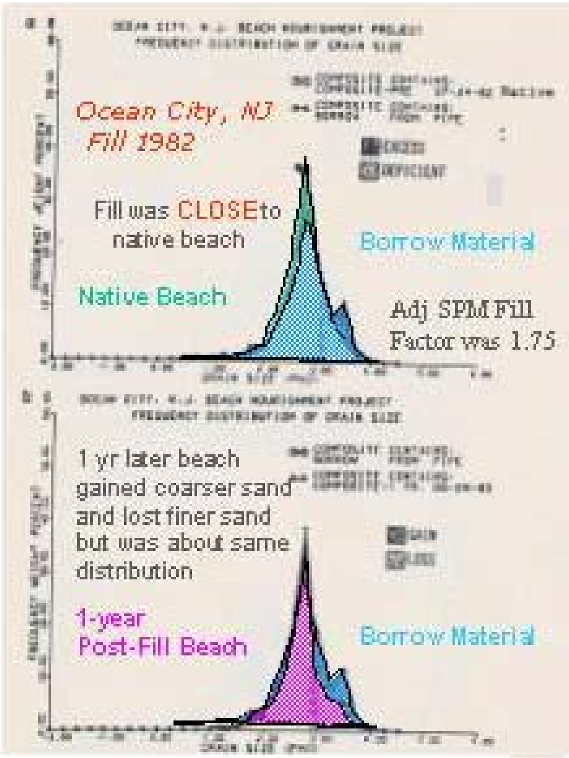

Figure 3. Change is grain size at Ocean City, NJ (after Stauble and Hoel 1986)

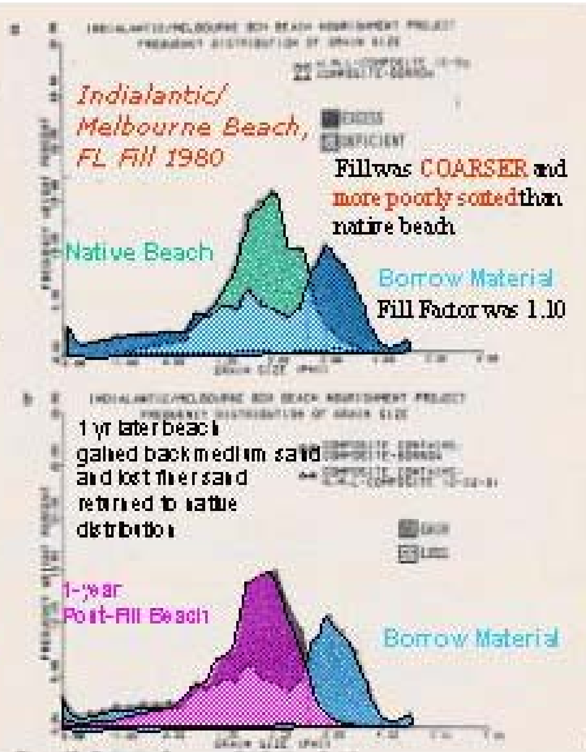

Figure 4. Change in grain size at Indialantic/Melbourne Beach, FL (after Stauble and Hoel 1986)

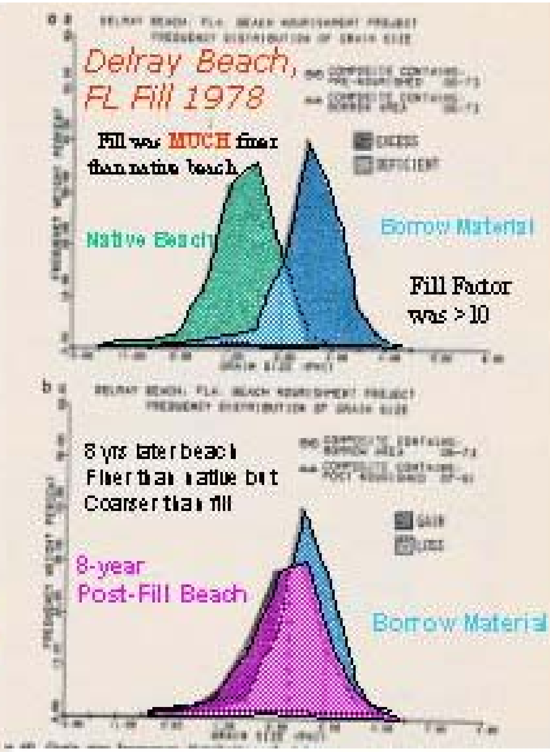

Figure 5. Change in grain size at Delray Beach, FL (after Stauble and Hoel 1986)

Design fill profiles given the native and fill grain sizes result in three profile types. The nonintersecting fill profile is formed when the fill grain size is coarser (represented by A_F) than the native beach (A_N). When the fill median grain size is similar to the native a nonintersecting profile is formed with a fill slope similar to the native beach but translated seaward. Finer fill material will form a nonintersecting profile with a narrow berm and flatter equilibrium slope.

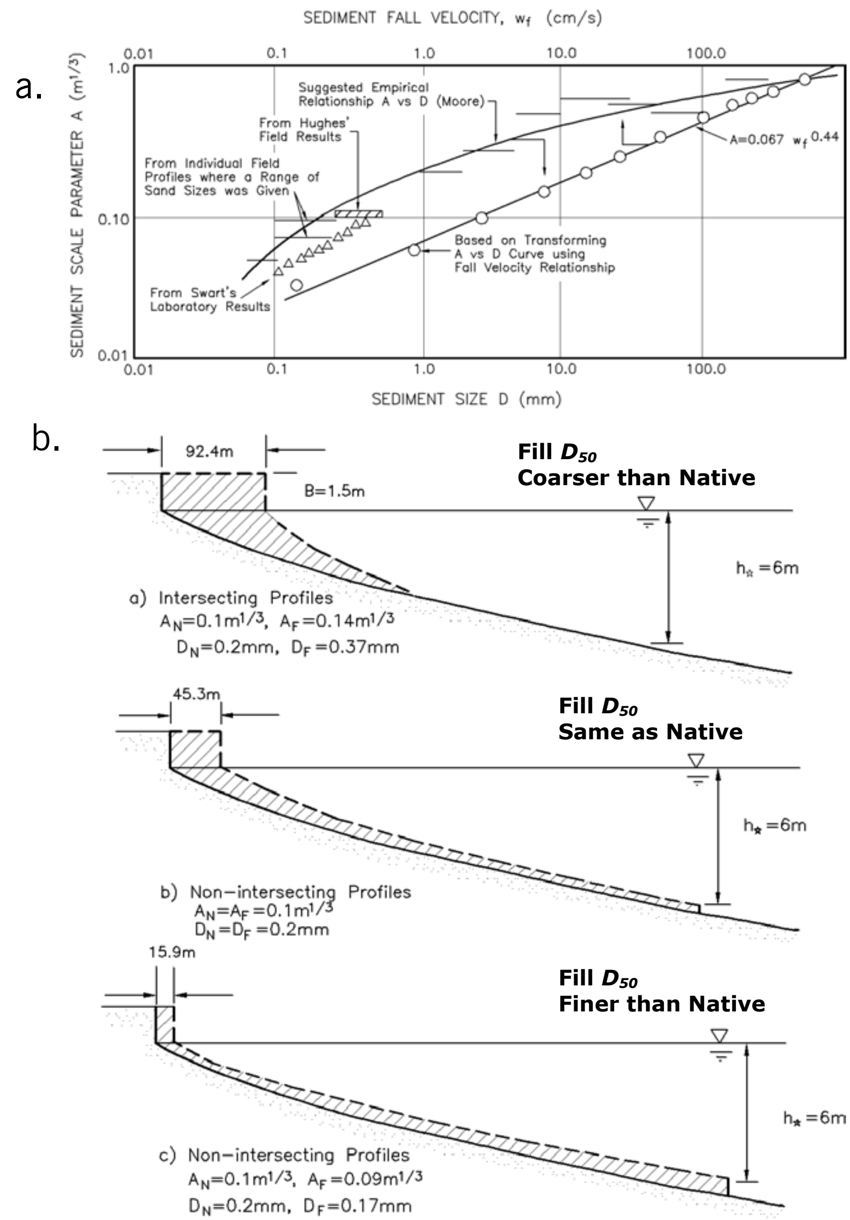

Figure 6. Dean Equilibrium Beach as a function of grain size a) *A* value as a fuction of grain size, b) three types of fill profiles depending on comparision of native to fill grain size (after Dean 2002)

The equilibrium profile shape is a smoothed curve of the $Ay^{2/3}$ form. The sediment scale parameter A is a function of grain size, with coarser sediment producing a larger A and a steeper profile form. The equilibrium profile shape also is based on the prevailing coastal processes that also influence the profile shape. The goodness of fit of the equilibrium profile to the actual profile indicates how out of equilibrium the profile is. Some projects, where sediment is well sorted and the native and borrow sands have a similar composition, have an equilibrium profile shape that matches the native form well. When the borrow material is not as well matched, the equilibrium profile shape deviates from the native profile and the correct calculation of required volume and dry beach width is less accurate.

While the equilibrium profile method was not used in the design of the Ocean City, MD project, 10-years of data exist on profile response and fill sediment resorting. A brief comparison of fill behavior at Ocean City, MD over ten years with profile equilibrium methods was done to examine applications of the A values (from actual sediment data) to the actual fill behavior. Two profile locations were used, one at 56th Street (represents a typical profile location) and one at 81st

Street (a hot spot profile area). The native profile and sediment data was collected in June 1988. The borrow material and fill profile was represented by the post-fill profile and sediment collection of September 1988, almost immediately after the State of Maryland Fill was placed. The post-fill sediment is representative of the borrow material since it was collected within a short time of actual placement. The Ocean City, MD project was a phased nourishment project, beginning with the State Fill, which placed 2.1 million cu m (2.7 million cu yd) of fill along the entire 12.9-km (8-mile) beachfront in 1988 from a finer Borrow Area 2. In 1990 and 1991, a Federal fill placed an additional 2.9 million cu m (3.8 million cu yd) of fill along the beach (southern portion of project in 1990 and northern portion in 1991 from two separate offshore borrow sources). This fill included a storm berm and dune feature and both borrow areas were coarser than the native beach. A series of storms impacted the area (Stauble and Bass, 1999) and the project was rehabilitated with an additional 1.2 million cu m (1.6 million cu yd) in 1992. This material was also coarser than native sediment. Additional storms required a second rehab with placement of another 0.9 million cu m (1.2 million cu yd) in 1994, again from a coarser borrow area. A total of 7.2 million cu m (9.4 million cu yd) were placed on the beach from 1988 through 1994. Monitoring was continued through 1998, to provide a long-tern 10-year evaluation of profile and sediment changes.

The BMAP program was used to plot equilibrium profiles based on A values input from the sediment data. Two A values were used, one based on the mean grain size of the composite of the foreshore area (consisting of the high tide, mid tide and low tide samples) and a nearshore area (consisting of the bar, -1.5 m (-5 ft) and -6.1 m (-20 ft) samples). An A_{Nf} was calculated using the native sediment foreshore composite mean grain size and A_{Nn} was calculated using the nearshore composite mean grain size at each of the two profile locations using the June 1988 data. All equilibrium profiles were calculated from the water line seaward past the closure depth, which was -6.1 m (-20 ft) at 56th Street and -6.7 m (-22 ft) at 81st Street. An A_{Ff} was also calculated using the post-fill foreshore composite mean grain size and A_{Fn} was calculated using the post-fill nearshore composite mean grain size at each of the two profile locations using the September 1988 data. An A_{F10yr} was also calculated using the 10-year post-fill foreshore composite mean grain size and A_{F10yr} was calculated using the 10-year post-fill nearshore composite mean grain size at each of the two profile locations using the April 1998 data.

Figure 7 shows the actual native profile and the equilibrium profiles using the foreshore and nearshore composite data at 56th Street. From the shoreline out to closure the coarser foreshore composite A_{Nf} value provides a closer fit to the actual profile. The equilibrium profile is a smooth representation of the actual profile and averages out the bar/trough morphology. Figure 8 shows the actual native profile and equilibrium profiles using the foreshore and nearshore composite data at the hot spot at 81st Street. Again, out to closure the coarser foreshore composite A_{Nf} value provides the closer fit to the actual profile. Because this area is a hot spot, the 81st Street profile is deficient in sand so the actual profile is below the equilibrium profile in the nearshore area. It is interesting to note that if the equilibrium profile is carried out a long distance offshore, the nearshore A_{Nn} eventually gives a better fit to the actual profile, but the area landward of closure where the fill was actually placed is better predicted by the foreshore A_{Nf} value. For the 1988 State Fill, the borrow area sediment was finer than the native sand and Figure 7 shows the actual post-fill profile and calculated equilibrium profiles based on the post-fill sediment data at 56th Street. The almost immediate post-fill profile is not in an equilibrium concave shape and the equilibrium profiles of both the foreshore composite and nearshore composite do not match the profile shape. The equilibrium profiles are shallower than the actual profile reflecting the finer grain sizes of the fill. The same post-fill analysis can be seen in the hot spot at 81st Street (Figure 8), where the actual fill profile is much steeper than the equilibrium profile shape. The coarser foreshore A_{Ff} eventually meets the actual profile around the closure depth, indicating the fill has

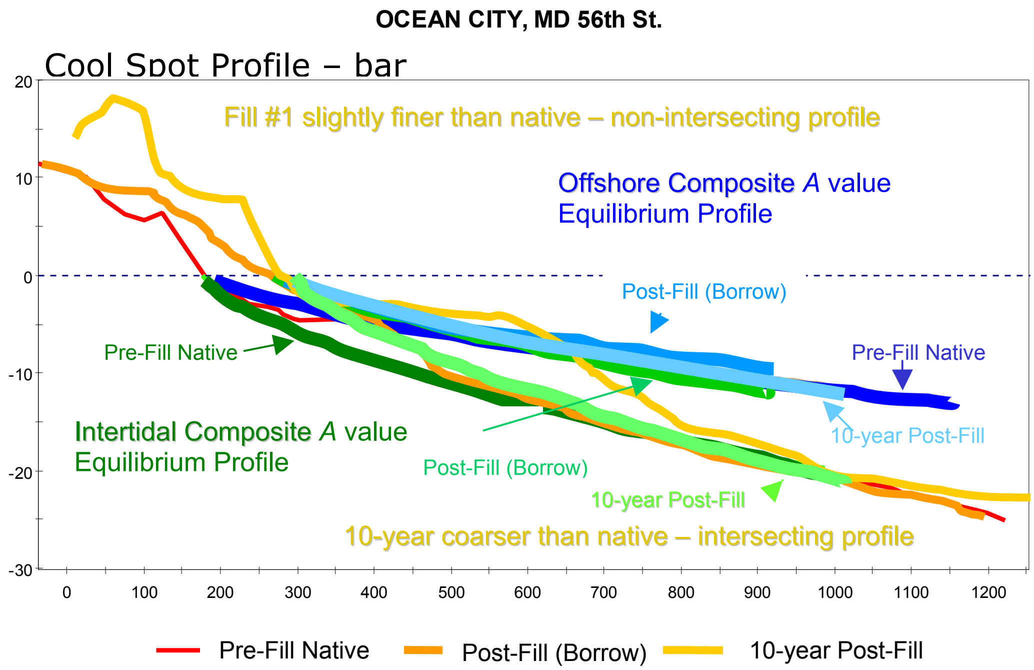

Figure 7. Equilibrium profiles using actual sediment data for the pre-, post-, and 10-year profiles at 56th Street, Ocean City, MD project.

not had time to reach an equilibrium shape. While not shown, the actual post-fill profiles come closer to the calculated equilibrium form using the actual post-fill grain size data within 8 to 10 months after fill placement, indicating that the profile reached an equilibrium shape by that time. Figure 7 shows the long-term profile change and calculated equilibrium profiles using the 10-year post-fill sediment data at 56th Street. The project storm berm and dune features are prominent even four years after the last nourishment. The equilibrium profile smoothes out the large nearshore bar form. The remnant coarser, borrow sands result in a steeper foreshore equilibrium profile that matches the pre-fill profile shape (the 10-year smoothed profile shape reflects fill resorting back to a coarser than native grain size distribution). The nearshore equilibrium profile has a flatter slope due to the finer sands in the nearshore composite. The coarser sands of the long-term profile forms an intersecting type profile landward of the closure depth. The erosional hot spot area at 81st Street has a long-term profile shape without a large nearshore bar feature. This long-term equilibrium profile based on the foreshore composite mean grain size follows the shape of the profile out to closure depth (Figure 8). The equilibrium profile based on the nearshore composite mean follows the shape of the longer profile shape seaward of closure depth, which includes a nearshore shoal feature. The hot spot beach has a more concave profile with a minimal nearshore bar as compared with the more typical 56th Street beach profile.

This analysis suggests that the foreshore composite mean provides a better *A* value to the equilibrium profile from the shoreline to the depth of closure than the nearshore composite mean does in matching actual profile shapes. As in the overfill factor calculations, the foreshore composite mean grain size values give a better indication of actual sediment data on beach fill projects. The equilibrium profile analysis using the foreshore composite mean values produced a smoothed profile shape close to the actual beach profile (without the bar feature), and should give a better profile shape to calculate volume of fill needed.

81st St - HOT SPOT.

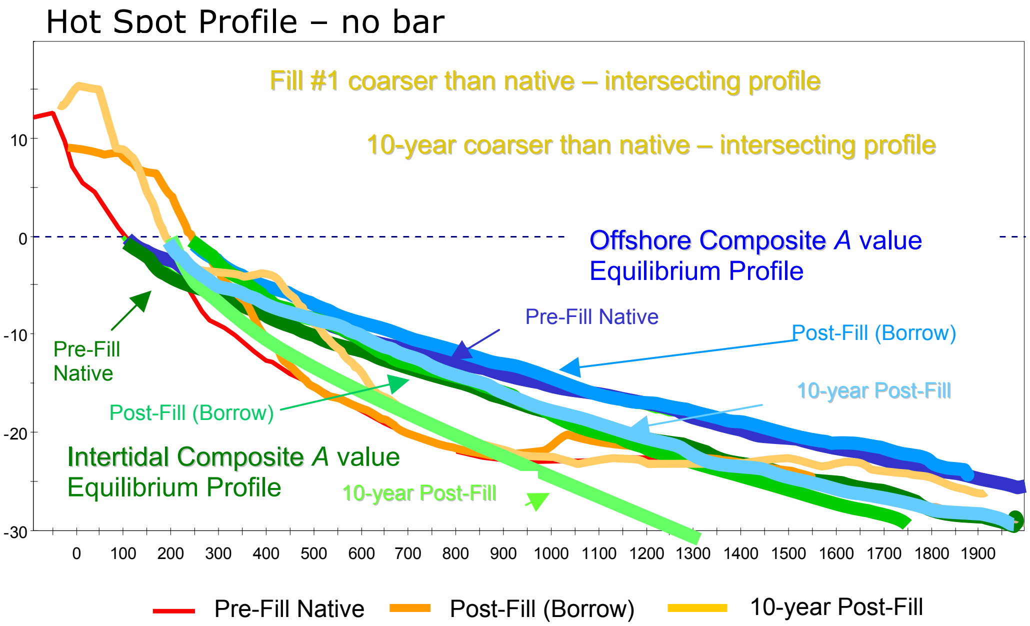

Figure 8. Equilibrium profiles from actual sediment data at a hot spot for the pre-, post-, and 10-year profiles at 81st Street, Ocean City, MD project

Q-MODE ANALYSIS

Analysis of a suite of sediment samples using just the mean and standard deviation or median values is somewhat limiting. The use of Q-mode factor analysis (Klovan, 1966) provides a method to determine the relationship between grain-size distribution and variability in the 3-dimensional sediment distributions of the beach and nearshore. Q-mode factor analysis, as applied to sediment investigation, involves the determination of interrelationship between sediment grain size distributions. With this method, a group of sediment samples can be arranged into a meaningful order so that the relationship between each sediment distribution is deduced. One of the main advantages of Q-mode factor analysis is that the entire grain-size distribution is considered in the analysis, yielding a detailed relationship especially when ¼ phi sample intervals are used. Using an analytical method to determine statistical relationships is more objective because it does not require arbitrary statistical descriptors or a-priori knowledge of the environment and location of samples (Klovan, 1966). A large number of samples can be objectively analyzed without having to manually compare each pair of curves. This reduces the "human interpretation" in relating large numbers of grain size distributions.

While this method has not been used with beach fills, it has been used to characterize the depositional patterns of a suite of sediment samples at inlets and infer sediment pathways (Stauble and Cialone, 1997) and a study to couple the beach profile evolution, sediment deposition patterns and their resulting grain size distributions with the physical processes active at a native pre- and pos-t storm beach (Stauble and Cialone, 1996). This method may provide a way to use the entire sediment grain size distribution of a native beach and borrow area to identify fill suitability and some indication of fill behavior. More research is needed to apply this analysis to beach fill projects to see if there is a way to utilize the results to improve beach fill sediment suitability and stability determination.

FILL DENSITY

Fill volumes of greater than 175 cu m/m (70 cu yd/ft) of beach were found to provide a greater than 70% retention of fill after one year based on review of several projects (Stauble and Hoel, 1986). Fill volumes less than the above resulted in projects with high fill losses in the first year. Inherent in the equilibrium profile model is the relationship between the mean grain sizes of the native and borrow sediment. Further research is needed to assess how well the method actually predicted dry beach width, on actual projects using a single A value. Recent work has attempted to apply several A parameters along the profile to better match the actual profile shapes and grain means, when multiple sand samples are available. Limits to the use of the equilibrium profile method include the fact that the modeled smoothed profile shape does not include the dry beach, where the profile shape is at its steepest slope and on profiles with a large bar/trough morphology. The use of the equilibrium profile method assumes a smooth profile through the bar/trough area and will under predict volumes needed. The use of multiple A values complicate the calculation of the volumes needed based on native and predicted borrow profiles but may be worth the effort in complex coastal systems. A single foreshore composite A value may be adequate to calculate volumes needed, but more study of actual projects is needed to verify this technique.

CONCLUSIONS

When the native and borrow sediment grain size distributions are similar, the native beach response over time is a good indication of how the borrow will behave when placed on the beach assuming that the native grain size is in equilibrium with the prevailing coastal processes. More uncertainty is introduced in the design process when the native and borrow sediments have different grain size characteristics. The overfill factor and equilibrium profile methods have been commonly used to determine borrow area suitability and the volume of fill needed to produce a desired level of shore protection. Each method requires a grain size analysis of both a representative sample of the native beach and the borrow area through standard sieve analysis. The mean or median grain size value and the sorting value are determined from the sieve analysis and are used in calculations.

The Overfill Factor Method uses the mean and sorting values of the native and borrows sediment. The Adjusted Shore Protection Manual method gives the best estimate of fill material to predict the volume of borrow material needed to produce a unit volume of stable fill material with the same general grain size as the native beach. This method does not take into account any coastal processes or profile changes. It should be used only to determine if the borrow material will be suitable to be placed on the beach, and give a ballpark value of a multiplier of how much borrow material will be needed to produce a stable fill. Overlaying a frequency curve of the representative native and borrow material will show the overlapping grain sizes and the excess or deficient grain sizes of the borrow material as compared to the native beach. The use of the foreshore composite in calculating the native beach and post-fill borrow sediment grain size data gave the best fit to actual fill project behavior and long-term resorting evaluation.

Sediment characteristics also play a role in the use of the Profile Equilibrium Method in the choice of the A value that is used in the calculation of equilibrium profiles of the native beach and design fill profile. Data collected during the monitoring of the Ocean City, MD beach nourishment project included profiles and sediments. The *foreshore composite* mean grain size produced a good A_{Native} and A_{Fill} value that produced an equilibrium profile that matched the actual pre- and post fill profiles. Long-term 10-year post-fill profiles also showed that the coarser fill created an intersecting profile with fill material still on the beach. This post-fill A_{10yr} using foreshore composite values gave equilibrium profile shapes that matched the actual profiles. A typical profile and a hot spot profile were compared, with the typical profile showing a large nearshore bar and the hot spot profile with a concave non-bar nearshore. The foreshore sediment composite data provided a better equilibrium profile shape than the nearshore composite data at both locations.

The CEM (2003) suggests methods for computing fill volumes and the shape of a design profile when the borrow material is of a different grain size distribution than the native beach. The design beach profile shape should be estimated based on the equilibrium profile concepts. A good representative beach profile of a sediment-rich native beach is translated seaward the distance of the added berm width after fill is placed. The part of the profile from the water line to depth of closure is translated seaward an additional distance based on the differences in the theoretical equilibrium profile shape based on an *A* value of the borrow sediment mean grain size. Finer borrow sands will produce a gentler nearshore slope and coarser borrow sands will produce a steeper slope. If a bar is present as in the 56th Street case, the equilibrium profile will smooth the bar feature. Additional volume is added for a particular dune and berm configuration and any advanced fill requirements

Additional research is needed to improve the suitability determination of a borrow material. New Q-mode analysis suggest using the entire grain size distribution to quantify the suitability and stability of all grain sizes of a borrow area as compared with native sediment. Fill density greater than 175 cu m/m (70 cu yd/ft) placed appears top play an important role in fill stability after one year based on case studies somewhat independent of grain size data alone.

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