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Analysis of nourished profile stability following the fifth Hunting Island (SC) beach nourishment project

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Abstract

A comparison of the geotechnical properties of beach fill vs. borrow area sediments for the fifth Hunting Island (SC) beach nourishment project is presented in this paper. Sediment samples were taken from the beach and borrow area to characterize pre-nourishment (1990) and post-nourishment (1993) conditions. Grain-size frequency curves were developed for these samples which were then used to perform the geotechnical analyses. The results indicate that post-nourishment profile stability can be improved measurably by variations in grain-size distribution, specifically where a coarse fraction is present (i.e., negative skewness). In other words, by using borrow sediments that are coarser than native, the nourished profile will adjust to a steeper configuration, producing a wider dry beach. Other factors influencing profile durability include fill placement techniques and environmental factors (waves, currents, storms, etc.). © 1998 Elsevier Science B.V.

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1. Introduction

Hunting Island, SC, has experienced severe erosion for over 100 years and is expected to continue eroding in the future. Average annual erosion rates have exceeded 35 m^3/m [14 cubic yards per foot (cy/ft)] since the 1960s (USACE, 1977). A federal nourishment project presented in a report to Congress involved four beach fills (1968, 1971, 1975, and 1980) totalling approximately 2.7 million cubic meters (3.5 million

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cubic yards) over the ~6400 m-long (~21,000 ft) island shoreline (USACE, 1964). These beach fills demonstrated that the rate of erosion can only be mitigated by frequent nourishment at relatively high unit (section) volumes.

Fig. 1 shows a general map of Hunting Island (SC) and includes a conceptual model of wave and sand transport patterns in the project vicinity. Note that the shoals are defined by the −1.8 m (−6 ft) mean low water contour as defined by NOAA (1985). Based on empirical evidence, the following factors appear to be most important for causing erosion at Hunting Island, SC (CSE, 1990):

1. Wave refraction around and diffraction between offshore shoals, producing longshore transport at the shoreline away from the center of the island;
2. Existing shoreline morphology which is out of equilibrium with normal wave approach directions;
3. Flood-tide currents associated with the St. Helena Sound ebb-tidal delta (a major entrance channel north of Hunting Island) and, to a lesser extent, Fripp Inlet (a moderate-sized inlet at the south end of Hunting Island) which have the tendency to shift sediment toward the ends of the island; and,
4. Sand trapping by the ebb-tidal deltas of St. Helena Sound and Fripp Inlet which may have both enlarged over the past 70 years (Stapor and May, 1981).

The gross and net longshore transport induced by wave refraction and diffraction between offshore shoals has been estimated to be 100,000 m^3/yr and 11,000 m^3/yr, respectively (May and Stapor, 1996). The estimated volume of sand trapped by the St. Helena Sound and Fripp Inlets are 622 million m^3 and 42 million m^3, respectively. These factors cause a considerable reduction in the volume of sand that would be available to the beach.

The mean significant breaker height and period of waves in the project area has been computed for February and June 1980 as 58 cm and 6.2 s, respectively, based on approximately 450 LEO (littoral environmental observations) measurements obtained near the center of Hunting Island (McCreesh, 1982). Visual measurements every 3 h yielded a much greater range of breaker heights in February (35–230 cm) vs. June (25–130 cm), but virtually the same computed mean height for each month.

Hunting Island experiences winds and storm patterns that are fairly typical for the South Carolina Coast. During winter, prevailing winds are northerly and northeasterly with approximately 10–12% exceeding 20 mph. Generation of extra tropical storms from these directions is the primary concern during this period. During summer, prevailing winds are less severe and are southerly with 12–14% exceeding 15 mph. Hurricanes are the primary storm concern during this period.

The Island experiences semidiurnal mixed tides, meaning that there are two highs and two lows per day of unequal elevation. The mean tidal range is 1.9 m, and the mean spring tide range is 2.2 m with a marked diurnal inequality in tide range (NOAA, 1993).

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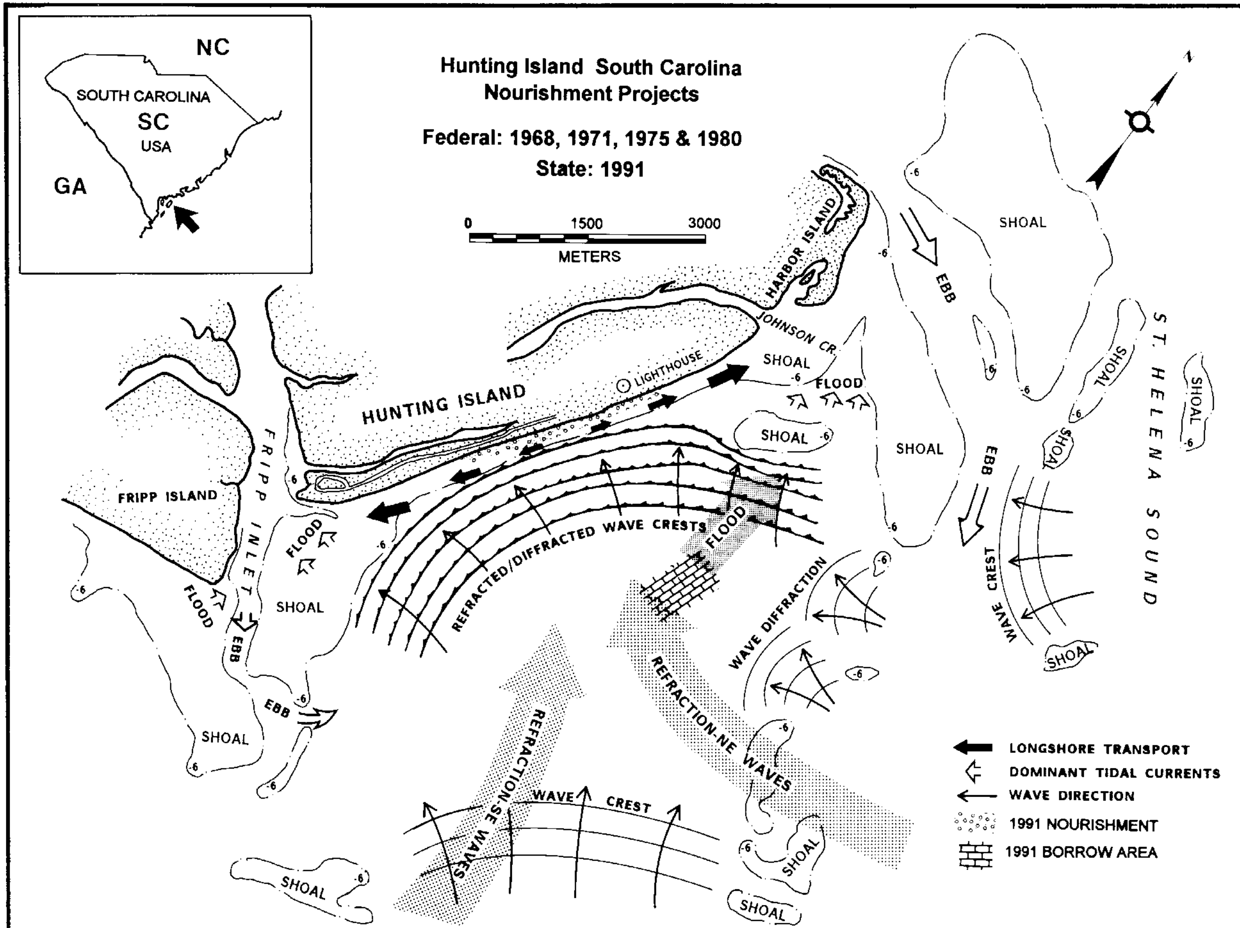

Fig. 1. General map of Hunting Island, SC, and conceptual model of coastal processes and principal sand transport patterns, and wave and current directions (modified from Kana and Andrassy, 1995).

The cumulative effect of the above discussed coastal processes control the erosional patterns of the Island.

The federal authorization for the Hunting Island project expired in 1985. Given continued erosion, the State of South Carolina elected to proceed with a fifth nourishment of the beach in 1991. This budget-limited project was completed as an interim measure until such time as a more permanent solution to erosion could be developed (CSE, 1990).

Project planning for the fifth nourishment of Hunting Island included a search for beach-quality sediment in an offshore borrow area and studies of alternative fill configurations. Several factors relating to sediment quality and environmental concerns were used in delineating a borrow area. These included:

1. Mean grain size > 0.20 mm diameter;
2. Mud content $< 5\%$;
3. Coarse-skewed deposit containing some shell material;
4. Minimum water depth of 3 m (10 ft) at mean low water;
5. Excavation range at 1.8–3 m (6–10 ft) of substrate;
6. Total area < 100 acres (40.5 ha);
7. Access to an 'escape' channel for a dredge;
8. Orientation parallel to principal current flow such that the natural supply of sand to the beach is not interrupted; and,
9. Location as close to the shore as possible.

Since nourishment costs are directly proportional to the distance of borrow area to the beach, it was decided to locate a borrow area as close as practicable to the beach. An extensive survey of Hunting Island's offshore area was conducted in April and August 1990 which involved collection of 45 vibracores at various locations (at distances ranging from 2000 m to 3000 m from the beach) within a predetermined grid (CSE, 1990). These borings were analyzed for grain-size and textural characteristics, and were used to delineate the optimal borrow area configuration. The selected borrow area was located 2800 m offshore from the beach with a footprint of 86 acres (35 ha) and contained upwards of 765,000 m^3 (1 million cubic yards).

The fifth nourishment project was constructed in February–March 1991 by Great Lakes Dredge and Dock (GLD&D), using the hydraulic, cutterhead-suction dredge, Georgia. The total fill volume was 579,000 m^3 (757,000 cy) over a length of 2300 m ($\sim$ 7500 ft) between Federal stations 25 + 00 N and 55 + 00 S. Unit fill volumes were purposely varied from 100–350 m^3/m (40–140 cy/ft) so that longevity might be improved at two principal beach accesses by placing more sand there, given budget limitations of the project.

Nourished profile stability, defined as the ability of a beach to retain a post-nourished dry beach, may be influenced by a number of variables. These include fill placement techniques, grain-size distribution of the fill material, and environmental factors (background erosion rates, shoreline morphology, waves, currents, tides, and storm frequency). Of these, the fill placement technique is controlled by the project construction equipment capabilities. This was rather constant for the Hunting Island projects since they were constructed using standard hydraulic dredging equipment. The grain-size distribution of the borrow sediments (especially mean grain-size, percent mud, and percent coarse material) is critical to the successful performance of nourishment projects. Monitoring of the environmental factors (waves, currents, storms, etc.) at the project site indicated that they were fairly normal (with significant wave heights and periods ranging from 20–200 cm and 4–8 s, respectively; breaker angles were less than 15% from shore normal at least 90% of the time) during the pre- and post-nourishment periods when compared to the typical climate of the Carolina coast (CSE, 1995). Significant Northeasters occurred in December 1992 and March 1993, but no hurricanes directly impacted the site between 1991 and 1995. Therefore, this investigation concentrated upon the influence of grain-size distribution on nourished profile stability at Hunting Island beach.

In order to evaluate this further, approximately two years after the project, borings were made across the beach and inshore zone at four transects to depths of 0.5–2.0 m. From these cores, 36 geotechnical samples of the post-nourished beach were taken in July 1993 to represent the post-nourished beach. Samples of the beach taken in a similar pattern in 1990 (before nourishment) were used to represent the pre-nourished condition. The pre-nourished and post-nourished grain-size frequency curves were then compared to gain a better understanding of the nourished profile stability. This paper presents an analysis of the nourished profile stability following the fifth Hunting Island beach nourishment project. Details of the correlation between pre-nourished beach (1990), borrow area, and post-nourished beach (1993) grain-size frequency curves are presented in subsequent sections.

Table 1
General relationship among selected control stations for Hunting Island nourishment project [Hunting Island is 6500 m (21,000 ft) long]

Location	USACE 1968, Baseline	SCCC 1988, Baseline	GLD&D 1991, Baseline
North end of island	73+00 N		−(50+00)
		1800	−(38+27)
	~44+00 N	1810A	−(24+24)
			0+00
	~24+50 N	1820A	3+42
			6+33
North Beach project limit	~20+00 N		8+31
			11+23
Lighthouse	~5+00 N	1830A	23+02
			35+09
	~15+00 S	1840A	42+11
			50+94
	~35+00 S	1850A	63+37
			70+92
Sorth Beach project limit	~55+00 S	1860A	83+31
			85+94
			101+16
	~88+50 S	1880	116+21
South end of island	141+00 S	1895	~169+00

USACE = US Army Corps of Engineers; SCCC = South Carolina Coastal Council; GLD&D = Great Lakes Dredge and Dock.

2. Native beach sediment characteristics

Ten sediment samples were collected along Hunting Island beach in October 1990 at five transects approximately located at federal (USACE 1968 baseline) stations 50 + 00 N, 0 + 00, 30 + 00 S, 70 + 00 S, and 100 + 00 S. The general relationship of these stations to State (South Carolina Coastal Council) profile lines (SCCC 1988 baseline) and the project contractor's baseline stations (GLD & D 1991 baseline) is given in Table 1. Samples were taken from the backshore at the base of erosional scarps and the mid beach face. Composite samples were prepared by mixing equal portions of each berm sample (composite berm) and each beach face sample (composite beach face), then performing sieve analysis at 0.84 mm (0.25ϕ) intervals. Krumbein (1934) presents the relationship between the Wentworth (mm) and phi (ϕ) units as $\phi = -\log_2$ mm. Second sample splits at 0 + 00 and 30 + 00 S, the two principal beach access stations were similarly combined to form a berm and a beach face composite. In general, the native beach samples had a mean grain size of 0.16 mm with a range of 0.15 mm to 0.18 mm. Samples were dominated by fine sand (about 65%) with a major fraction of very fine sand (about 20%) being present. Most of the sediments fell in the median grain-size range (0.06 to 1.7 mm), yielding only 0.075% coarse fraction and 0.395% fine fraction. Details of the grain-size statistics and frequency curves of these samples may be obtained from CSE (1991).

3. Borrow area sediment characteristics

Preliminary investigations of potential borrow sediments located offshore Hunting Island predicted overfill ratios in the range of 1:1.1 to 1:6 (USACE, 1984). Additional borings were taken in and around the proposed borrow area located approximately 2800 m offshore from the beach in August 1990 to better define the borrow sediments. Cores were taken in shallow water depths (3.7 m; ~ 12 ft) with the intent of defining conditions to operational depths of 6 m (~ 20 ft) below mean sea level. Most samples were dominated by fine sand, but differences occurred in the percent shell or percent mud content. A common trend included a somewhat muddier and shellier zone between 0.91 m (3 ft) and 1.8 m (6 ft) below the surface substrate. The lowermost sections tended to contain 'cleaner' sediments. Mud content tended to be dispersed in a series of thin layers that alternated with sand. These layers, referred to as flasers (Reineck and Wunderlich, 1968), were as thin as a few millimeters or occasionally 5–15 cm (2–6 in) thick. Another common occurrence was higher mud content occurring in sections containing more shell. This could be partly due to the chemical breakdown of shell material forming carbonate-rich mud.

Analysis of the borrow area samples confirmed that a particular grouping of closely spaced cores tended to have coarser mean grain sizes with relatively low mud content, making them preferable for borrow material (Fig. 2a). In general, the borrow area sediments had a mean grain size of 0.22 mm and a narrow range of means from sample to sample of 0.18 mm to 0.23 mm (Table 2). The percent mud content over the upper 3 m (10 ft) of section averaged around 5%, with most of it dispersed as thin lenses

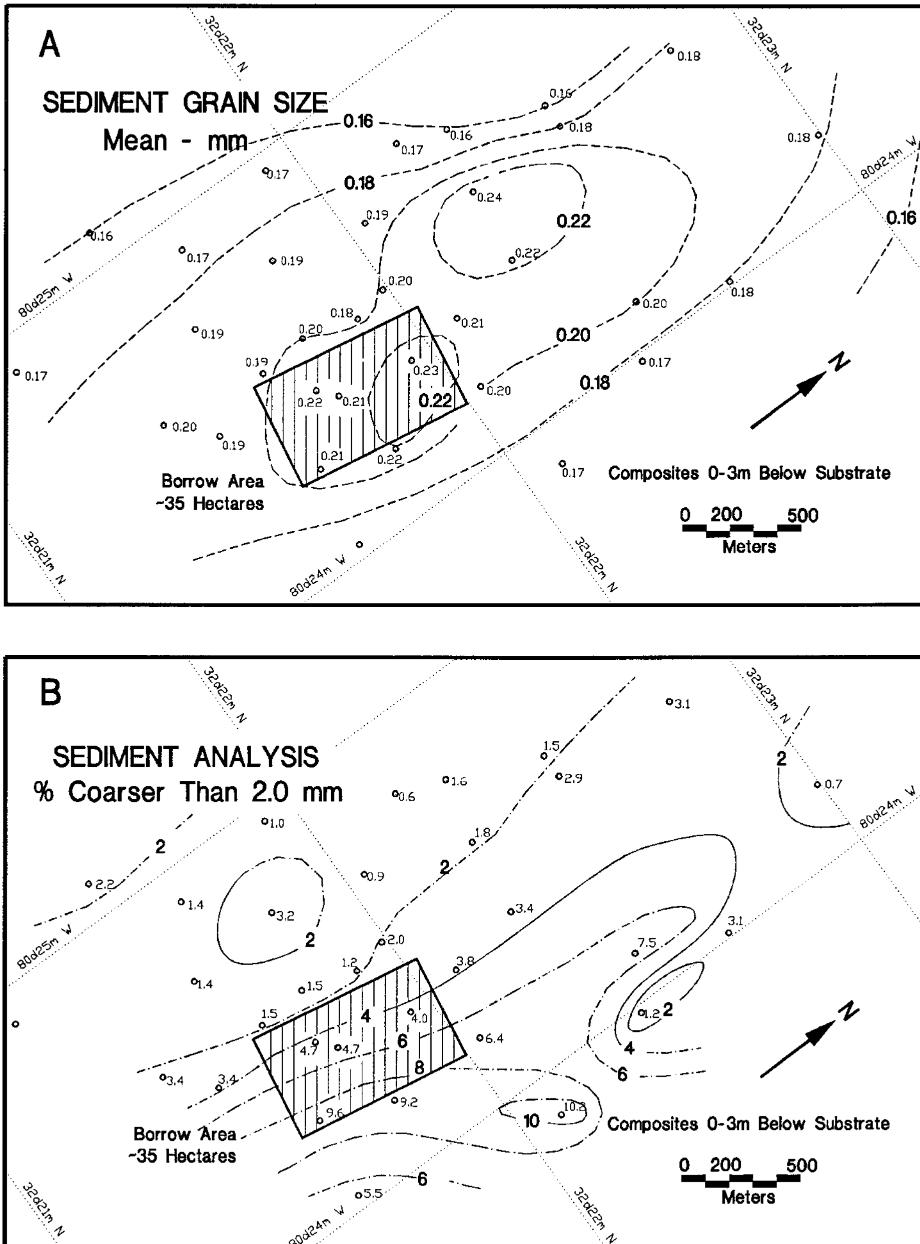

Fig. 2. Isopach maps of sediment parameters around the offshore borrow area for the 1991 nourishment project based on sediment samples from cores [These results, combined with a similar map of mud content, were used to optimize the final borrow area location (after CSE, 1991)].

Table 2
Hunting Island sample locations and grain size characteristics [SCCC stations 1830A and 1850A are 'north beach' and 'south beach' project areas; 1810A and 1870A are control stations outside of the project area]

SCCC profile line or sample ID	Location on profile	Interval (m)	% Coarser than 1.7 mm	% Finer than 0.06 mm[b]	Mean grain size (mm)
Native Beach (1990)					
Composite	Project Area Beach Face	Composite	0.10	0.10	0.18
Composite	Overall Area Beach Face	Composite	0.10	0.10	0.18
Composite	Project Area Berm	Composite	0.00	0.99	0.15
Composite	Overall Area Berm	Composite	0.10	0.39	0.15
		Averages	*0.075*	*0.39*	*0.16*
Borrow area (1990)					
H6	N/A	0–3.0	1.96	1.23	0.20
H11	N/A	0–3.0	1.47	1.54	0.20
H20[a]	N/A	0–3.0	4.03	0.73	0.23
H21[a]	N/A	0–2.0	5.61	1.33	0.22
H39	N/A	0–3.0	6.42	0.93	0.20
H40	N/A	0–3.0	9.19	0.63	0.22
H41	N/A	0–3.0	3.77	0.64	0.21
H42	N/A	0–3.0	1.15	0.85	0.18
H43[a]	N/A	0–3.0	4.74	1.08	0.21
H44	N/A	0–2.0	1.91	2.21	0.19
H46[a]	N/A	0–3.0	9.57	1.14	0.21
		Averages (for [a] samples)	*5.99*	*1.07*	*0.22*
Nourished Beach (1993)					
1810A	Berm-1	0–0.6	0.00	0.20	0.18
1810A	Berm-2	0.6–1.1	0.00	0.00	0.17
1810A	Upper Beach Face-1	0–0.6	0.20	0.00	0.18
1810A	Upper Beach Face-2	0.6–1.4	0.00	0.00	0.17
1810A	Lower Beach Face-1	0–0.8	0.41	0.41	0.17
1810A	Lower Beach Face-2	0.8–1.7	0.80	0.00	0.15
1810A	Lower Shore Face	0–0.2	0.21	2.26	0.14
1830A[c]	Berm Crest-1	0–0.6	2.67	0.00	0.51
1830A[c]	Upper Beach Face-0	0–0.6	6.72	0.61	0.21
1830A[c]	Upper Berm-1	0–0.6	3.41	0.20	0.33
1830A[c]	Upper Berm-2	0.6–1.2	5.35	0.21	0.36
1830A[c]	Upper Berm-3	1.2–1.4	0.20	0.00	0.21
1830A[c]	Berm Crest-2	0.6–0.8	2.90	0.00	0.38
1830A[c]	Berm Crest-3	0.8–1.4	1.02	0.20	0.25
1830A	Upper Beach Face-1	0.6–1.4	0.82	0.41	0.17
1830A	Upper Beach Face-2	1.4–2.0	0.00	0.41	0.16
1830A[c]	Lower Beach Face-1	0–0.2	2.28	0.41	0.24
1830A[c]	Lower Beach Face-2	0.2–0.8	0.20	0.41	0.17
1830A	Lower Beach Face-3	0.8–1.8	0.00	0.83	0.15
1830A[c]	Lower Shore Face-1	0.0–0.2	0.61	0.61	0.17
1850A[c]	Upper Berm 1A	0–0.3	0.00	0.00	0.20
1850A[c]	Upper Berm 1B	0.3–0.6	15.80	0.00	0.47
1850A[c]	Berm Crest-1	0–0.6	2.59	0.00	0.34
1850A[c]	Upper Berm-2	0.6–1.4	9.47	0.00	0.40

Table 2 (continued)

SCCC profile line or sample ID	Location on profile	Interval (m)	% Coarser than 1.7 mm	% Finer than 0.06 mm[b]	Mean grain size (mm)
Nourished Beach (1993)					
1850A[c]	Berm Crest-2	0.6–1.2	8.78	0.20	0.39
1850A[c]	Upper Beach Face-1	0–0.5	14.02	0.20	0.32
1850A	Upper Beach Face-2	0.5–1.6	0.00	0.21	0.17
1850A[c]	Lower Beach Face-1	0–0.9	0.21	0.21	0.19
1850A	Lower Beach Face-2	0.9–1.9	0.20	1.63	0.14
1850A[c]	Lower Shore Face-1	0–0.2	0.21	0.41	0.17
1870A	Berm-1	0–0.6	0.00	0.20	0.17
1870A	Berm-2	0.6–1.6	0.00	0.00	0.17
1870A	Upper Beach Face	0–1.2	0.00	0.00	0.18
1870A	Lower Beach Face-1	0–0.8	0.00	0.20	0.18
1870A	Lower Beach Face-2	0.8–1.7	1.22	0.61	0.17
1870A	Lower Shore Face-1	0–0.2	0.00	0.83	0.15
1870A		*Weighted averages (for [c] samples)*	*4.28*	*0.28*	*0.25*

[a]Samples used for primary borrow area composite.
[b]Excludes mud content determined by wet sieving.
[c]Represents beach fill samples in the project area.

(flasers) that were expected to form a suspension before discharge at the beach. The 5% mud content was considered to fall within a tolerable range and not produce significant changes in the nearshore zone which contains surficial mud deposits.

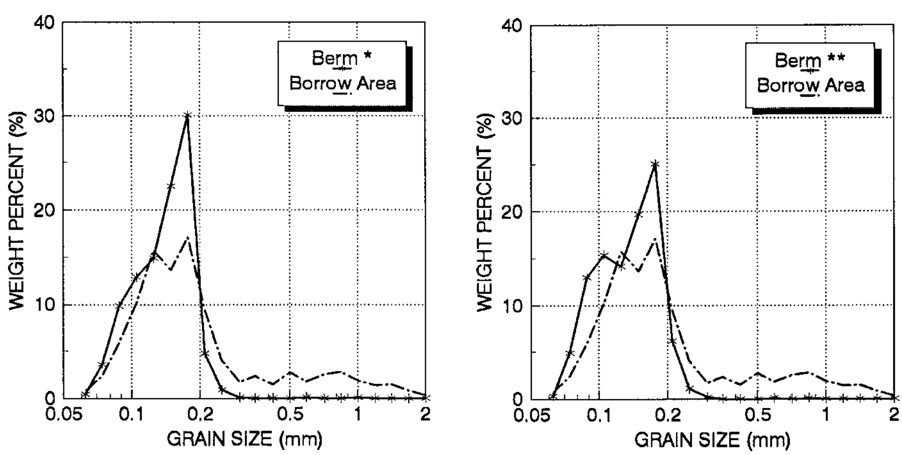

Fig. 3. Grain-size frequency distributions for October 1990 native beach (berm) samples and borrow area samples (Berm * represents project area; Berm * * represents entire Hunting Island shoreline).

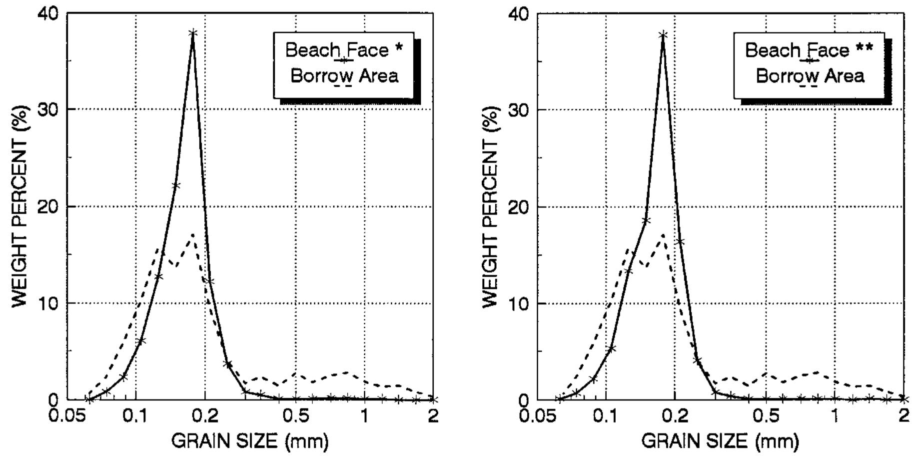

Fig. 4. Grain-size frequency distributions for October 1990 native beach (beach face) samples and borrow area samples (Beach Face * represents project area; Beach Face * * represents entire Hunting Island shoreline).

The borrow area also contained about 6% coarse material (grain diameters > 1.7 mm) with higher concentrations along the seaward margin of the borrow area (Fig. 2b). This was considered beneficial since it might help stabilize the fill after placement. Details of the grain-size distribution parameters and frequency curves are given in CSE (1991). Figs. 3 and 4 compare the pre-nourishment borrow area sediment (composite) with the native (1990) berm and beach face composites. As the frequency curves show, sorting on the beach was better than in the borrow area. Further, the beach sediments were slightly fine-skewed, whereas the borrow area sediments were strongly coarse-skewed.

4. Nourished beach sediment characteristics

Thirty-six borings of the post-nourished beach were taken in July 1993 to analyze the grain-size distribution characteristics across the profile from berm to upper beach face, lower beach face, and lower foreshore. The cores were cut into smaller sections in the field to determine the type of sediments at each interval, then capped, and transferred to the lab. Each section was opened, faced, logged, photographed, and split for sampling and archiving.

Standard grain-size analysis tests were conducted for all the samples to obtain their grain-size distribution curves. Approximately 100 g of the sample were used in each laboratory test. Samples were wet-sieved with a 0.06 mm (no. 230) screen to separate mud (silt and clay) from the sand and coarser fractions. For selected samples, the resulting parts were dried and weighed to yield a percent mud fraction out of the total. The sand and coarser fractions were then dry-sieved at 0.84 mm (0.25ϕ) intervals and plotted. The coarsest screen used was 2.0 mm diameter (no. 10). Broken shells generally comprised the bulk of material that did not pass the coarsest screen. Raw weight results were entered into the computer for automated computation of size-frequency distributions and moment measures using sediment analysis software. Details of the core logs and grain-size statistics and frequency curves may be obtained from Mohan et al. (1993).

Three geotechnical parameters are critical for beach nourishment projects: (1) mean grain size, (2) percent mud, and (3) percent coarse material. These are of particular interest for beach nourishment projects because they affect the performance of the fill. Mean grain size is important because it affects the equilibrium slope of the beach (Bascom, 1951; Dean, 1983). Percent mud should be kept as low as possible since it represents the portion that is unstable and likely to increase turbidity in the receiving waters. Percent coarse material affects the erodability of the fill (James, 1975).

Previous studies of Hunting Island reported a trend of slightly coarser material being left on the beach after nourishment. Prior to nourishment, USACE (1949) reported that Hunting Island beach sand had a median diameter of 0.20 mm (with shell) and 0.17 mm (without shell) around the lighthouse area. Subsequent investigations by USACE (1964) reported median grain sizes of 0.15 mm to 0.17 mm diameter along various sections of the beach and offshore profile. Stapor and May (1981) reported general uniformity of sediments along the beach in the 0.14 mm to 0.20 mm size range (fine sand). A post-nourishment analysis after the second beach fill (USACE, 1977) reported mean grain size on the beach and in borrow areas as 0.16 mm (1963, native) and 0.18 mm (1971, beach fill). The dry-sand beach (berm) contained median sand sizes generally between 0.19 mm to 0.21 mm in March 1971 prior to the second nourishment.

The 1991 state project (CSE, 1991) sought coarser material than 0.20 mm, or borrow sediments having a coarse fraction (negative skewness). The resulting borrow sediments had a mean size of 0.20 mm to 0.23 mm and upwards of 5% coarser than 2.0 mm. Table 2 shows the Hunting Island sediment sample locations and summarizes the grain size characteristics. The post-nourishment beach samples (1993) had mean grain sizes in the range 0.14–0.51 mm, with a composite mean grain-size of about 0.25 mm. These results suggest that after nourishment and winnowing of fines, a slightly coarser material was left on the beach.

Higher fraction of fines (mud) is undesirable since it washes out, reducing the net volume of material placed on the beach. It may also raise the turbidity levels, reduce rates of photosynthesis, or cause adverse impacts to bottom-dwelling organisms. Generally, mud content should be kept below 10% (or even lower) for any nourishment project. The mud content of the borrow area was approximately 5%. The post-nourished beach (1993) fell much below this limit with an average of 0.33% fines and a range of 0.0–2.26% fines. Pre- and post-nourishment construction surveys confirmed about 5% volumetric losses in the project area comparing borrow area volumes with in-place volumes on the beach (Kana and Andrassy, 1995).

The coarse fraction of the deposit generally represents shell material. A size of 1.7 mm was used in this study to mark the lower limit of shells although crushed fragments are often smaller than this size. While it is recognized that coarse material is generally advantageous for beach nourishment, large shell percentages may sometimes be detrimental for recreational beaches because they change the character of the beach and may form a rough pavement along the backshore. The post-nourished beach (1993) retained a coarse fraction (i.e., > 2.0 mm), but it was in the low range of 0.0–15.8%, with an average of 4.28%.

5. Comparison of native beach vs. borrow area sediments

A review of Table 2 indicates that the pre-nourished beach had mean grain-sizes in the range of 0.15 mm to 0.18 mm (0.16 mm average), with 0.0 to 0.10% (0.075% average) coarser than 1.7 mm, and 0.10 to 0.99% (0.395% average) finer than 0.06 mm. The post-nourished beach (project area) on the other hand was measurably coarser with mean grain sizes in the range of 0.14 mm to 0.51 mm (0.25 mm weighted average), with 0.0 to 15.8% coarser (4.28% weighted average) and 0.0 to 2.26% finer (0.28% weighted average). The primary borrow area (cores H-20, H-21, H-43, and H-46) had mean grain-sizes in the range of 0.21 mm to 0.23 mm (0.22 mm average), with 4.03–9.57% coarser (5.99% average) and 0.73 to 1.33% finer (1.07% average).

Comparisons of beach vs. borrow area sediments were conducted using the SPM model (USACE, 1984). The average overfill ratio for the comparison with the 1975 'native' beach samples was 1:1.15 with a low standard deviation of 0.04. The average overfill ratio for the comparison with the 1975 nourished native beach samples was 1:1.2 with a standard deviation of 0.06. Both these results confirm that the borrow sands had good compatibility with native sands. Comparison of the offshore composite samples with the existing native beach samples (1990) indicates good compatibility with an average overfill ratio of about 1:1.1 [for 11 borings in and around the borrow area].

6. Comparison with actual beach observations

Comparison of the pre-nourished (1990) and post-nourished (1993) grain-size frequency curves for the berm and beach composites are given in Fig. 5. The size distributions show a clear trend of the sediments at the berm becoming coarser after nourishment with those along the beach face becoming finer with time after nourishment, relative to the nourishment sand. 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 sizes down-profile and has a smaller modal size than native in the lower shoreface.

The authors used two schemes of statistical analyses to compare the native beach (1990) and nourished beach (1993) sediments. In the first method (method A), medium to coarse sand, very coarse sand and gravel were grouped together to form percent coarse material (i.e., $d > 0.50$ mm, or $\phi < 1.0$). Similarly, very fine sand, silt, and clay were grouped together to form percent fine material (i.e., $d < 0.13$ mm, or $\phi > 3.0$). According to this scheme, the total sediment volume of the borrow area (579,295 m^3 or 757,644 cy) consisted of about 15.35% (88,922 m^3 or 116,298 cy) coarse material and about 19.17% (111,051 m^3 or 145,240 cy) fines. The results obtained by this method are summarized in Table 3. While the results show the expected trend of increased coarsening in the berm and increased fines in the lower beach, they do not include the

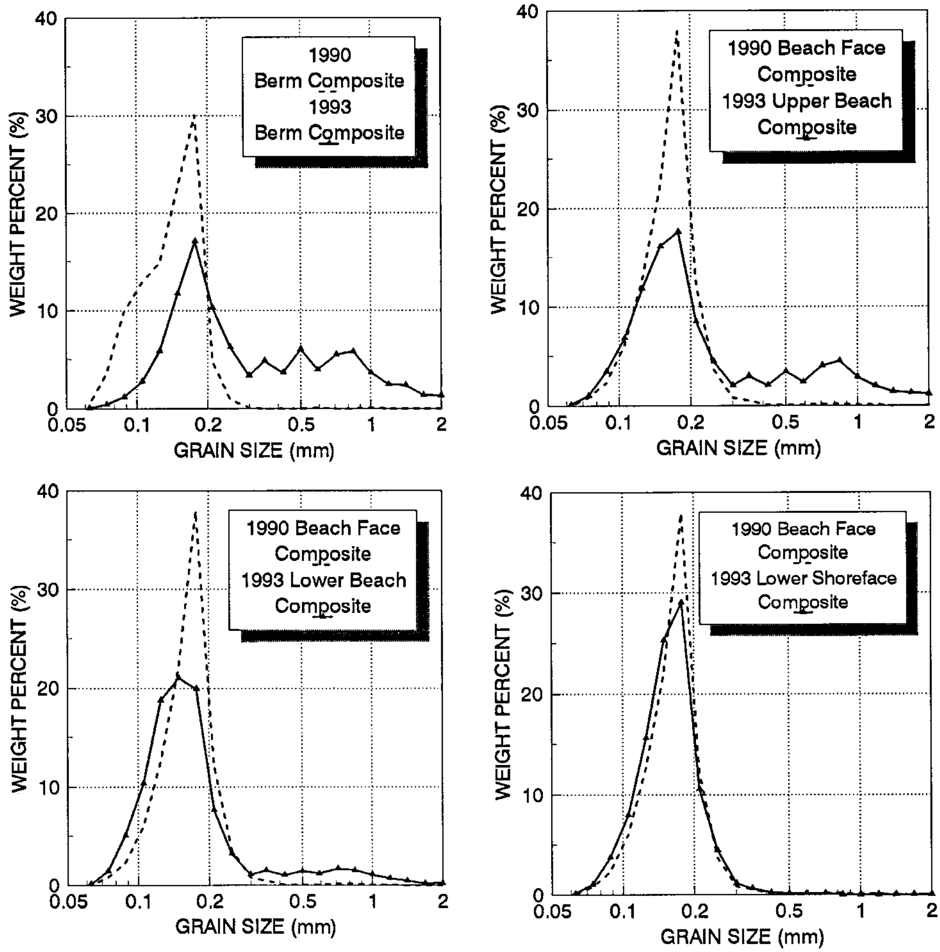

Fig. 5. Grain-size comparison plots of 1990 (---) vs. 1993 (———) beach composites in the project area (Note systematic fining of the post-nourishment samples down profile).

largest portion of the fill represented by size classes 0.13 mm to 0.50 mm. Therefore, a second analysis was prepared whereby the entire sediment grain-size range was divided into two broad subdivisions comprising coarse and fine groups.

In the second method of analysis (method B), materials with grain sizes > 0.18 mm ($\phi < 2.5$) were classified as coarse and those with grain sizes $d < 0.18$ mm ($\phi > 2.5$) were classified as fines. Accordingly, fine sands (most), medium sands, coarse sands, very coarse sands and gravel fall into the 'coarse' category. Similarly, fine sands (some), very fine sands, silts and clays fall into the 'fine' category. Conveniently, this size division divides the total sediment volume of the borrow area into nearly equal parts comprised of about 51.44% (297,989 m^3 or 389,732 cy) 'coarse' material and about 48.56% (281,306 m^3 or 367,912 cy) 'fines.' Using the 0.18 mm (2.5ϕ) size division as

Table 3
Comparison of native beach (1990) vs. nourished beach (1993) composite samples [coarse > 0.50 mm; fine < 0.13 mm]

Location	Mean grain size (mm)		% Coarse		% Fine	
	1990	1993	1990	1993	1990	1993
Berm	0.15	0.34	0.20	32.52	26.70	4.35
Upper Beach Face	ND	0.26	ND	23.05	ND	11.39
Lower Beach Face	0.18	0.19	0.80	8.66	9.15	17.01
Lower Shore Face	ND	0.17	ND	0.31	ND	12.83

the break point, it is then possible to determine the percent ‘coarse’ or the percent ‘fine’ sediment distributions in the post-nourishment samples. Table 4 summarizes the results obtained by this method which indicate that coarse sediments in the berm increased from 36% to about 78% of the sample population after nourishment, whereas those at the beach face decreased from 56% to about 42% of the sample population.

Grain-size statistics in Tables 3 and 4 confirm these trends but also show that the fill, two years after nourishment, retains a coarse tail and is more graded. Sorting increased significantly between 1990 prefill and 1993 postfill conditions (~ 0.75 mm to 0.56 mm on average, respectively); and skewness increased in the 1993 samples. Skewness after nourishment was higher on the beach face than on the berm or lower foreshore.

USACE (1977) conducted yearly post-nourishment surveys (at approximately 300-m spacing) of the beach after the December 1968 and December 1971 projects (fill placement between USACE 50 + 00 N and 50 + 00 S). Kana and Andrassy (1995) and

Table 4
Comparison of native beach (1990) vs. nourished beach (1993) composite samples [coarse > 0.18 mm; fine < 0.18 mm]

Location	Mean grain size (mm)		% Coarse		% Fine	
	1990	1993	1990	1993	1990	1993
Berm	0.15	0.34	35.98	78.04	64.02	21.96
Upper Beach Face	ND	0.26	ND	60.71	ND	39.29
Lower Beach Face	0.18	0.19	56.02	43.25	43.98	56.75
Lower Shoreface	ND	0.17	ND	46.28	ND	53.72
Sorting (mm)						
Berm	0.75	0.46				
Upper Beach Face	ND	0.46				
Lower Beach Face	0.75	0.57				
Lower Shoreface	ND	0.75				
Skewness						
Berm	0.99	1.22				
Upper Beach Face	ND	1.40				
Lower Beach Face	1.49	1.88				
Lower Shoreface	ND	1.10				

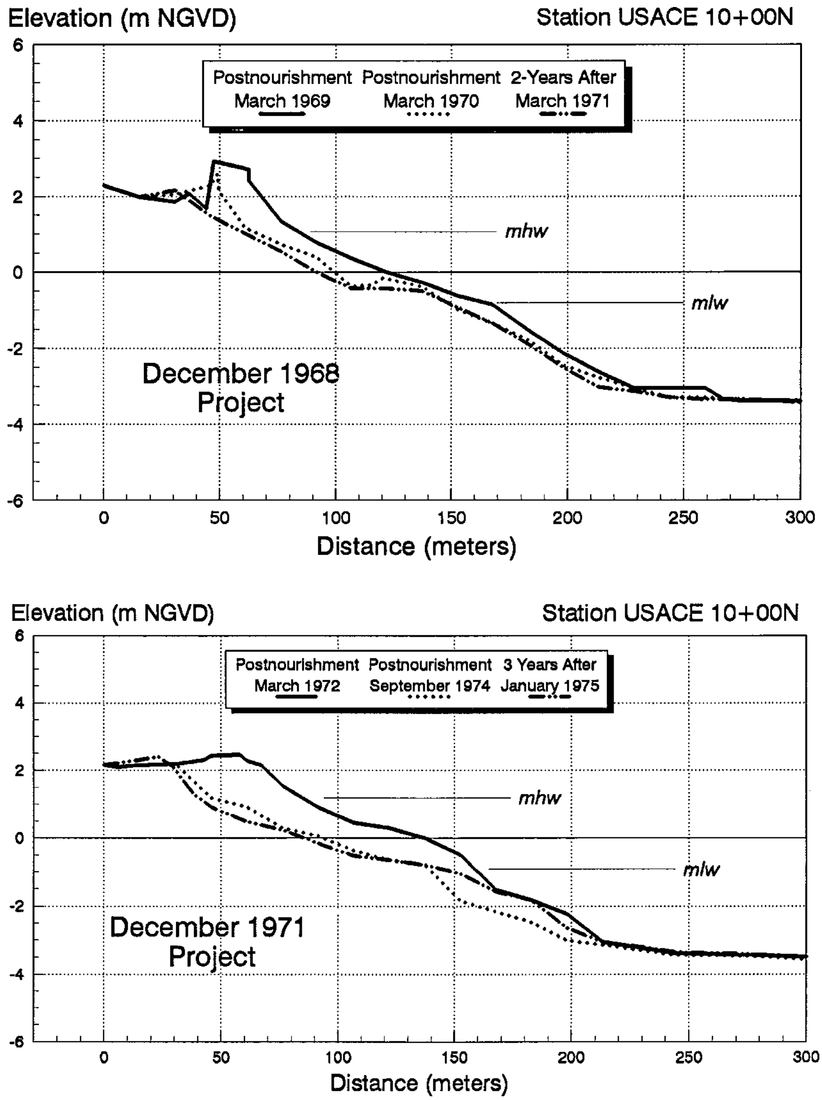

Fig. 6. Representative profiles illustrating beach fill retained after two years at USACE station 10 + 00 N (Hunting Island north beach project area) after the first (December 1968) and second (December 1971) nourishment projects [unpublished profile data, courtesy of US Army Corps of Engineers, Charleston District].

CSE (1995) conducted yearly surveys (at approximately 60-m spacing) after the 1991 project (fill placement between USACE 20 + 00 N and 55 + 00 S, see Table 1). Example profiles from the three nourishments are given in Figs. 6 and 7 (Note that all the nourishments involved approximately 575,000 m^3, and were located approximately in the same project reach). Representative profiles illustrating the beach fill remaining after two to three years show rapid erosion of the fill in each case. However, visual

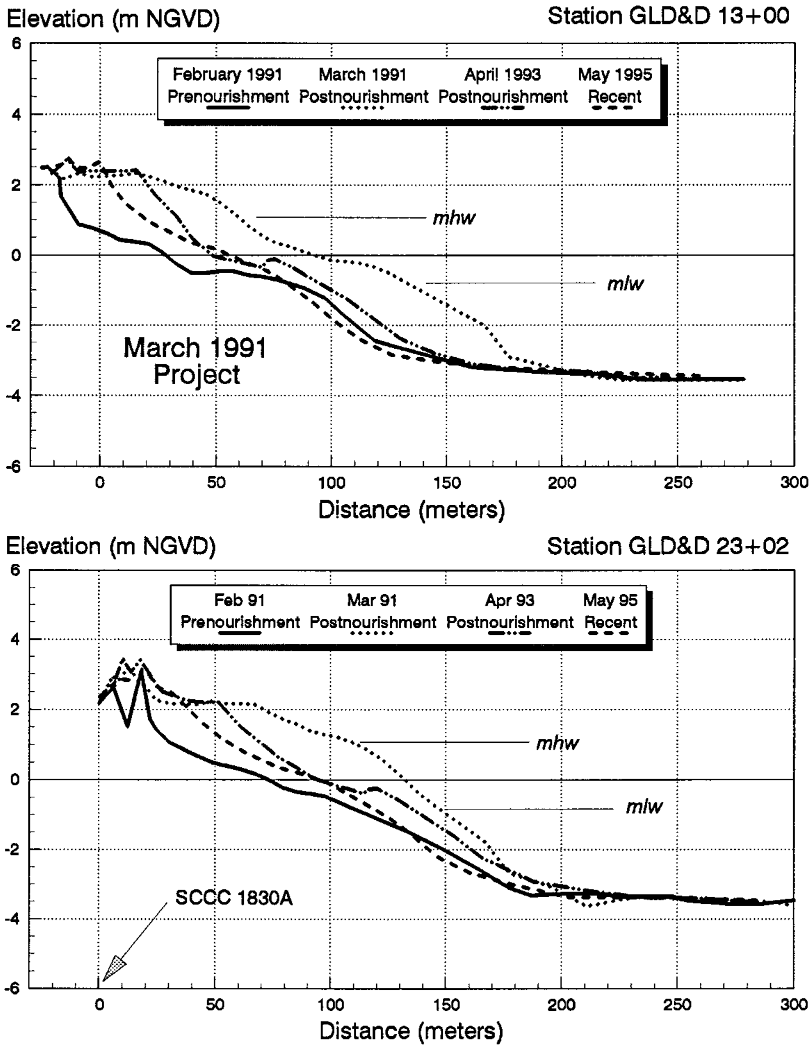

Fig. 7. Representative profiles illustrating beach fill retained after two years at GLD&D stations 13 + 00 and 23 + 02 (Hunting Island north beach project area) after the 1991 nourishment project (from CSE, 1995).

inspection of Figs. 6 and 7 show more rapid erosion above mean low water after the 1968 and 1971 projects, compared to the 1991 project. Elevations in the profiles are referenced in m-NGVD, where NGVD is the National Geodetic Vertical Datum which is approximately 0.15 m (0.5 ft) below the present mean sea level along the Carolina coast.

Fig. 8. Percent fill volume remaining after the 1968, 1971 and 1991 nourishment projects within the project areas.

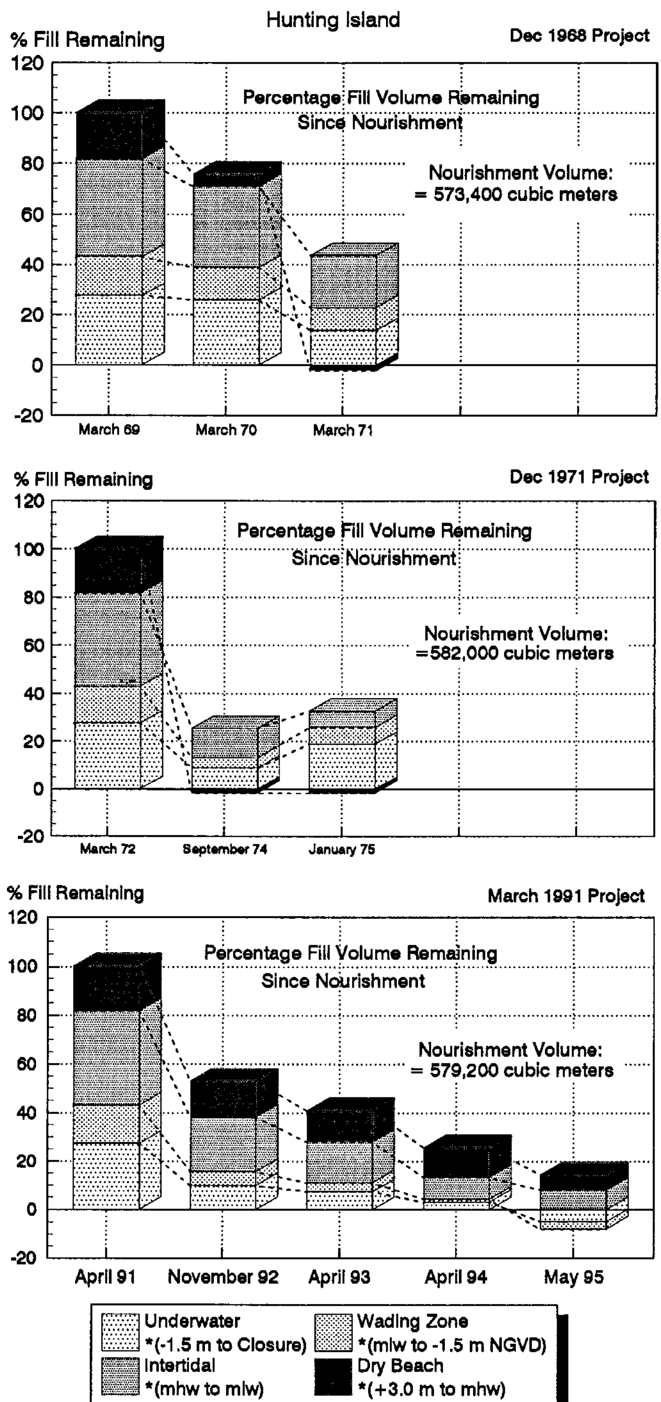
Hunting Island
% Fill Remaining
Dec 1968 Project
Percentage Fill Volume Remaining
Since Nourishment
Nourishment Volume:
= 573,400 cubic meters
120
100
80
60
40
20
0
-20
March 69
March 70
March 71
% Fill Remaining
Dec 1971 Project
Percentage Fill Volume Remaining
Since Nourishment
Nourishment Volume:
=582,000 cubic meters
March 72
September 74
January 75
% Fill Remaining
March 1991 Project
Percentage Fill Volume Remaining
Since Nourishment
Nourishment Volume:
= 579,200 cubic meters
April 91
November 92
April 93
April 94
May 95
Underwater
*(-1.5 m to Closure)
Wading Zone
*(mlw to -1.5 m NGVD)
Intertidal
*(mhw to mlw)
Dry Beach
*(+3.0 m to mhw)

Fig. 6, which presents profiles typical of the 1968 and 1971 projects, indicate that most of the sand loss occurred within one to two years after nourishment with extensive erosion above mean low water. By contrast, Fig. 7 (which presents profiles typical of the 1991 project) indicates that a greater proportion of the nourishment remained above mean low water two to three years later. While rapid (expected) erosion continued through the most recent survey in April 1995 (CSE, 1995), these results reveal an interesting factor: the loss rate for the upper beach lenses was much lower than the underwater lenses. Fig. 8 summarizes the percentage of fill remaining based on the results from available profiles. Four contour intervals are considered. The dry beach to MHW [+3 m to +1 m NGVD (+10 ft to +3.2 ft NGVD)] within the project area retained 70% of the fill through April 1993. The intertidal beach [MHW to MLW; i.e., +1 m to −0.7 m NGVD (+3.2 ft to −2.2 ft NGVD)] retained about 45% of the fill two years later. In contrast, the underwater lenses [−0.7 m to −3.7 m NGVD (−2.2 ft to −12.0 ft NGVD)] retained only 27% of the fill by April 1993. By April 1995, all underwater fill had eroded and the only remaining fill was concentrated on the recreational beach above mean low water. The distribution of erosion lenses across the profile after the 1991 project is exceedingly favourable compared to the performance of the 1968 and 1971 projects. Note in Fig. 8 (upper two bar graphs) the near-total loss of fill above mean high water after 1 to 2 years.

Based on the rate at which sand was applied and the rate of historical erosion, the 1991 Hunting Island project was expected to last only three years (CSE, 1990) before complete erosion. However, post-project surveys confirm retention of a viable high-tide beach for at least one additional year. Particularly remarkable about these results was the fact that contrary to the trend for many nourishment projects (USACE, 1984), more sand was retained at the berm than on the lower beach after the fifth Hunting Island nourishment.

7. Conclusions and recommendations

A geotechnical analysis of nourished profile stability for Hunting Island (SC) was presented in this paper. Comparison of the actual (observed) data before and after nourishment showed that the berm sediments became measurably coarser in both mean grain size and degree of grading (i.e., poor sorting). The post-nourishment profile yielded a distinct gradient in sediment size downslope with most of the coarse fraction from the borrow source concentrated in the berm and upper beach face, and increasingly fine sands dominating along the lower beach face and lower foreshore.

Comparative profiles and a detailed, volume change analysis revealed that the dry beach retained 70% of its fill, whereas the underwater profile retained only 27% of its fill after two years. This suggests that use of coarsely skewed borrow material can improve longevity of the recreational beach. Beach face slopes, in this case, became somewhat steeper after nourishment (see Figs. 5–7), but given the pre-existing gentle slope averaging approximately 1 on 35, this did not inhibit use and enjoyment of the beach.

Evidence from this study and practical experience from other fill placements suggest three factors become important in controlling the post-nourishment profile stability (in order):

(1) 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 minimum whenever possible.

(2) Placement technique of fill material. The most common method of placing fill material on a nourishment project is by the use of pipelines. If discharge is along the backshore, coarse material (particularly the minor fraction in a coarse-skewed deposit) will settle near the berm and fines will shift downslope with the slurry. This type of placement concentrates the coarse material where it is most needed and improves berm longevity. If the discharge point is along the lower foreshore (i.e., profile nourishment, Bruun, 1988), coarse material will have less chance of concentrating on the berm before it is dispersed across- and alongshore.

(3) Environmental factors. These include the magnitude and interrelationships 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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