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The Mobility of Beach Fill in Front of a Seawall on an Estuarine Shoreline, Cliffwood Beach, New Jersey, USA

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ABSTRACT

A field investigation was conducted to identify beach change associated with emplacement of a stone seawall and beach fill designed to protect an eroding cliff near the west end of a meso-tidal estuary. Visual observations of wave processes reveal a mean breaking wave height of 0·2 m at the most exposed monitoring site, a storm-wave height of 0·43 m and a maximum longshore current velocity of 0·55 m s^{-1}. Maximum net erosion at any one monitoring site over 44 months was 26·3 m^{3} m^{-1} of beach, resulting in a rate of erosion of 2·3 m year^{-1}. Up to 6·8 m^{3} m^{-1} of eolian accretion occurred due to the overly wide nourished beach.

Local differences in shoreline orientation, sheltering by headlands, position of the seawall on the beach profile, shore-perpendicular structures and sediment availability resulted in variability in beach processes and changes in beach profile. Flanking occurred at the southeast end of the seawall, where fill material bypassed the upper foreshore and moved along the low tide terrace, favored by a pronounced break in shoreline orientation. Net erosion did not occur at the west end of the seawall because sufficient fill sediment was available from updrift sources. Where no fill remained in front of the seawall, wave energy dissipation on the outer low-tide terrace at low *tide and wave reflection off the structure without breaking at high tide diminished the effectiveness of wave-energy concentration and turbulence on the low-tide terrace at the base of the wall, and there was no net scour. Shore-parallel structures constructed on the low-tide terrace on meso-tidal estuarine shorelines may not require a fronting protective beach to prevent net toe scour, but nourishment may delay flanking problems on the upper foreshore at downdrift sites.*

INTRODUCTION

Shore-parallel walls are the most common type of erosion control structure in many estuaries,[1-3] but only a few studies have been conducted to assess their performance in an estuarine setting.[4,5] Beach nourishment is often combined with seawall construction to protect the structure and provide a recreational beach.[6] Nourishment is considered an important component of project success,[7-11] and any management strategy that includes construction of a seawall on an estuarine shoreline should also include an assessment of the option of beach nourishment.

In estuarine environments, local variations in shoreline orientation and sheltering associated with headlands and coves result in great differences in processes and beach profile change over short distances alongshore.[7,12,13] There is a great difference in processes and the form of the beach profile in the cross-shore direction as well. Beaches in estuaries with appreciable tidal range have steep upper foreshores and gently sloping low tide terraces.[13] Wave energies are dissipated across the low-tide terrace at low water levels; waves break directly on the upper foreshore at higher water levels, resulting in a cross-shore wave-energy gradient.[14] These local variations affect decisions on implementation of protection projects for eroding estuarine shorelines. The purpose of this paper is to evaluate the applicability of previous findings about seawalls and beach nourishment to an estuarine beach site by examining wave and current processes and beach and shoreline response at Cliffwood Beach, New Jersey.

STUDY AREA

Geographic setting

Cliffwood Beach (Fig. 1) is located on the southwest side of Raritan Bay, a funnel-shaped estuary on the coast of New Jersey. Tides are

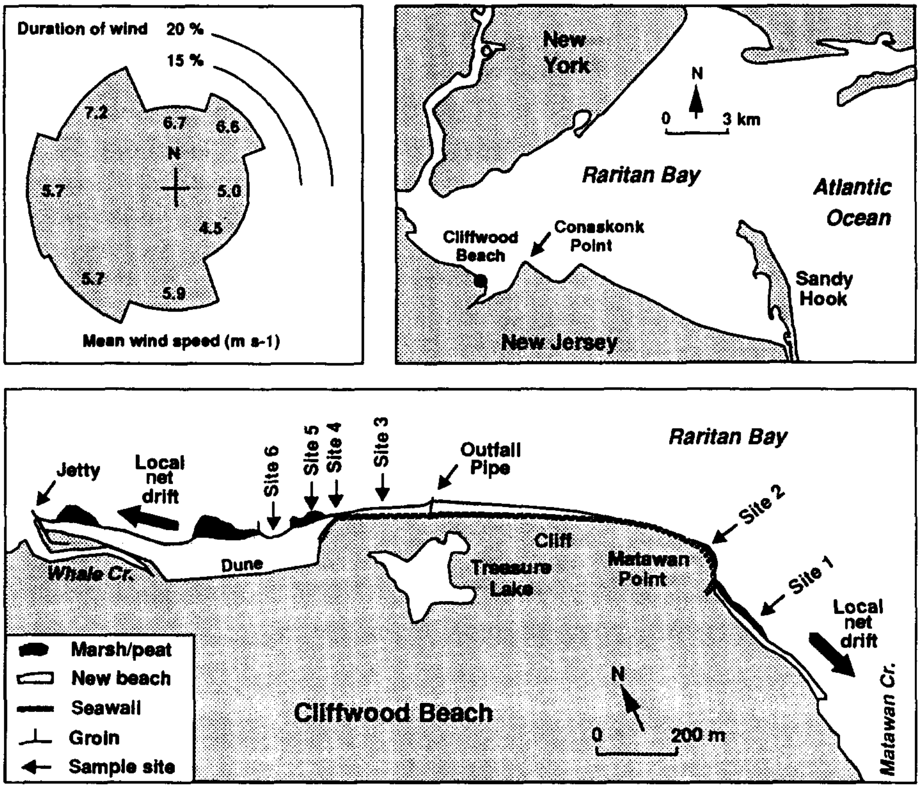

Fig. 1. Cliffwood Beach study area showing wind rose from 19-year record at Sandy Hook (top left);[26] regional setting in Raritan Bay (top right); and location of data collection sites and segments used for long-term shoreline change (bottom).

semi-diurnal with a mean range of 1·5 m and a spring range of 1·8 m.[15] The shoreline of interest is 2·3 km long and is bounded by Matawan Creek to the south and by Whale Creek to the west. The beach is exposed to ocean sea and swell that enters the bay to the north of Sandy Hook, but locally generated wind-waves are dominant. Prevailing winds are from the west, but northwest winds and northeast storm winds are common and blow with higher velocity (wind rose, Fig. 1). The southwestern portion of the shoreline of Raritan Bay is irregular, causing pronounced local differences in wave angles and longshore current directions. The most important differences in shoreline orientation that affect beach change at Cliffwood Beach are: (1) the sheltering that Conaskonk Point provides to the southeastern portion of the Cliffwood Beach shoreline against waves generated by northeasterly winds and ocean waves that enter the estuary; and (2) the difference in shoreline orientation on either side of Matawan Point that causes northeasterly waves to generate currents to the south-southeast in the southern portion of the Cliffwood Beach shoreline and currents to the west in the western portion of the shoreline. Fetch distance to the northeast is over 22 km, and the western section is exposed to waves generated by northeasterly winds. Drift to the east occurs along the entire Cliffwood Beach shoreline during northwesterly winds, but the fetch distance is <7·0 km, and wave and current energies are low under these conditions. The only artificial obstructions to longshore transport that extend bayward of the beach fill are a timber groin to the west of the seawall and a shore-perpendicular rubble mound structure, built to secure the outfall pipe from Treasure Lake (Fig. 1).

There are several outcrops of marsh peat evident on the mid-foreshore that extend onto the broad low tide terrace (Fig. 1). Sediment samples gathered for this study reveal very well-sorted sand with a mean diameter of 0·51 mm on the upper foreshore. The surface of the low-tide terrace is composed largely of poorly sorted sediments with lag pebbles, a sand fraction less than 20%, and biogenic material (Fig. 2), with exposures of peat and clay in places.

History of protection efforts

The earliest documented shore protection efforts consisted of seven timber groins placed in front of the cliff in the center portion of the study area by the early 1930s, followed by 18 timber groins and 1·6 km

Fig. 2. The low-tide terrace at Site 3 looking east in 1989, showing pebbles, cobbles, and mounds created by tube-building worms.

Fig. 3. Near Site 3 looking southeast in 1974, before construction of the seawall/beach nourishment probject.

of timber bulkhead in about 1935. By 1957, only 9 groins and about 310 m of bulkhead remained; many of the remaining structures were ineffective within a few years and riprap was used in places to protect the eroding shoreline (Fig. 3).[16] The seawall (Figs 4 and 5) is a stone structure with splash pad, concrete void filler and interior fill and is backed by a graded cliff-face slope planted with stabilizing vegetation and a layer of gabions to prevent loss of fill landward of the structure. The outfall at Treasure Lake and a jetty at Whale Creek were also constructed as part of the project. An artificially nourished beach was placed in front of the seawall as a precaution against damage from wave attack (Fig. 5). An artificial beach and dune were also constructed in

Fig. 4. View from Site 4, looking toward Site 3, showing seawall and nourished beach, March 24 1990.

Fig. 5. Study site in January 1983 just after implementation of the first beach-fill operation.

the low-lying area just west of the seawall to provide flood protection, and a sand fence was placed along the backbeach at that location to trap sand blown off the beach by onshore winds.[17]

The structures were completed in 1976. The initial beach fill was emplaced by October 1982.[16,18] There are no documented figures for the actual volume of sediment emplaced in the initial fill operation, but design figures include 145 260 m^3 in front of the seawall and 170 520 m^3 between the west end of the seawall and Whale Creek. Post-fill surveys reveal that about 31 000 m^3 of sediment were lost in the first $5\frac{1}{2}$ months following emplacement.[18] Most of the fill placed in front of the seawall had been transported downdrift by 1984. A second, smaller operation (about 45 000 m^3) was implemented in 1985 to partially replace these losses.[19] An additional estimated 33 500 m^3 of new beach were added following Hurricane Gloria in September 1985. Fill sediments are moderately sorted medium sand (0·35 mm mean diameter). Native

Fig. 6. Site 1, looking south. The sand on the low-tide terrace is fill material that has been transported from the vicinity of the seawall near Site 2 and is moving south to form the accretional lobes at Matawan Creek.

beach materials were not analyzed for grain size characteristics prior to covering them with the fill.

Field sampling sites

Six sites (Fig. 1) were selected to identify differences in wave and current processes and profile changes at locations fronting the seawall and immediately to the southeast and west of the structure. The low-tide terrace at Site 1 (Fig. 6) to the southeast of the seawall is different from the other five sites. It is about 0·5 m higher and sediments are well-sorted sand due to the abundance of fill material removed from in front of the seawall and transported to the southeast. The low-tide terrace here provides a partial energy filter for waves striking the upper foreshore and increases wave refraction, resulting in a lower angle of breaking waves. The upper foreshore is low and narrow because of limited reworking by the low-energy waves. Site 2 fronts the seawall near Matawan Point. The fill at this site during the field study was only a thin veneer resting on the upper portion of the low-tide terrace and was submerged at mid-tide.

Sites 3–6 are exposed to the effects of storm processes from the northeast, but they are dissimilar in their positions relative to the trapping effects of the groin and outfall pipe (Fig. 1). Site 3 is downdrift of the rubble mound structure at the outfall pipe at Treasure Lake. The quantity of sediment in front of the seawall at this site prevented waves from breaking on the structure under most storm conditions that occurred during the beginning of the study. Site 4 is located at the west bend in the seawall. The beach is narrow at this site relative to adjacent areas (foreground, Fig. 4), and waves reached the seawall during all storms and spring tides. Site 5 is just downdrift of the west end of the seawall and provides the opportunity to compare changes at a beach backed by a seawall (Site 4) with a beach with no structure behind it. Site 5 is underlain by peat that resulted in minimal net change on the low-tide terrace. Site 6 is located at the apex of a re-entrant bounded by two peat outcrops. The low wooden groin just downdrift of this site is still effective as a barrier to longshore transport (Fig. 1).

METHODS

Visual process data were gathered on wind and wave characteristics at all six sites on ten separate days, five of which were characterized by low-speed onshore winds ($<3{\cdot}2\,\mathrm{m\,s^{-1}}$). Three of the days were storm days (onshore winds $>8{\cdot}9\,\mathrm{m\,s^{-1}}$). Wind direction was measured with a compass by sighting along the fall paths of dry sand grains. Local wind speed was measured on the dune or top of the seawall using a hand-held digital anemometer. Wave heights were measured visually with reference to a graduated staff held in the breaking waves. Breaker periods were determined by averaging the time taken for 30 wave crests to pass a given point. Breaker angle was determined by taking the difference between the azimuth of the beach along the waterline and the average azimuth of the breakers by sighting along these features with a compass in the surf zone. Longshore currents were measured in the surf using a Marsh McBirney model 201 unidirectional electromagnetic current meter. Refracted ocean waves were occasionally larger than bay waves. The wave parameters for these days represent ocean wave characteristics. Process measurements were gathered during high water levels because wave energies are greatest at those times and the data are more representative of the conditions that cause the greatest beach change.

More detailed wave and current data were gathered on the upper foreshore at Site 4 during the storm of October 18, 1989 (one of the days when visual observations were taken) to characterize shore-normal and shore-parallel horizontal fluid flows. Data on flow velocities were measured 0·12 m above the bed using a Marsh McBirney Model 511 bidirectional electromagnetic current meter. A pressure transducer was co-located with the current meter to obtain data on surface water-level displacement. Data were recorded on a Sea Data Model 1255B-27 data logger. The data were collected at a sampling interval of 0·5 s in

17·1-min durations. The data were analyzed using the BMDP software program for univariate and bivariate spectral analysis.[20]

Topographic survey data on changes in beach elevation were gathered at 5-m intervals with a rod and transit once every two months between January 24, 1989 and March 31, 1990 and within 5 days after passage of 5 storms. A survey was conducted September 24, 1992 to identify changes over a longer term.

RESULTS

Processes

Wave and current energies are lower on the two sites in the eastern portion of the study area than on the four sites in the western portion (Table 1). The beach at Site 2 is too low for waves to break over it at high tide when process measurements were taken. Process measurements at this site represent non-breaking conditions, which accounts for the low values of breaker height and longshore current velocity. Breaking wave heights on the upper foreshore are lower at Site 1 (Table 1) than on the western sites, because Conaskonk Point shelters the site from northeasterly winds and refracted ocean waves. Refraction is greatest at Site 1, which has the shallowest offshore depths. As a result, this site has the lowest breaker angles, and longshore current velocities are low. The low breaker angles and longshore current

TABLE 1
Averaged Daily Process Measurements from Visual Observations

Variable	*Site 1*	*Site 2*	*Site 3*	*Site 4*	*Site 5*	*Site 6*
Significant breaker height (m)						
Mean	0·12	0·12	0·18	0·17	0·18	0·20
Standard deviation	0·08	0·10	0·12	0·11	0·12	0·14
Significant breaker period (s)						
Mean	2·9	2·8	3·4	3·3	3·1	3·3
Standard deviation	0·5	0·7	1·2	1·3	0·8	0·9
Breaker angle (deg)						
Mean	5·2	N/A	11·3	10·5	13·5	8·4
Standard deviation	3·1		4·4	6·3	7·1	3·5
Longshore current velocity ($m\ s^{-1}$)						
Mean	0·10	0·05	0·20	0·20	0·23	0·17
Standard deviation	0·12	0·08	0·17	0·20	0·22	0·18

Number of cases is 10, except for Site 2 where all wave measurements were taken under non-breaking conditions; here the number of cases is 9 for breaker height and 8 for breaker period.

velocities at Site 6 occur because the sampling location is at the apex of a shoreline re-entrant (Fig. 1). The direction of the longshore current at Sites 1 and 2 was always to the south, in contrast to the dominant westerly flow of the current at Sites 3–6.

Winds blew from the northeasterly quadrant on five of the ten days that visual measurements were taken. They blew at an average speed of 7·4 m s^{-1}, or slightly greater than the means from the northeast and east over the 19 years portrayed in the wind rose in Fig. 1. The three storms that occurred during the ten days of process observations were low-pressure centers that brought winds from the northeast (averaging 11·5 m s^{-1}) and raised water levels from wind and wave setup and flow from the ocean. The highest significant wave height during the study was 0·43 m at Site 6, when the wind blew from east-northeast at 12·5 m s^{-1}. The highest longshore current velocity measured at any site during the 10 days was 0·55 m s^{-1} to the west observed on Site 5 when wind velocity was 8·9 m s^{-1} from the northeast and waves were breaking at an angle of 24° from shore-parallel. The direction of the longshore current at Site 1 at this time was to the southeast (at 0·17 m s^{-1} with a wave angle of 11°). The highest longshore current velocity at Site 1 was 0·34 m s^{-1} to the southeast when wind was blowing out of the northeast at 13·1 m s^{-1} on October 18.

Waves broke landward of the instruments deployed on Site 4 on October 18. Calculation of wave heights from the pressure transducer records reveal that significant wave heights (4 × the standard deviation) ranged from 0·20 to 0·24 m. Observed significant wave heights were 0·35 m at this site. Spectral analysis of the pressure transducer record (Fig. 7) reveals a bimodal distribution with two statistically significant peaks. The low-frequency peak at 0·14 Hz (7·1 s) is narrow-banded and

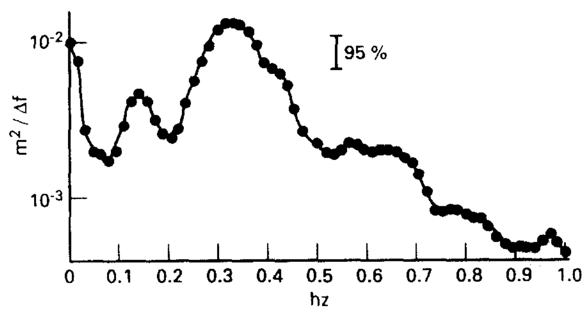

Fig. 7. Spectral estimate of pressure transducer data recorded at Cliffwood Beach, New Jersey on 18 October 1989. Bandwidth = 0·0791 Hz.

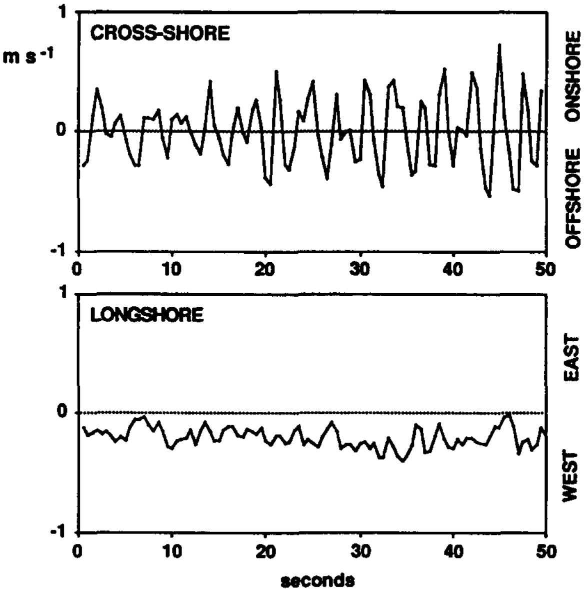

Fig. 8. Fifty-second partition of data records of shore-normal and shore-parallel currents measured on the upper foreshore at Cliffwood Beach on rising tide on October 18, 1989. Velocities are in m s^{-1}.

is attributed to ocean waves that typically have periods near this value.[21] The incident wave band is broad with a peak frequency expected of locally generated bay waves (0·34 Hz or 2·9 s).

Examination of the data records of the shore-normal and shore-parallel current records on the rising tide (Fig. 8) reveals that the cross-shore velocities are symmetrical while the longshore velocities are skewed in the westerly direction. The cross-shore mean flow during the monitoring period was near zero. The longshore flows were to the west during this experiment. The mean longshore flow was 0·33 m s^{-1}. These data reveal a dominance of net longshore flow over cross-shore flow.

Beach change

The net change in beach profile during the 44 months from January 24, 1989 to September 24, 1992 (Fig. 9) indicate the following: (1) considerable erosion occurred on the upper foreshore of Site 1, while deposition occurred on the low-tide terrace; (2) mobility of the upper foreshore was lowest at Site 2, which is low in elevation and has limited sediment in the beach prism; (3) the greatest amount of erosion occurred on the upper foreshore at Site 3; (4) the profiles at Site 4

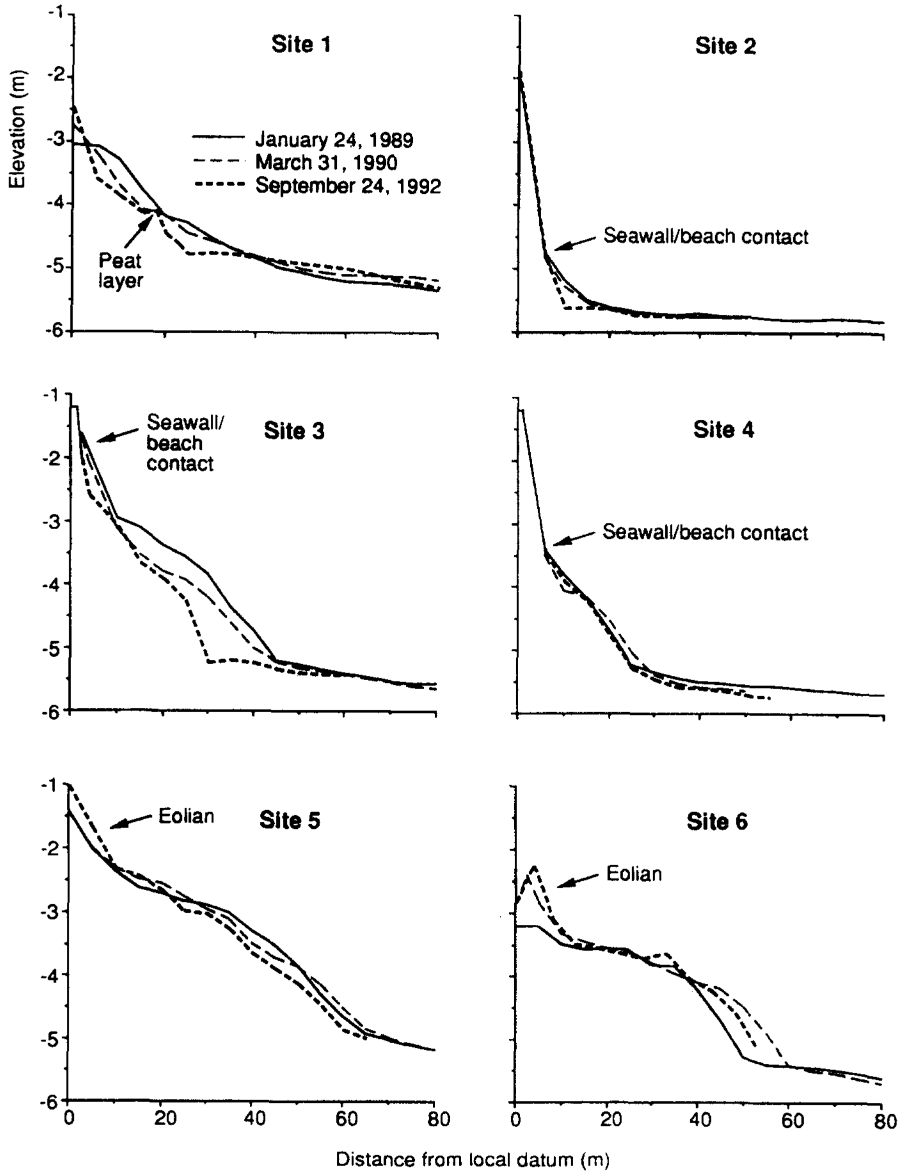

Fig. 9. Beach profiles showing net change during the 44-month study. All profiles are tied into the same vertical datum. Horizontal distances are relative to local data placed on each profile line.

show little net change on the upper foreshore; (5) considerable deposition occurred on the upper foreshore at Site 6 in the first 14 months of the study, followed by erosion, but the net result is accretion over the 44 months; and (6) profiles at Sites 5 and 6 show eolian accretion above the limit of wave reworking.

Examination of pre- and post-storm profiles at Site 1 indicates that much of the deposition on the low-tide terrace occurred at a different time from erosion on the upper foreshore. The sediment on the low-tide terrace that was removed from in front of the seawall, and the sediment removed from the upper foreshore, is transported to a location southeast of Site 1, where it is contributing to the buildup of several accretional lobes extending into Matawan Creek (Fig. 6). Most of the fill sediment that was on the upper foreshore between Site 1 and the seawall on January 24, 1989 has been removed, exhuming the peat layer that was exposed near mid-foreshore before the fill was emplaced. Further evidence for net transport to the south is seen in the direction of the observed longshore currents that flowed south on all days on which measurements were taken, even days when the winds blew out of the east. The high mobility of the low-tide terrace on Site 1 is attributed to the addition of the sand from the fill. The finer and better-sorted surface material on the low-tide terrace at Site 1 (Fig. 6) is in striking contrast to the lag surface that exists on the low-tide terrace at the other sites (Fig. 2).

Much of the fill had already been removed from the profile at Site 2 by the time of the first topographic survey (Fig. 9). Change during the 44-month period was confined to removal of most of the remnant upper foreshore, but the elevation of the low tide terrace did not change.

The greatest amount of erosion occurred at Site 3. Sediment from this site was transported to the west during northeasterly storms. The lack of significant net change at Site 4 implies that this beach is a transport surface rather than a source or sink. Profiles from Sites 3 and 4 (Fig. 10) taken before and after the storm of October 18–19 reveal the relationship between Site 4 and the updrift source. Profiles for both sites document the typical morphologic response to storms on mesotidal estuarine beaches.[14] The volume of sediment deposited low on the profile of Site 4 is considerably greater than the volume removed from the upper part of the beach at this site, and this volume change is attributed to longshore rather than cross-shore transport.

Net long-term erosion at Site 3 (Fig. 9) is attributed to its location downdrift of the outfall pipe (Fig. 1) that reduces the rate of transport into the area. The data for Site 3 (Fig. 9) indicate a loss of $26{\cdot}3\ \mathrm{m^3\ m^{-1}}$ of shoreline over the 44-month period; average shore-normal linear

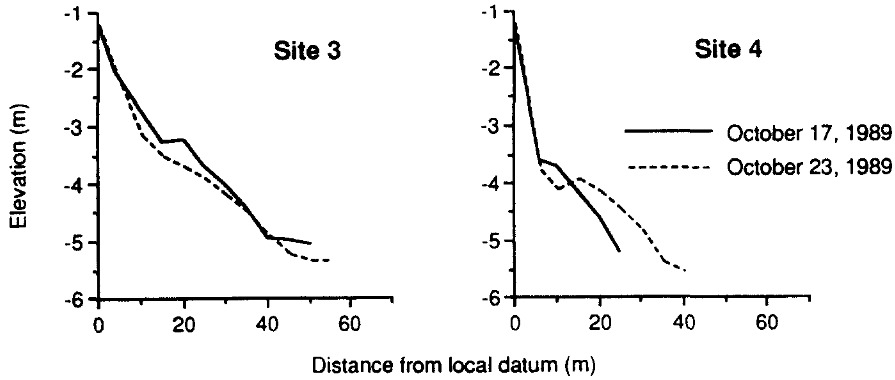

Fig. 10. Pre- and post-storm profiles at Sites 3 and 4. The accretion at Site 4 shows both the potential for high mobility in the short-term and showing the potential for Site 3 to function as a feeder beach in the short-term.

retreat across the upper foreshore at this site was 8·5 m. This represents a rate of erosion of 2·3 m $year^{-1}$.

There was little net change at Site 5 in the first 14 months, presumably because adequate fill material was transported into the area, but net erosion occurred in the portion of the profile affected by wave processes over the following 30 months. Net deposition at Site 6 may be attributed to trapping by the low wooden groin downdrift of it and reduction in sand transport potential within the shoreline re-entrant formed by the peat outcrops (Fig. 1) due to reduced longshore current velocities (Table 1).

Eolian transport

Wind-blown sediment frequently overtopped the seawall at Site 3, where the elevation of the backbeach was close to the top of the seawall in January 1989. A quantitative evaluation of losses from the fill sediment due to eolian transport is provided by comparing changes in the volume of sediment deposited in the dune at Site 6. A sand fence was emplaced at the landward side of the backbeach at Site 6 just prior to the monitoring period. The accretion within 12 m of the datum revealed on Fig. 9, indicates that 6·8 m^3 of sand m^{-1} of shoreline was transported from the beach by eolian processes. Sediments in the dune are well-sorted medium sand (0·30 mm). The size of the dune and the rate of growth are greater than are commonly found in an estuarine setting[13], presumably due to the great width of the source area provided by the fill. The width of an unvegetated natural estuarine beach with similar tidal range, wave energy regime and beach slope would be about 30 m, including the wetted intertidal portion of the profile.[12] The widths of the beach at the beginning and end of the 44-month period are about 40 m and 50 m, respectively. The extra width at Cliffwood beach is on the dry, flat, unvegetated backbeach where eolian transport would be maximized.

The fence at Site 5 had deteriorated and was ineffective in trapping sand, so less accretion is evident on the upper portion of that profile. Approximately $2{\cdot}9\,m^3$ of sand m^{-1} of shoreline accumulated within 10 m of the datum at Site 5. Field observations indicate that significant eolian accumulation also occurred at the seawall just to the southeast of this profile line.

DISCUSSION AND CONCLUSIONS

The performance of the beach nourishment must be placed within the context of the variability in processes along the shoreline as influenced by the macro-scale shoreline orientation and revealed in the pronounced differences in profile changes. The seawall at Cliffwood Beach is not situated at the same relative location on the beach profile at all sites, and the segments in front of the seawall respond differently.

Studies of the effect of seawalls on nearshore fluid motions and sediment transport have documented differences in beach change at sites backed by seawalls and adjacent unarmored sites.[22,6,23,24] Storm response includes impoundment on the updrift side, flanking on the downdrift side and scour at the toe. Impoundment on the updrift side at Cliffwood Beach is not applicable because the zone of drift divergence was within the limits of the seawall. There was removal of sediment at the southeast end of the seawall as a result of the net transport to the southeast caused by the sheltering of the Conaskonk Point headland. The seawall prevents removal of sediments from the cliff to nourish downdrift beaches, and flanking has occurred as a result of removal of the fill and loss of the updrift source. The net loss of sediment on the west side of the seawall (at Site 5) is small. There has been sufficient sediment available to pass freely along the beach to allow the beach just to the west of the seawall to maintain its position. Flanking almost certainly would have occurred at this location in the absence of fill, due to the pronounced net rate of longshore transport.

Scour of a beach seaward of a shore-parallel structure has been observed at some estuarine sites.[1] The most dramatic changes associated with the interaction between the seawall and the upper foreshore were expected at Site 4, where the seawall intersects the profile at a location where waves would break at high water levels. The availability of sediment from updrift of Site 4 obscured any detrimental net effects of increased turbulence at that location. Given an adequate sediment supply, the magnitude and variation of beach change in front of seawalls is similar to change measured at sites not backed by seawalls.[6] The upper foreshore at Site 4 serves as a transport surface, evidenced by the high mobility rate over periods of days and weeks but by limited net change over the 44-month period.

Locations where seawalls are seaward of the normal breaker line are subject to the action of non-breaking waves, and little scour is expected.[25] At Site 2, wave energy dissipates across the broad surface of the low-tide terrace at low stages of the tide and reflects without breaking at high stages of the tide. The rapid migration of the breaker zone across the low-tide terrace during the rise and fall of the tide results in minimum duration of wave-energy concentration and turbulence at the base of the wall. There was no net scour on the low-tide terrace at Site 2; it appears that critical scour may not occur due to the presence of a seawall on the low-tide terrace of meso-tidal estuarine beaches because of both low wave energy and a more cohesive surface.

Differences in beach profile response at Sites 3, 4, 5, and 6 are attributed to shore-perpendicular structures, sediment availability, and local shoreline characteristics. Pronounced changes in beach volume occurred despite relatively low wave energies. The high rates are attributed to the unidirectional nature of the longshore current and the high mobility of the fill materials, coupled with trapping effects of structures and peat outcrops. The lack of recent beach mobility at Site 2 is due to the virtual elimination of the upper foreshore, leaving only the low-energy portion of the profile on the low-tide terrace.

The nourishment operations at Cliffwood Beach contributed large amounts of sediment to the low-tide terrace at Site 1 and altered the characteristics of the surface. Rates of mobility are high relative to the other sites, where mobility is diminished due to the armoring effect of the shell, lag gravels, clay, and peat representing the former surface uncovered through removal of fill. Transport of fill material to and across this surface from the vicinity of the seawall is favored by the pronounced break in shoreline orientation. The lack of similar quantities of fill on the low-tide terrace at the other sites implies that this is a site-specific phenomenon. Transport of fill material from the upper foreshore to the low-tide terrace can occur on sheltered beaches, but the size of the sand fraction that moves offshore would be finer than that found on the low-tide terrace at Site 1.

The results of this field investigation imply that shore-parallel structures constructed on the low-tide terrace on meso-tidal estuarine shorelines may not require a fronting protective beach to prevent net scour, but nourishment is important to retard flanking on the upper foreshore, provided that transport can occur along the upper foreshore from updrift sources. Decisions concerning implementation of beach nourishment in association with construction of seawalls should consider the macro-scale effects of shoreline orientation and location within drift cells and local site-specific effects in addition to the theory of the behavior of sediment in front of and adjacent to structures.

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