CHAPTER 228

Cohesive Profile Erosion by Waves

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Abstract

Hydraulic tests of the erosion by waves of a shore profile made from intact samples of till, a cohesive material comprising a large part of the Great Lakes shorelines, have been completed. Over 1000 h of testing in a laboratory flume with random depth-limited breaking waves, varying conditions of sand cover, and varying mean water levels have been run. The vertical erosion rates of the till were measured along the centreline of the 8 m long, 0.35 m wide and 0.25 m thick till profile; its initial shape was the equilibrium form $y = Ax^{2/3}$ common on sandy beaches. Some of the important findings are that this type of hydraulic test is viable, the role of sand in the erosion process is similar to its role in unidirectional flow model tests but the thickness and volatility of the sand layer are also factors, the main effect of varying water levels is to shift the zone of erosion activity up and down the profile, and that erosion can occur in the absence of sand if the rate of wave energy dissipation is high enough (plunging breakers, steep slopes).

Introduction

A large part of the Laurentian Great Lakes shoreline consists of cohesive materials, especially till. Similarly, much of the Black Sea coast, England's North Sea coast and others consist of cohesive materials. These shorelines are typically characterized by an eroding backshore bluff and a small, thin beach; cohesive material underlays the beach of cohesionless (sandy) materials. A shore can be defined as cohesive when a cohesive sediment substratum occupies the dominant role in the change in the shoreline shape (i.e. through erosion). It has been recognized that there are fundamental differences in the erosion process between sandy and cohesive shores. Cohesive shores are often glacial in origin, and they derive their strength from the cohesion of the clay as well as their consolidation from the period of glacia-

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tion. Once the material is eroded, it cannot reconstitute itself; it's cohesive nature is lost and the fine particles are advected away from the nearshore zone. Therefore, unlike sandy shores, erosion on cohesive shores is irreversible. The recession of cohesive bluffs is now understood to be controlled by the vertical erosion (downcutting) of the nearshore profile (Kamphuis 1987). Typically, the beach of cohesionless material in front of a cohesive bluff plays a complex role in the erosion process; it can provide some protection or can serve as an abrasion agent depending on its volume and the wave energy. Only when the volume of cohesionless material overlying a cohesive layer is large (of the order 200 m^3/m for the Great Lakes), as can occur at a large obstruction such as a harbour jetty or a headland, does the erosion process return to being the same as that on a sandy shore (Nairn 1992).

The erosion process on a cohesive coast can be demonstrated by a comparison of two cross-sections of a bluff and nearshore profile at a site in Lake Ontario (Nairn 1992). Figure 1 shows the estimate of the underlying cohesive profile and the sand cover in 1952 and again in 1989. The bluff face has receded about 30 m over this 37 year period for an average recession rate of 0.8 m/yr. In order for this to occur, the nearshore lake bed had to be downcut considerably. Furthermore, the profile shape in 1952 is very similar to that in 1989; it has simply shifted shoreward by 30 m. In a review of many field data sets throughout the Great Lakes, profiles were generally found to retain their shape as they receded (Nairn 1992). There appears to be an equilibrium or preferred cohesive profile shape.

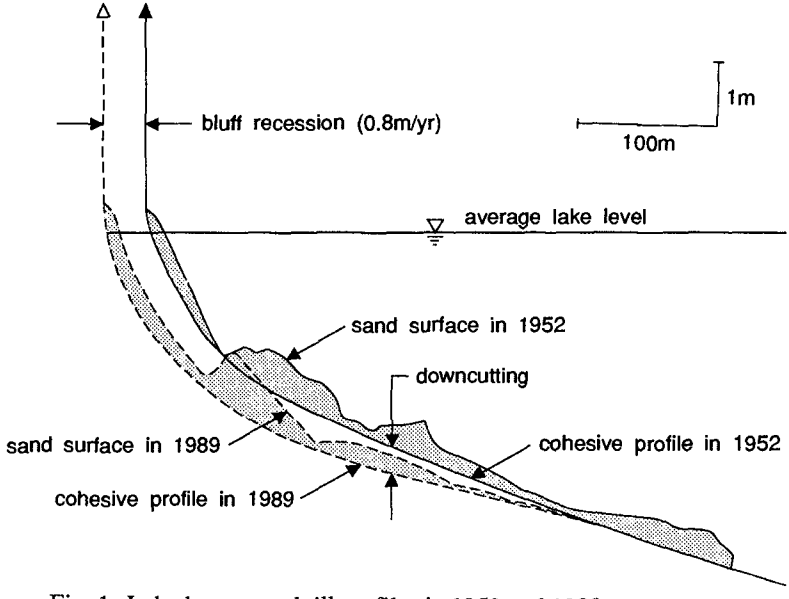

Fig. 1 Lake bottom and till profiles in 1952 and 1989 at Scarborough Bluffs, Lake Ontario (after Nairn,1992).

In the present work, the processes important in the erosion by waves of a nearshore profile made from intact samples of till are examined by means of hydraulic tests.

Field Work

A vital component of this study was the collection of intact till samples in the field. Remoulded clays are known to have much reduced resistance to erosion compared with the undisturbed or intact clay (Lefebvre and Rohan 1986). After several field reconnaissance visits to the Lake Erie shoreline, a suitable site located about 200 m from the northshore bluff of Lake Erie was found. The site, Shanks' Gravel Pit #1, is located just west of Port Alma on Highway 3, where, after stripping off the overburden, a sand-gravel layer which overlies Port Stanley till is mined using a dragline. The bluffs and lake bottom over a large part of northwestern Lake Erie consist of Port Stanley till, a relatively homogeneous, cohesive material laid down by glaciers over 10,000 years ago.

Open-ended steel boxes were manufactured using 1/8 inch (3.2 mm) thick steel. The box dimensions are 1.0 m long, 0.35 m wide and 0.45 m high. The front (cutting) end of each box has a bevelled edge and sloped back at an angle of 2, 3 or 7 degrees; these slopes were intended to minimize the surface gaps between blocks when installed in the flume.

2a Backhoe clearing face of till

2b Cutter frame with till sample

2c Till sample in steel box

2d Field site after removing 25 samples

Fig. 2 Photographs of field site

On October 9, 1990 Shanks removed the overburden and sand-gravel layer, prepared a work area and scraped the till surface smooth using a mid-sized bulldozer and a 25-ton crane with a dragline. On October 10, after pumping out accumulated rainwater, the till surface was trimmed by another 30 cm. Then a trencher was used

to cut a smooth vertical face in the till. A backhoe and bulldozer were used to clear the working face of the till (Fig. 2a).

A custom made aluminum cutter frame was positioned and levelled in front of the prepared vertical till face; it was held in place by the trencher and bulldozer. A portable diesel hydraulic unit was used to power a 20-ton hydraulic ram. The ram slowly pushed an empty steel box guided by the cutter frame into the till (Fig. 2b). The end of the box in the till was cut away using a chainsaw with a trenching chain. The box was then lifted (Fig. 2c) and transported to a flatbed truck using the crane. The tops of the samples were covered with cheesecloth, sprayed with water, then the whole till-filled steel box was wrapped in plastic. By repeating this procedure, 25 till blocks were collected on October 10-11 by 8 people (Fig. 2d). When the samples arrived at NWRI, each block was misted again with water, and then put into 2 plastic bags which were then taped shut. Later, on May 23, 1991 all unused till blocks were stored under water until needed.

Size analysis and geotechnical tests on samples of the till gave the following average properties: 21% sand and gravel, 33% silt, 46% clay, mean grain size D_{50} = 0.0052 mm, liquid limit 27, plastic limit 17, plasticity index 10, and vane shear strength 86 kPa.

Laboratory Flume Setup

Tests were conducted in the 100 m long wind-wave flume at the NWRI Hydraulics Laboratory. An existing smooth plywood beach at a slope of 1:20 was modified to incorporate a 0.37 m wide channel along its centreline. Fig. 3 shows the test setup. A motorized carriage, equipped with a variable speed motor, traversed the working length of the test channel. Its position was monitored using an electronic synchro transmitter with horizontal accuracy of about +/- 3 mm. Profile data were collected at horizontal speeds of the order of 10 mm/s. Vertical profile data were measured with an optical bedplotter device mounted on a bracket attached to the carriage. Light from a light emitting diode is sent through a probe of fibre optic cables; a servo system raises or lowers the probe so as to maintain a preset voltage, corresponding to a vertical gap of about 15 mm, from the light signal reflected from the bed. The accuracy of the system is about +/- 1 mm. A bedplotter reading was taken on a fixed reference plate before and after each profile. Typically, variations between before and after readings were about 0.5 mm.

Waves

Waves were generated by a piston-type wavemaker using GEDAP (Funke and Mansard 1984) software. One random wave voltage sequence was used to drive the wavemaker for all tests. It was developed for a mean water depth of 100.0 cm, a peak frequency of 0.4 Hertz, a duration of 500 s (200 waves), unspecified groupiness, and a ratio of mean wind speed to wave phase speed (U/c_p) of 1.3. Waves were measured by 3 capacitance wave gauges. The spacing between gauges 1 and 2 was 0.706 m, and between 1 and 3 was 1.696 m. Incident and reflected wave spectra were separated using the method of Mansard and Funke (1980). The characteristic wave height (H_{m0}) of the incident waves was 0.31 m at a water depth of 1.00 m, 0.29 m at 0.95 m, 0.26 m at 0.85 m, and 0.26 m at 0.75 m. The corresponding values

of peak frequency (f_p) varied between 0.33 and 0.39 Hertz.

Since the laboratory tests used intact samples of prototype till and depth-limited breaking waves over most of the profile, these tests can be considered as full scale of the nearshore zone to a water depth of 0.5 to 0.75 m. There may be some model effects due to the peak frequency of the waves being higher than typical storm values of 0.1 to 0.2 Hz in the field.

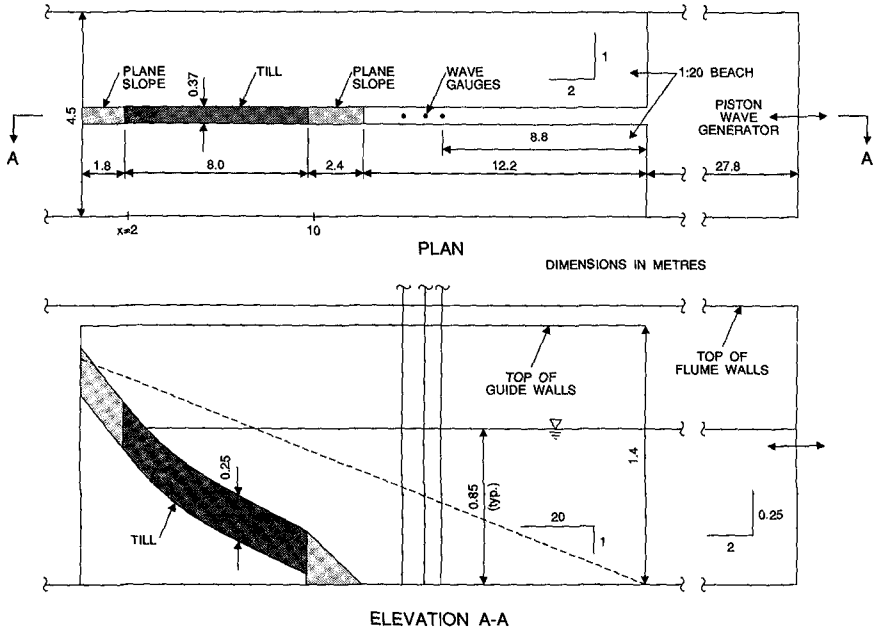

Fig. 3 Test setup in laboratory flume

Initial Profile

According to Kamphuis (1987), nearshore profiles on cohesive coasts in wave-dominated environments have a long term, stable shape similar to the so-called "equilibrium" shape of sandy beaches described by Dean (1977). This shape is of the form $y = Ax^{2/3}$ where y is the vertical distance measured downward from the mean water level, x is the horizontal distance measured from the mean water line, and A is a shape factor. This equation is for the mean profile and inherently ignores sand bars. Moore (1982) relates the shape factor to the mean grain size present on the beach. A medium sand, with $D_{50} = 0.51$ mm, available in the laboratory, was put in the testing part of the flume and subjected to about 20 h of the test wave spectra. The sand profile reached a stable shape and was measured. Ignoring the bars, the shape corresponds well with the predicted shape using the value of A given in Moore (1982) for the 0.51 mm sand (Fig. 4).

Based on these preliminary tests with sand, the starting profile for the till was designed to be of the form $y = 0.18x^{2/3}$. Eight till blocks, trimmed to a height of 0.25 m, were installed in their steel boxes in the flume; loose till was packed into the seams and then the profile was measured under water. The initial till profile is compared to the design profile in Figure 4. Only a brief summary of results of several different test categories are given here; for a detailed description of tests and results, refer to Bishop and Skafel (1992).

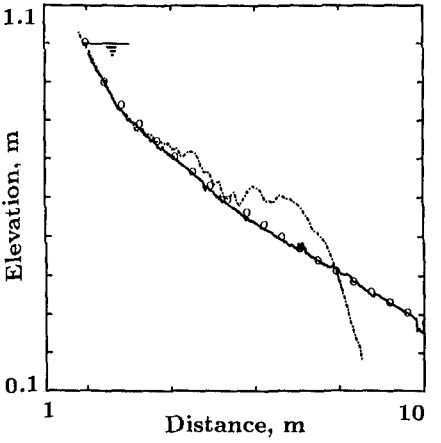

Fig. 4 Equilibrium sand profile (---), design profile (ooo), and initial till profile (—). Water depth = 1 m.

Scour Hole Formation

The first (exploratory) test series (TS1) was run with a mean water level of 100.0 cm; the most striking observation was the formation of a significant scour hole at the plunge point for a majority of the breaking waves, located in the top till block just below the mean water level. The test began with a large supply (est. 100 L) of 0.51 mm sand on the profile above the top till block. This acted as a sand dune and provided unlimited sand to the till profile for the first few hours of testing. After only 2.08 h of waves, the beginning of the formation of a scour hole from the mean water line to a depth of about 0.18 m was observed. Then, to restrict the sand supply, the sand dune was flattened and then covered with fibrous matting; however, sand was still available by leaking out from under the matting. Sand was being lost from the till surface through gaps at the seams between till blocks; this implies that sand was moving across the till surface. Fig. 5 shows the till profile and rate of change in elevation (erosion rate) at t = 8.33 h at which time only a few sand ripples were left at the bottom of the profile. (In Figures 5 to 13 the solid and dashed lines are the initial and final profiles respectively for the test sequence under discussion; they refer to the left hand vertical axis. The dot-dash line is the erosion rate (right hand vertical axis) and the dotted line is the zero erosion rate.) The scour hole continued to erode rapidly. Over the first 8.33 h the peak erosion rate at the scour hole averaged 13 mm/h; this was the highest rate measured over the entire test program.

The seams were repaired by excavating a narrow trench at each seam, grouting the bottom of the trench, and then backfilling and compacting the seam with remoulded till. A variety of tests were run with and without sand. After 140 h, the till profile is shown in Fig. 6. The scour hole continued to grow in size but the rate of change decreased dramatically.

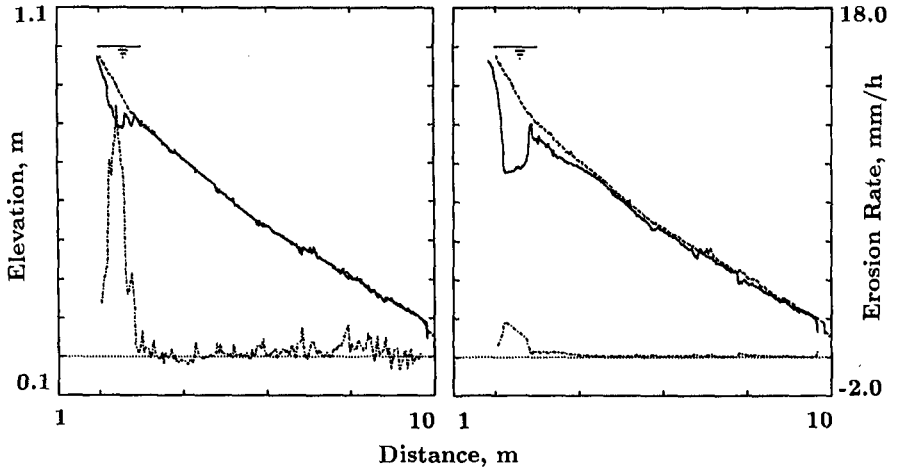

Fig. 5 Till profile and erosion rate after 8.33 h of testing at d = 1 m.

Fig. 6 Till profile and erosion rate after 140 h at d = 1 m.

The second test series (TS2) began with an initial profile that was the eroded profile after 145 h from TS1. In order to avoid effects due to the scour hole, the mean water level was lowered to 85.0 cm. In this and subsequent test series, the test conditions were varied in systematic fashion and the response of the till was measured. At the end of TS1, somewhat less than 8 L sand was left on the profile. This sand moved quickly from $4 < x < 5$ m to $5 < x < 6$ m, the latter being the stable sand bar position for the lower water level of TS2. For the first 15 h of TS2, no new sand was added.

The most striking feature of TS2 was that a large scour hole did not form below the MWL as had occurred in TS1. The dominant zone of plunging breakers moved offshore from the scour hole area of TS1 to the region around $x = 4$ m. In TS1 the scour hole formed where plunging breakers struck an initially steep (1:5.5) till slope. In contrast, for TS2, at the lower water level, the breakers struck a flatter (1:10) initial till slope and were not plunging as intensely.

No Sand

From the results of unidirectional flow lab tests by Kamphuis (1990), it is known that the erosion rate of till is strongly dependent on the presence of sand in the water. As part of the present study, Kamphuis carried out erosion tests on till samples from Shanks pit in a manner identical to earlier tests of Kamphuis (1988).

When clear water was used to erode the samples, the "critical shear stress" required to begin erosion was about 7 Pa. When sand was introduced into the flow, erosion began at a much lower shear stress of about 0.8 Pa, which corresponds to the threshold for movement of the sand. This indicates that erosion of a cohesive layer subjected to a flow containing some sand begins when the sand becomes mobile as discussed in Kamphuis (1990).

A "no sand" scenario was investigated by draining the flume, washing the till surface, and then running 62.5 h of waves; the only cohesionless material on the profile was that which had been missed in the washing and that which eroded from the till surface during the test. Fig. 7 shows that the erosion rate (note the change in erosion rate scale) is very small (less than 0.2 mm/h); the higher rate around x = 4.8 m is due to some protruding grout having been manually removed. The results agree with the findings of Kamphuis (1990).

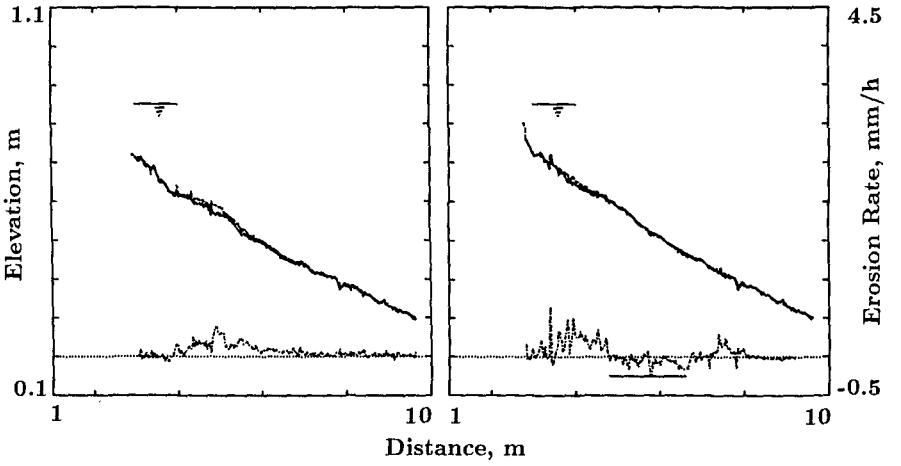

Fig. 7 Till profile and erosion rate after 62.5 h, d = 0.85 m, no sand.

Fig. 8 Till profile and erosion rate after 37.5 h, d = 0.85 m, stationary sand bar.

Stationary Bar

A stationary bar scenario was investigated by placing 24 L of sand evenly on the profile at $5 < x < 7$ m; the waves caused a bar to form at the location indicated by the short horizontal line in Fig. 8. Waves were run for 12.5 h, the sand was scraped from the bed and then, after profiling, the sand was placed evenly at $5 < x < 7$ m again. This sequence was repeated two more times. Over this time Fig. 8 shows virtually no erosion beneath the bar, but some erosion both onshore and offshore; the small accretion rate indicated under the bar is due to some sand being missed when cleaning the till surface. From the results of this and other tests, it has been shown that the presence of a stationary sand layer of 10 mm or more thickness is sufficient to prevent erosion of the underlying till for the wave conditions and grain size characteristics associated with these tests.

Sparse Sand Cover

A sparse sand cover environment was created by leaving an estimated 2-3 L of sand on the bed after it had been scraped, adding no new sand and running 37.5 h of waves. After this test, the flume was drained, the profile was washed and about 1.5 L of sandy gravel was recovered from the profile and another 0.5 L may have been washed away or missed. Grain size analysis of the recovered material gave D_{50} = 1.3 mm. The profiles and erosion rate for this period are shown in Fig. 9. Clearly, the erosion rate is higher than the case of a stationary bar and the zone of erosion extends across most of the profile, including the former bar location; the null spot around x = 4.8 m is at a hardened seam.

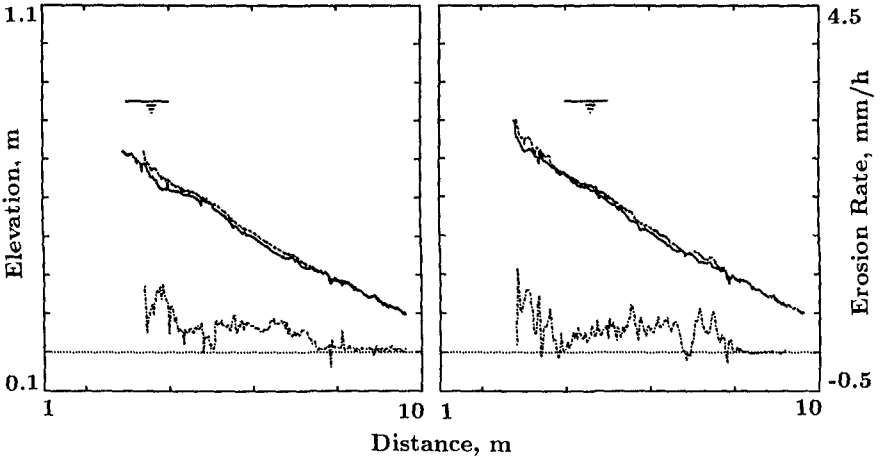

Fig. 9 Till profile and erosion rate after 37.5 h, d = 0.85 m, sparse sand cover.

Fig. 10 Till profile and erosion rate after 40 h, d = 0.85 m, recycled bar.

Recycled Bar

An artificially recycled bar environment was created by adding about 20 L sand at the scour hole, letting it move to the bar location, then scraping it off the bar and placing it in the scour hole again at intervals of 1.25 h. Earlier tests had determined that all the sand moved to its stable bar position within 1.25 h. Fig. 10 shows the erosion rate over this 40 h period. There are null spots around x = 3.8 m and 6.8 m, both at hardened seams, and relatively high erosion rates (up to 0.5 mm/h) out as far as x = 8 m. This scenario is probably fairly representative of three-dimensional conditions in that sand is moving over the profile out to a least x = 6 m and all parts of the profile are fully exposed for some of the time. From the results of this and other tests, the exposure of the till to moving sand, or, expressed another way, the volatility of the sand cover, is an important factor in the erosion process.

Varying Water Levels

The objective of this test series (TS4) was to investigate the influence of changing mean water levels on the erosion of the till profile. Tests were conducted at water levels 85, 95, 75 and back to 95 cm. The 8 till blocks used for the first tests were removed and replaced with new till blocks plus an extra one, the ninth, above block 1. The shape of the profile was the same as before, i.e. $y = 0.18x^{2/3}$, except that the slope of the top two blocks was reduced to 1:9.4 so as to be the same as the third block, formerly the second block. A sealed wood beach with fibrous matting on top was installed above block 1 at the same 1:9.4 slope.

After 140 h of tests at a mean water level of 85 cm, the mean water level was raised to 95 cm. For the next 60 h waves attacked the profile without any supplementary sand. However, it was observed that quite a lot of gravel eroded from the till and collected over $3.7 < x < 4.6$ m; gravel filled in any low spots, especially a runnel along the centreline. At 30 h the profile was washed and about 5 L sandy gravel was recovered. For the subsequent 30 h, a recycled bar environment was created again by adding 2 L sand at the mean water level at 3.33 h intervals and scraping the bed underwater at 10 h intervals. After washing the bed, about 5 L sandy gravel was recovered. Fig. 11 shows the profiles at the start and end of the 90 h test with a depth of 95 cm and the corresponding erosion rates. Clearly, the major zone of activity is the upper part of the profile near the mean water line. A distinct scour hole again formed at the upper (steep) part of the profile at the zone of dominant breaking.

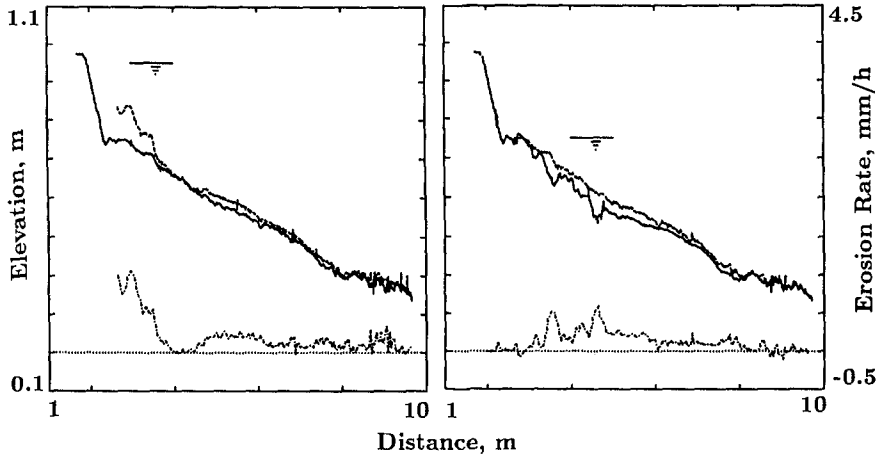

Fig. 11 Till profile and erosion rate after 90 h, d = 0.95 h.

Fig. 12 Till profile and erosion rate after 120 h, d = 0.75 m.

After lowering the mean water level to 75 cm, 70 h of waves were run without adding any sand. About 0.5 L of sandy gravel was eroded from the till, and removed by scraping, during each 10 h period. After 70 h the flume was drained and the bed was washed. For the next 50 h, a recycled bar environment was created by

adding 2 L sand just below the mean water line at 3.33 h intervals and scraping the bed underwater at 10 h intervals. Fig. 12 shows the profiles at the start and end of the tests at 75 cm. The major zone of erosion has shifted offshore to the zone of dominant breaking corresponding to the lower water level. The main effect of a change in mean water level is to shift the location on the profile that experiences the breaking waves; for high water, the zone of erosion is further onshore, while for lower water, the zone moves offshore.

The mean water level was raised again to 95 cm and 50 h of waves were run without adding any sand. Fig. 13 shows the beginning and end profiles, and the erosion rate, for TS4 after 400 h (of the series of four water levels). The profile has shifted shoreward and has steepened slightly at its top end. The erosion rate starts near zero around the highest mean water level, quickly reaches a maximum near the dominant plunge point of the breakers at the highest mean water level, then decreases quite uniformly in the offshore direction. These trends agree with the field results depicted in Figure 1.

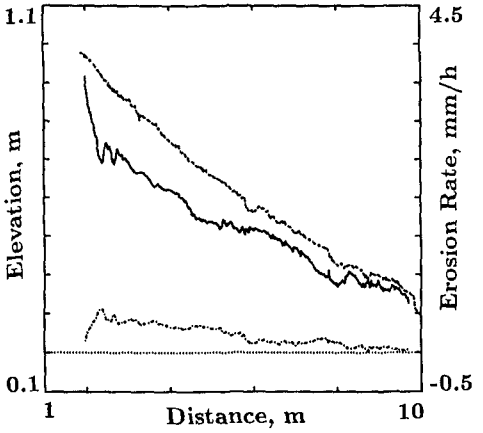

Fig. 13 Till profile and erosion rate after 400 h, d = 0.85, 0.95, 0.75 and 0.95 m.

Numerical Model

A numerical model has been developed to simulate the processes on a cohesive shore profile. The downcutting process of a cohesive profile is more complicated and less well understood than the transport of the overlying sand. The model, first presented by Nairn et al (1986), empirically relates downcutting to two processes: (1) the shear stresses on the bed due to the wave orbital velocities; and (2) the intensity of wave breaking (as indicated by the local gradients in wave energy dissipation across the surf zone) and associated turbulence and jets (due to plunging breakers) impinging on the bottom. The former is dominant outside the surf zone, while the latter is dominant in the surf zone. These concepts are in agreement with the observations that the degree of downcutting increases towards the shore, a result that

cannot be sustained by a model based only on shear due to orbital velocity. Two empirical coefficients are used to relate the downcutting to these processes. The presence of sand overlying the cohesive layer has two distinctly different roles, depending on its thickness. A thin veneer acts as an abrasive agent, increasing the downcutting. A thicker layer, typically greater than 5 to 10 mm in these tests, protects the underlying cohesive material. An updated version of the original model (Nairn 1990) is able to predict the movement of the sand layer over a fixed surface, and so the resultant effects on the cohesive layer can be predicted in the short term. The model upgrade includes the consideration of supply limitation to sediment transport predictions. This type of short term modelling is helpful in developing a better understanding of the erosion processes through an extension of the physical experiments. For long term predictions heavy computational demands of the model and cumulative errors in simulating the sand movement require the use of the model without explicitly accounting for the sand cover, with appropriate coefficients.

Results of the calibration runs for the two types of simulation are shown in Fig. 14 in which the dashed line is the initial profile, the solid line is the experimental erosion rate and the dot-dash line is the numerical model erosion rate. In Fig. 14a, sand cover was explicitly considered in the case of the recycled bar: the relatively high downcutting rates are well represented over most of the surf zone except the very top part. Under the influence of the sparse sand cover the downcutting was reproduced equally well (Fig. 14b) with coefficients that did not take the presence of sand into account. For the sparse sand cover case, the ratio of the values of the coefficients from the two types of simulation indicate that, at any one point, the profile was subjected to downcutting for only 10 to 20% of the time. These numerical model calibration runs provided valuable guidance in extending the numerical work to prediction of the evolution of various cohesive shore types in the Laurentian Great Lakes (Nairn 1992).

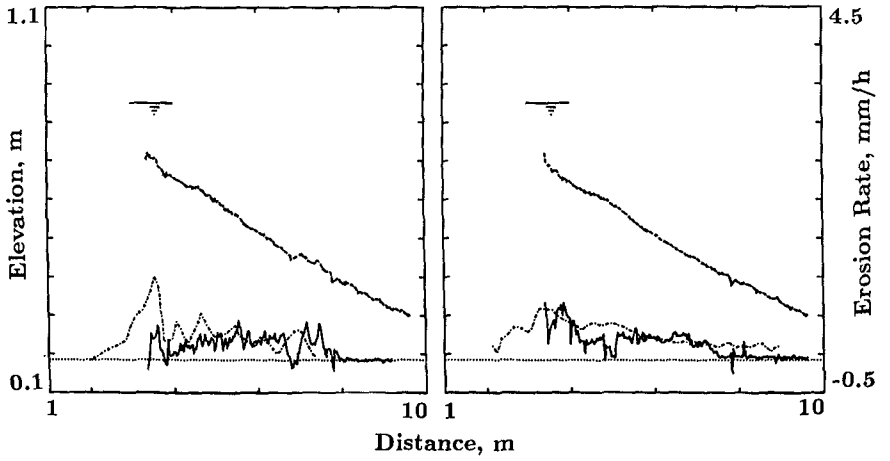

Fig. 14 Till profile (---), lab (—) and numerical model (-·-) erosion rates.
(a) After 40 h, d = 0.85 m, recycled bar
(b) After 37.5 h, d = 0.85 m, sparse sand cover

Conclusions

Hydraulic tests of the erosion by waves of a shore profile made of intact till samples have been conducted successfully and have helped to advance our understanding of coastal processes on cohesive shores. The role of sand in the erosion process is very important: in the absence of sand, there is virtually no erosion except where turbulence and/or hydraulic jets reach the cohesive bed; a stationary sand layer of 10 mm thickness or more is sufficient to protect the underlying cohesive material from erosion due to waves tested in this study (H_{m0} = 0.3 m, T_p = 0.35 Hz); and, other factors being equal, the greater the volatility of the sand cover, the greater the erosion rate will be. Long term erosion rates measured inside the surfzone for the wave and water level conditions of this study are of the order of 0.5 mm/h, peaking at the zone of dominant breaking, and decreasing monotonically in the offshore direction. The main effect of varying mean water levels is to shift the zone of dominant breaking up or down the profile: for higher levels, the zone of highest erosion rates shifts onshore, while for lower levels, the zone of highest erosion rates shifts further offshore so that, in the long term, the whole profile tends to maintain an equilibrium shape.

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