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Coakley (44)
Rukavina (48)
Zeman (23)

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WAVE-INDUCED SUBAQUEOUS EROSION OF COHESIVE TILLS: PRELIMINARY RESULTS

by

J.P. Coakley, N.A. Rukavina and A.J. Zeman

Shore Processes Section
Hydraulics Division
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario, Canada L7R 4A6

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MANAGEMENT PERSPECTIVE

Development of models to assess the effects of diversions or regulation on lake shores, composed of cohesive soils, requires a basic knowledge of the relationship between wave eroding stresses and the response of the lake bottom.

This paper gives new laboratory data and compares predictions for a proposed theory with field observations. More work is necessary to reconcile model and nature. However, results are encouraging. More field data would improve the possibility of developing a useful model. It should also be noted that eroded materials deposit ultimately in the basins where they clearly influence the chemical reactions on the lake bottom.

T. Milne Dick
Chief
Hydraulics Division

PERSPECTIVE-GESTION

Pour élaborer des modèles permettant d'évaluer les effets des ouvrages de dérivation ou de retenue sur les rives des lacs composées de matériaux cohésifs, il faut posséder une connaissance fondamentale des liens entre les efforts des vagues contribuant à l'érosion et les réactions du fond du lac.

La présente étude divulgue de nouvelles données de laboratoire et établit une comparaison entre les prévisions théoriques et les observations en milieu naturel. Il y a lieu de poursuivre les travaux de recherche pour rapprocher le modèle de la réalité mais les résultats sont encourageants. La collecte de données supplémentaires en milieu naturel améliorerait les possibilités d'élaborer un modèle représentatif. Soulignons en outre que les matériaux entraînés par l'érosion se déposent éventuellement au fond du lac et participent aux réactions chimiques qui s'y produisent.

Le chef
Division de l'hydraulique

T. Milne Dick

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Hydraulics Division, National Water Research Institute
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ABSTRACT

NWRI research on subaqueous erosion of nearshore till slopes includes analysis of wave effects, laboratory measurements of till erodibility and field measurements of elevation change. The field site at Stoney Creek, Ontario consists of sand inshore and exposed Halton Till offshore. An analysis of wave-induced shear stresses on the till bottom in 7 m of water was conducted for the average significant wave conditions at the site. Values used for the friction factor were taken from direct flume-based measurements of bottom roughness using precise castings of the natural till bottom at the site. Shear stresses calculated reach as high as 6.4 Pa, and equal or surpass critical erosion shear stress values (average: 1.3 Pa) obtained from our laboratory determinations on the same tills. Erosion rates, predicted from an empirical shear stress/erosion rate relationship and based on shear stress values obtained from wave data over the 13-month period (October 1984 - October 1985), were approximately 10 cm/y. However, high-resolution acoustic monitoring of bottom elevation changes over the same period shows less than 2 cm change in spite of relatively high wave intensities. Possible reasons for this inconsistency are discussed.

SOMMAIRE

Pour étudier l'érosion sous-marine des zones littorales, des chercheurs à INRE ont analysés les effets des vagues et ont mésurés l'érodabilité des tills en laboratoire et les changements d'élévation sur les lieux. Le relief du site de Stoney Creek, Ontario, est composé d'un littoral sablonneux et du Halton Till au large dont la partie supérieure est émergée. On a mené une étude fondée sur les vagues correspondant aux conditions significatives moyennes à cet endroit pour déterminer l'effort qu'elles exercent au pied du till à 7 m de profondeur. Les valeurs du facteur de friction ont été dérivées à partir des mesures directes de la rugosité du fond prises dans un canal à houle en utilisant des moulages fidèles du fond au pied du till en question. On a découvert que l'effort du cisaillement pouvait s'élever jusqu'à 6,4 Pa et donc égaler et même dépasser l'effort de cisaillement d'intensité critique pour l'érosion (intensité moyenne de 1,3 Pa) qu'on a pu établir en laboratoire pour des tills de constitution semblable. En traçant la courbe du taux d'érosion en fonction de l'effort de cisaillement, d'après les données obtenues en laboratoire, et en s'appuyant sur l'effort de cisaillement estimatif produit par les vagues ayant fait l'objet de prévisions a posteriori fondées sur les données du vent pour une période de 13 mois (octobre 1984 - octobre 1985), on calcule que l'érosion sous-marine devrait progresser au rythme de 10 cm par année. Toutefois, les relevés acoustiques à haute

résolution du fond qu'on a faits sur place depuis l'automne de 1984 n'indiquent aucun changement décelable de l'élévation malgré le fait qu'on ait enregistré des vagues d'intensité relativement forte au cours de la période correspondante. Dans le rapport, on discute des raisons qui peuvent expliquer l'écart entre les observations sur les lieux et les données prévisionnelles établies en laboratoire.

INTRODUCTION

Till shorelines in the southwestern portion of Lake Ontario are presently receding at up to 1.2 m/y. In contrast to sandy coasts, recession of such cohesive shores is irreversible, and therefore has important implications for long-term shoreline evolution and sand supply to local recreational beaches. Earlier work in Lake Erie (Coakley, 1985) suggests that the rate of subaqueous erosion of the nearshore bottom profile is an important factor in determining how fast, and ultimately how far, cohesive shorelines will recede. To investigate the mechanisms controlling this process, a study site was established in Lake Ontario near Stoney Creek. The initial goal is to investigate the response of nearshore lake-bottom slopes composed of cohesive materials to oscillatory wave forces. A more long-range goal is to apply the results to predicting future shoreline recession and bottom-scour depths in natural and man-made lakes, and in computing sand budgets for downdrift beaches.

The approach used was to compute wave-generated bottom shear stress at the sites from hindcast wave data, to determine in the laboratory the critical shear stress - erosion rate relationship, and to make direct measurements of till erosion in situ. Computed shear stress was then converted to an annual erosion rate by using the laboratory data, and the result was compared with the measured rate as a test of the validity of the analysis.

Theory of subaqueous erosion by waves

The erosion-inducing shear stress (τ) applied to a sediment surface is related to the flow velocity near the bottom (U) and the bottom geometry or microtopography, expressed as the friction factor (f_w) (Jonsson, 1966; Kamphuis, 1975). Sunamura and Kraus (1985) express the relationship as follows:

$$\tau = \frac{1}{2} \rho_w f_w U_{max}^2 \qquad (1)$$

where (ρ_w) is the density of water and U_{max} is the maximum wave orbital velocity on the bottom. The friction factor depends on both the nature of the flow regime and the bottom microtopography, measured in terms of the equivalent sand roughness (K_s). The above relationship holds regardless of whether the water motion is due to oscillatory waves, unidirectional streamflow, or to controlled flows in a rotating cylinder. Of these, wave-induced oscillatory flow presents the most difficulty in determining bottom shear stress because of the complications of flow velocity changes and reversals, and vertical pressure gradients (Yalin and Russell, 1966; Teleki and Anderson, 1970; and Kamphuis, 1975). Jonsson and Lundgren (1964) and Kamphuis (1975) determined empirical relationships between (f_w) and (K_s) under oscillatory wave conditions. That of Kamphuis is given below:

$$\frac{1}{4\sqrt{f_w}} + \log\left(\frac{1}{4\sqrt{f_w}}\right) = -0.35 + \frac{4}{3}\log\left(\frac{a_\delta}{K_s}\right) \qquad (2)$$

where (a_δ)is the maximum wave orbital amplitude at the bottom.

Generally speaking, subaqueous erosion of any cohesive sediment occurs when the shear stress applied by the fluid motion exceeds a certain critical value (τ_c). The relationship between the critical shear stress and erosion resistance of cohesive sediments is complex, as it depends on a number of physical and chemical factors. The effect of particle size is much less important than for granular sediments because the erosion resistance is controlled primarily by interparticle electrochemical forces rather than by gravitational forces.

Attempts to correlate the shear strength directly with the erosion resistance of very soft sediments have met with little success (Partheniades, 1965; Kelly et al., 1982). However, it is generally agreed that for consolidated cohesive sediments, the erosion resistance increases with increasing shear strength, clay content, plasticity index, and with decreasing water content (Smerdon and Beasley, 1959; and Masch et al., 1968). Subaqueous erosion may be further influenced by processes such as abrasion and sand-blasting by surficial granular materials, bioturbation by benthic organisms, groundwater seepage, or desiccation below the shrinkage limit.

Previous work

Much research has gone into the problem of erosion resistance of cohesive sediments, mainly in connection with the management of open channels and water-courses constructed in such materials. Annotated abstracts of 40 research papers and state-of-the-art reports concerned with this topic are presented in Zeman (1983).

Less work has been done on subaqueous erosion of nearshore cohesive tills in the Great Lakes region. Field investigations into factors controlling bottom erosion were carried out by Davidson-Arnott and students near Grimsby (Davidson-Arnott and Askin, 1980; Davidson-Arnott, 1986). Philpott (1983) estimated bottom erosion by comparing 1896 and 1979 bathymetric charts for the north-central shore of Lake Erie; his data were used by Rukavina and Zeman (1985) to estimate volumetric erosion rates of the till shelf in this area.

Site description

The study area (Figure 1) extends along a shore-normal profile from the shoreline for a distance of approximately 1 km, out to a depth of 10 m. Exposed (or thinly covered) Halton Till is the dominant

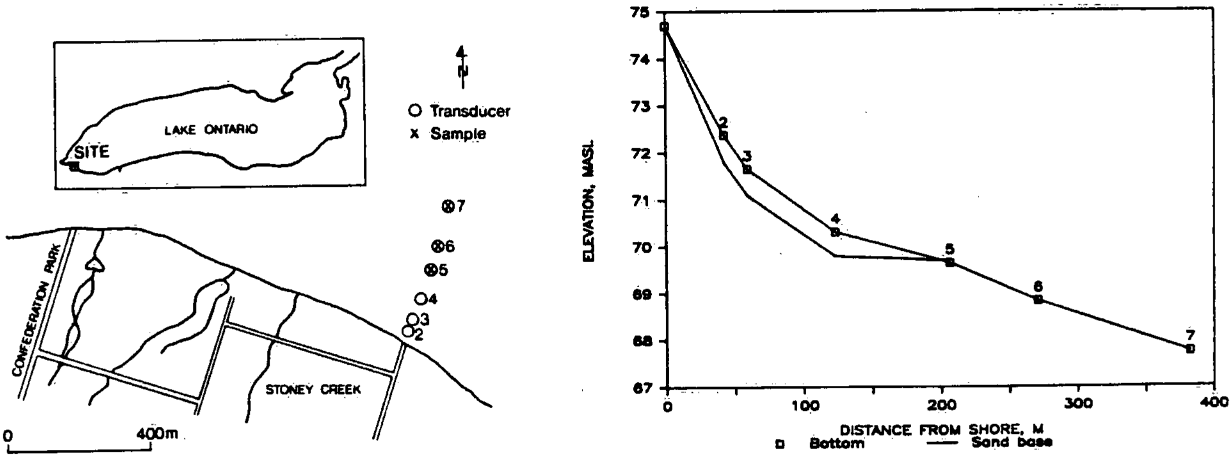


Fig. 1. (Left) Location map of study site. (Right) Study profile showing numbered fixed-transducer stations and substrate types.

sediment type offshore, and sand occurs as an inshore prism. The shoreline is comprised of low till bluffs up to 5 m in height. The wave climate is seasonal, with easterly storms occurring most frequently in the winter and early spring months. Waves from the east exert the most influence on shoreline and nearshore processes because of the long fetch (> 300 km) in that direction. These waves are responsible for the net east-to-west littoral drift in the area (Rukavina, 1976). Coakley and Boyd (1979) estimated the net littoral drift volume at Fifty-Mile Point several kilometres east of the site at approximately 3000 m^3/y.

METHODS AND PROCEDURES

Wave climate

Short-term wave measurements carried out in 1984 as part of the overall study were not representative of the sometimes intense wave climate in this part of Lake Ontario. It was therefore decided to use hindcast deep-water waves for western Lake Ontario for a period corresponding as closely as possible to the direct measurement period of bottom elevation changes, i.e. 10 October 1984 to 31 October 1985. The hindcasts (Table 1) were prepared by the Marine Directorate of Public Works Canada from hourly wind records obtained from the Toronto

Island Airport weather station, using a procedure developed by Public Works Canada (Baird and Glodowski, 1978). The wind data was referred to a 16-point compass. The Toronto Island location represented the closest weather station where wave hindcasts synchronous with offshore wave measurements were available.

Hindcast wave data were mathematically transformed to shallow-water values corresponding to the depth of the study site before being used in further calculations.

Bottom shear stress determination

To determine the friction factor appropriate for flow over rough bottoms, the equivalent sand roughness of the bed (K_s) must be determined. The following technique was used.

Plaster moulds of the natural till surface at the site were collected using a technique developed by Parks Canada (Daley and Murdock, 1984). Although it was planned to collect a representative number of different surfaces, only one mould survived the process. The mould surface measured 100 cm x 37 cm. A plaster casting of the mould was made in the laboratory, and sealed with varnish (Figure 2a). Seven replicate plaster casts were used to line the end portion of the 31 m x 60 cm recirculating flume in the Hydraulics Laboratory (Figure 2b). K_s was determined from the flow characteristics measured above the plaster cast segment, using standard flow-depth and velocity profile

Table 1. Wave summary for western Lake Ontario, 10 October 1984 to 1 October 1985, showing frequency (in hours and percent) of each wave group. (-) signifies less than 0.1%.

Wave Height (m)	Wave Period (s)								Total
	<4	4	5	6	7	8	9	10	
<0.5	6623 (72)	20 (0.2%)	2 (-)	5 (-)					6650 (72.3%)
0.5	1338 (14%)	569 (6.1%)	53 (0.6%)	18 (0.2%)					1978 (21%)
1.0		82 (0.9%)	180 (1.9%)	47 (0.5%)	5 (-)				314 (3.3%)
1.5			8 (0.1%)	155 (1.7%)	20 (0.2%)				183 (2%)
2.0				8 (0.1%)	69 (0.7%)	1 (-)			78 (1%)
2.5					1 (-)	13 (0.1%)			23 (0.2%)
3.0						12 (0.1%)	1 (-)		14 (0.1%)
3.5						5 (-)	5 (-)		10 (0.1%)
4.0							4 (-)	1 (-)	5 (-)

measurement procedures (Yalin, 1977, p.42; Kamphuis, 1974; Coakley, 1986, in prep.). A total of 13 separate determinations of K_s was made.

The wave friction factor was then obtained from K_s by substituting the appropriate value of a_δ in equation (2). Values of a_δ and U_{max} were calculated from the wave properties (period, height) at the 6.9 m depth site using linear wave theory. By providing the appropriate f_w value to equation (1), we obtained corresponding τ values for the predominant wave groups.

Laboratory erodibility measurements

Erodibility tests were conducted on 6 undisturbed samples of Halton Till collected by divers from the Stoney Creek site (Figure 1). The tests were carried out in a rotating-cylinder apparatus (Zeman, 1984) and critical shear stresses and erosion rates were measured for each of the 6 samples (Zeman, 1986, these Proceedings). Other tests carried out included particle-size analysis (Duncan and Lahaie, 1979), natural water content (ASTM D2216), and Atterberg limits (ASTM D423 and D424). Vane shear strength tests were also performed using a Wykeham Farrance vane apparatus.

Field measurements of subaqueous erosion

Changes in elevation of the profile at the field site were monitored acoustically at 6 sites (Figure 1). A pair of small echo-sounder transducers fixed to a T-frame provided the sound source, and transducer-to-bottom distances were read from a portable digitizer deployed from a small boat (Figure 3). A detailed description of the procedure is available in Rukavina and Lewis (1979). The site was monitored bi-monthly from October to December 1984 and May to December 1985. Twenty-two sets of acoustic and nine sets of diver control measurements were collected.

RESULTS

Laboratory geotechnical and erodibility tests

Results of geotechnical tests carried out to characterize the Halton Till at the study site are presented in Table 2. According to Shepard's textural classification (Shepard, 1954), samples 5A, 5B, 6A and 6B are sandy silty clays, while samples 7A and 7B are silty clays. The higher clay content of the latter two samples is reflected in slightly higher water content, higher plasticity index and lower shear strength. The consistency of sample 7B is firm, according to the criteria proposed by Terzaghi and Peck (1968); the remaining five samples are stiff.

Values of the critical shear stress, τ_c, defined here as the lowest shear stress at which a sediment loss from a sample is measured, are presented in Table 3. The values range from 0.53 Pa for sample 7B to 2.28 Pa for sample 5B; the mean value is 1.28 Pa.

Fig. 2. a) Plaster cast of till surface.
b) Seven plaster casts formed the bottom of the flume working section.

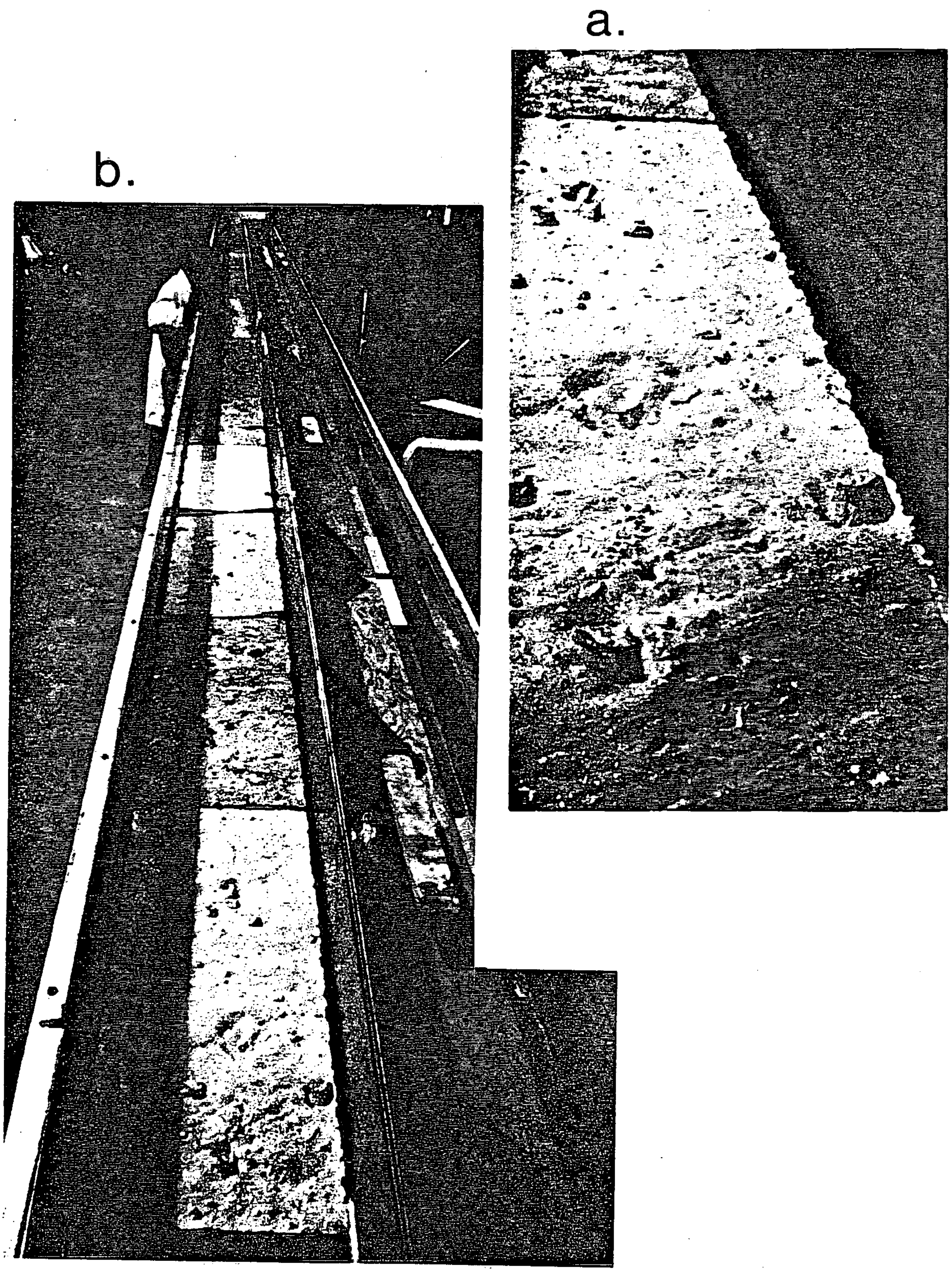
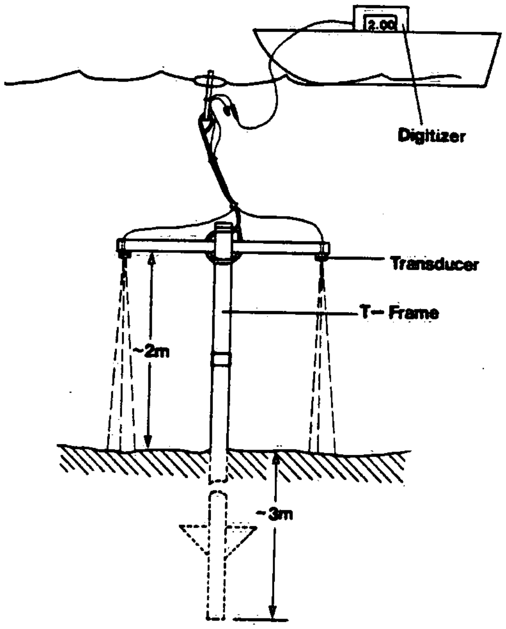


Fig. 3. Schematic diagram of fixed transducer system



The normalized sediment loss, recorded at 50-rpm increments within the general range from 50 rpm to 1750 rpm, was converted to a normalized mass erosion rate, ε. The rates for individual samples are quite irregular due to changes in surface roughness, the effect of sediment microfissures and the deterioration of samples at high shear stresses. For this reason, the data for 6 samples were combined and the resulting plot (Figure 4) shows averaged values of τ and ε obtained at different values of rpm. The horizontal and vertical bars in the plot correspond to 2 σ, where σ is the standard deviation. The linear regression for 32 data points with $\varepsilon > 0$ yielded the following relationship:

$$\varepsilon = 0.120 + 0.386\tau \qquad (3)$$
$$r^2 = 0.899 \text{ (significant at 1\% confidence level)}$$

The above regression line intersects the abscissa to the left of the origin and thus cannot be used for the determination of τ_c, which has been the method occasionally employed in erodibility tests on artificially-compacted samples (e.g. Arulanandan et al., 1975). We attribute the trend obtained for the undisturbed samples described herein to a sudden disruption of the sediment surface, accompanied by a rapid increase in surface roughness at the onset of erosion.

The ε values can be used for estimates of vertical downcutting rate, h_d, of the nearshore till slope at different shear stresses. Assuming that the till is fully saturated, the relationship between ε and h_d is given by the equation:

$$h_d = \frac{\varepsilon}{\rho_w} \left(1 + \frac{1 + G_s}{G_s(w+1)}\right) \qquad (4)$$

Table 2. Geotechnical and Grain-Size Properties of Samples from the Study Site

Sample No.	Natural Water Content %	Liquid Limit %	Plastic Limit %	Plasticity Index %	Vane Shear Strength kPa	Sand %	Silt %	Clay %
5A	15.73	24.27	17.34	6.93	68.4	26.3	28.4	45.3
5B	16.38	25.34	15.00	10.34	60.2	25.1	35.2	39.7
6A	18.01	24.94	14.97	9.97	66.9	22.5	34.3	43.2
6B	16.86	25.36	15.54	9.82	81.5	25.4	35.1	39.4
7A	19.11	29.02	15.98	13.04	53.1	15.9	26.1	58.0
7B	18.52	36.85	25.15	11.70	48.1	12.2	20.2	67.6

Table 3. Critical Shear Stresses Measured

Sample No.	Critical Shear Stress (Pa)	RPM at Onset of Erosion
5A	1.71	400
5B	2.28	450
6A	1.21	300
6B	1.46	250
7A	0.99	300
7B	0.53	200

where (w) is the natural water content and (G_s) is the specific gravity of solids. The value of (w) used in this paper is the mean of measured values shown in Table 2 and the value of G_s is assumed to be 2.7.

Estimate of surface roughness in laboratory erodibility tests

For the determination of K_s, surfaces of irregular geometry should be compared with the standard equivalent sand roughness (Schlichting, 1968). Six calibration cylinders with closely-packed granular surfaces were used to obtain equivalent sand roughness values for grain sizes ranging up to 4.0 mm (-2.0 phi). The six resulting curves of rpm vs τ are shown in Figure 5. Also shown in this figure are shear-stress measurements obtained for sample 5A. Below the τ value of 1.71 Pa, the surface roughness is close to $K_s = 0$. At higher shear stresses the K_s values vary, but they do not exceed $K_s = 0.5$ mm. Similar results were obtained for the other five samples.

Wave-induced shear stress on till bottoms

The results of the 13 K_s determinations on casts of the local till surface are presented in Table 4. Only those indicated by an asterisk were used in determining the average K_s value. The others

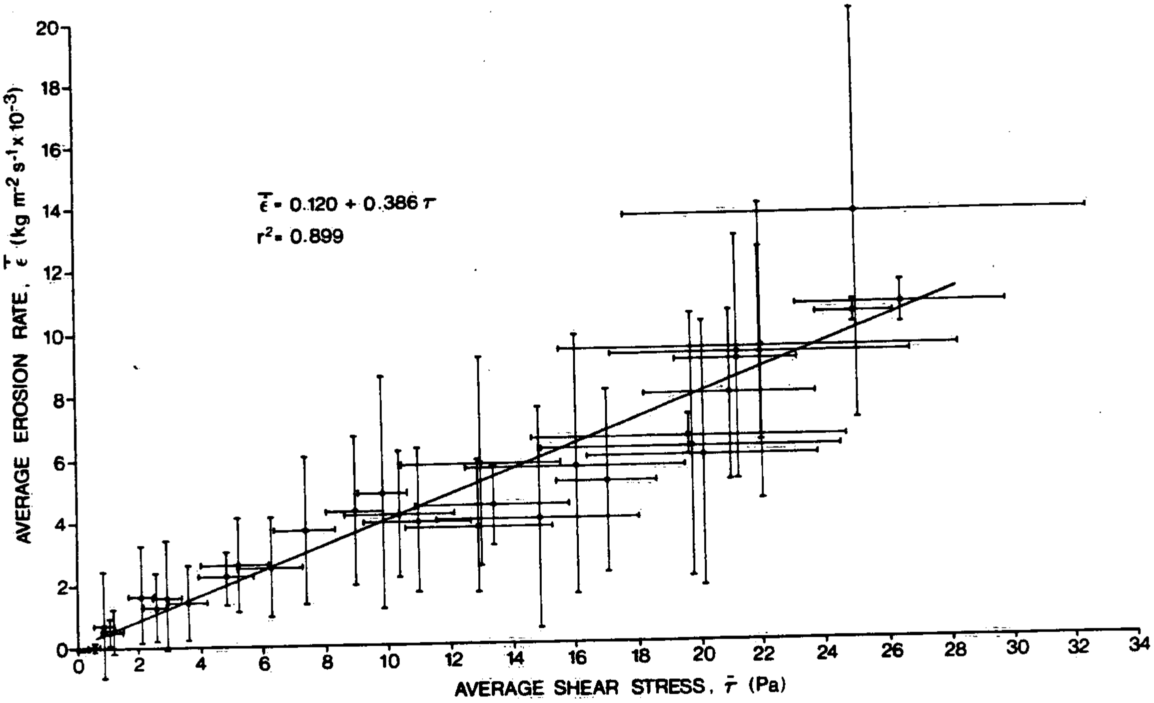


Fig. 4. Relationship between average shear stress and average erosio rate for different values of cylinder rotation (rpm). Error bars correspond to 2 standard deviations.

were disregarded, mainly because flow conditions in the flume were not rough turbulent. Two of the non-turbulent K_s values were included in the average because they could be calculated using a special empirical technique (Yalin, 1977; p.28). K_s values ranged from 0.1 to 0.38 cm, and averaged 0.25 cm.

From the 13-month wave summary for the area, shear-stress calculations were made for the larger waves whose bottom orbital velocities exceeded those associated with the critical shear stress for subaqueous erosion. The annual frequency in hours of such waves was also recorded. Because the orbital velocity under a wave is oscillatory, the resulting bottom shear stress is also oscillatory, and is independent of flow direction. Because the shear stress is super-critical only for a portion of the total wave period, the total super-critical duration was determined by integrating the area under the shear stress curve above the critical value. The results are summarized in Table 5. It is evident that wave-induced shear stresses exceeded the critical value only for a small fraction of the total time; 61 hours or 0.7% of the 13-month record.

The above super-critical duration was entered into equation (4) to obtain an estimate of total annual downcutting, or subaqueous erosion. The result was 10 cm/y at the 6.9 m depth. Similar analyses will be carried out later for the other sites along the study profile where till is exposed.

Table 4. Determinations of K_s in flume, using flow properties, discharge (Q) and velocity (V).

Run	Date	Slope	Q	V	Re	K(F)	K(1)	K(2)	K(3)
1	8/4/86	0.001	7750	33.1	23	0.14	0.03	0.17	0.38
-	-	-	-	-		0.31*	-	-	-
2	10/4/86	0.002	10130	45.5	50		-	-	-
-			-	-	-	0.29*	-	-	-
3	11/4/86	0.004	14460	61.6	84	0.26*	-	-	-
-	-	-	-	-	-	0.36*	-	-	-
-	-	-	-	-	-	0.22*	0.16*	0.10*	0.25*
Ave. K_s = 0.25 cm									

* These values were used to calculate the average K_s

K(F): K_s determined by flow-depth and average velocity

K(1,2,3): K_s determined by velocity profiles at three locations in flume.

Q is in cm^3/s; V, in cm/s; K, in cm.

Field measurements of subaqueous erosion

Results are summarized in Figure 6. The data presented are averages of acoustic measurements for each site, supplemented by diver data where acoustic data were not available. Precision of the data, as determined from comparison of acoustic and diver measurements, was ±2 cm.

Exposed till is present at two sites - nos. 6 and 7 (water depths of 5.9 and 6.9 m respectively, referred to a surface water level of 74.7 m IGLD). In both cases, variations in elevation during the survey period were within 2 cm of the starting elevation, and could not be considered significant. Erosion, if it did occur, did not exceed 2 cm, the precision of the method.

Inshore sites with sand cover showed larger elevation changes associated with sand migration. Negligible change took place during the storm-free fall of 1984, but significant change was observed at sites 3 - 5 over the winter period. Elevation increased by about 10 cm at sites 3 and 5 and decreased by 8 cm at site 4 between them. Subsequently there were smaller-scale changes in elevation throughout the summer period, followed by an end-of-season decrease in elevation at site 4 and increase in elevation at sites 3 and 5. The pattern observed suggests the establishment of a two-bar system in which sites 3 and 5 are near the bar crests, and site 4 near the intervening trough.

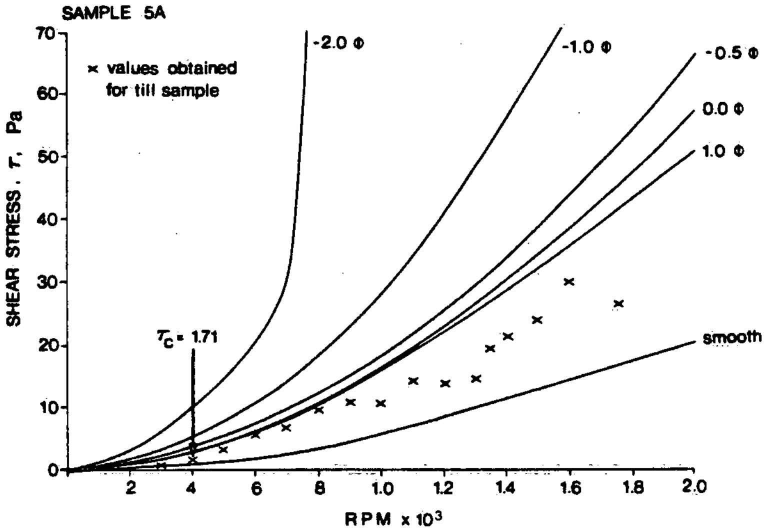


Fig. 5. Change in surface roughness during erodibility testing on sample 5A. Smooth curves represent values obtained with calibration cylinders of known equivalent sand roughness.

DISCUSSION

The study is presently only in the intermediate stage, and the results presented here are based on limited data. This data base will be expanded in the coming months, so a more definitive report will have to wait until then. Although major discrepancies exist between predicted and measured erosion rates, the results validate the concept that shear stress acting on the bottom is a very important, if not dominant, factor in subaqueous erosion. The following observations and conclusions can be made:

1. The flume-derived value for the average K_s for the local Halton Till is .25 cm, or approximately 5 times those obtained in the rotating-cylinder measurements. The difference is likely due to the effect of larger-scale microtopography in the natural situation that is absent from the small-scale laboratory samples. Also, it was noted that K_s values in the erodibility tests did not increase with increasing shear stress, except at very high τ levels. Because of this, it appears unlikely that K_s varies seasonally. In any event, because the till-surface cast used in this flume experiments was taken in the Fall, plans have been made to collect and take measurements on samples taken in the early part of the year as well. The considerable scatter in the roughness determinations also suggests that additional data are necessary before a firm value can be assigned.

2. The critical shear stress for the onset of erosion for the Halton Till samples measured in the rotating cylinder ranged from 0.5 to 2.3 Pa and averaged 1.3 Pa. These values are all below those obtained on clay tills from the Lake Erie area (Zeman, 1986, these Proceedings) and considerably below those for high-sensitivity clays from the St. Lawrence Valley (Lefebvre and Rohan, 1986, these

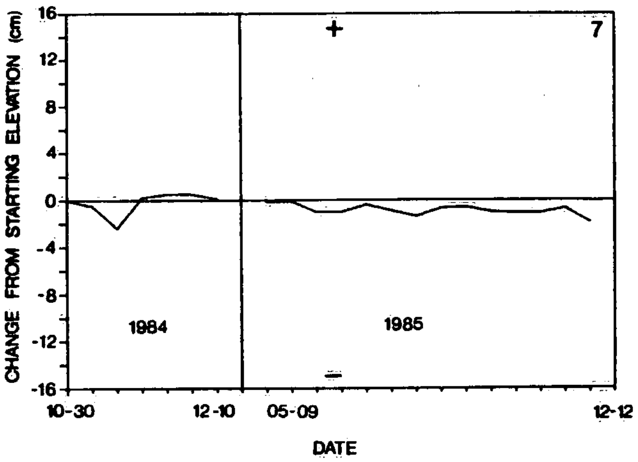


Fig. 6. Elevation changes vs time for fixed transducer site No. 7 (depth: 7.9 m) for period 30 October 1984 - 12 December 1985. Negative change denotes erosion.

Proceedings). In the latter case, τ_c values, measured using a technique different from ours, were two orders of magnitude higher. The discrepancy likely reflects not only the different erosion resistance of sensitive marine clays and tills, but also the effect of the different procedures employed. Further attempts should be made to standardize critical shear stress determinations. Systematic errors associated with shear stress measurements in the rotating-cylinder apparatus are unlikely (Zeman, 1984). Differences between in situ and laboratory-measured erosion resistance cannot be discounted,although the local till is characterized by low sensitivity, and is therefore not considered prone to appreciable sample disturbance.

3. Waves at the site generate bottom shear stresses up to 6.4 Pa at the 6.9 m deep site; these values correspond to waves of 10 s period, and > 4 m significant height (deep water). Waves whose induced shear stress in such depths exceeded τ_c (i.e, waves of $T > 6$ s, and $H > 2$ m) occurred at the site 0.7% of the time between 10 October, 1984 and 31 October 1985, for a total of 61 hours. Therefore the data indicate that wave-generated bottom shear stresses above the critical erosion threshold do occur at significant frequencies at the site. The amount of vertical erosion due to such shear stresses was calculated at approximately 10 cm/y.

4. The less-than-2 cm/y subaqueous erosion rates measured by the fixed transducer array were an order of magnitude less than those predicted on the basis of bottom shear stress, i.e. 10 cm/y. The measured rates agree reasonably with rates of 1.1 cm/y obtained in comparable depths by Davidson-Arnott (1986, these Proceedings) at Fifty Point several kilometres to the east. The most likely reason for the discrepancy between calculated and measured rates

lies in the wave inputs used. Visual comparison of plotted heights and periods of hindcasted waves and those measured in deep water nearby indicated that the hindcast waves tended to overestimate the wave height and period, especially during wave decay and at the lower frequencies (higher periods). A similar trend was also noted in Bishop (1983). For example, the hindcasts indicated deepwater waves of periods equal to or greater than 8 s occurring for a total of 42 hours during the 13-month hindcast period. At the study site, no waves having such periods were ever observed visually. Because the actual wave climate at the site is critical for the shear-stress measurements and the predicted erosion rates, the results obtained suggest strongly that in future studies, efforts should be made to collect synchronous records of wave and fixed-transducer data at the site.

5. A very important point is that the results show that high-energy waves create shear stresses sufficient by themselves to explain all the subaqueous erosion measured. Supplementary processes such as abrasion by sand does not appear to be necessary, at least in water depths of 6.9 m or more, where coarse materials are rare.

6. Areas where future work might profitably be directed are:

- in situ determination of τ_c with a Seaflume device (Young, 1977), and better definition of the effects of sample preparation and chemistry of the eroding fluid.
- closer examination of the effects of applying unidirectional flow principles to oscillatory wave conditions.
- continued field measurement of the erosion rate of the till and monitoring of the thickness of the inshore sand layer to determine whether there is seasonal exposure of the underlying till, and whether the presence of sand accelerates erosion rates.

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