COMPUTER SIMULATION OF NEARSHORE PROFILE EVOLUTION IN COHESIVE MATERIALS

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RESUME

On a effectué une simulation de développement de profil dans une zone près du rivage constituée de till cohésif en utilisant une équation obtenue en laboratoire qui établit un rapport entre les caractéristiques d'érosion du substrat et la contrainte de cisaillement appliquée, les calculs étant faits sur micro-ordinateur. La contrainte de cisaillement obtenue pour la simulation de l'évolution du profil a été calculée à partir des vitesses orbitales du fond déterminées pour un climat représentatif de vagues (a posteriori). Le modèle de simulation a d'abord été testé afin de vérifier son aptitude à reproduire la forme caractéristique d'un profil d'érosion. Un autre essai portait sur la prévision de la vitesse d'érosion verticale des deux profils surveillés dans le lac Ontario. Même si les résultats du premier essai étaient satisfaisants, le modèle tendait à surestimer l'érosion des deux profils. Pour un premier essai, ces résultats sont encourageants, bien qu'ils indiquent que d'autres facteurs doivent être pris en considération pour la mise au point d'un modèle fiable permettant de faire des prévisions.

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ABSTRACT

Simulation of profile development in a nearshore zone composed of cohesive till was carried out on a micro-computer using a laboratory-derived relationship between substrate erodibility and applied shear stress. The shear stress for the profile evolution simulation was calculated from bottom orbital velocities determined for a representative hindcast wave climate. The simulation model was first tested for its ability to reproduce the characteristic shape of an erosional profile. A further test was the prediction of the rate of vertical erosion of two monitored profiles in Lake Ontario. Although the first test was satisfactory, the model tended to overestimate the erosion of the two profiles. As a first attempt, this result is encouraging, although it indicates that other factors must be taken into account before any reliable predictive capability is possible.

INTRODUCTION

Cohesive shorelines, developed in silts and clays, are found along many coasts, particularily in the lower Laurentian Great Lakes where they are frequently associated with glacial and glaciolacustrine deposits. They are characterised by steep bluffs, narrow beaches of coarse sand and gravel, and by extremely high recession rates compared to rocky coasts.

Bluff recession is triggered by erosion, dominantly by wave action, at the toe of the bluff (Sunamura, 1983), and this in turn leads to instability of the sub-aerial slope with failure occurring through a wide range of processes (Quigley et al., 1977; Hutchinson, 1986). The intensity of wave erosion at the toe in turn is dependent on a number of factors, including the wave climate and rate of removal of debris alongshore. It is also evident that the rate of vertical erosion of the nearshore profile is an important control. If vertical erosion in the nearshore is disproportionally large compared to horizontal bluff recession, the profile steepens and the bluff toe is subject to greater wave attack. Conversely, if bluff recession exceeds vertical erosion, a flat platform develops which dissipates wave energy and reduces wave erosion at the toe. The shape and evolution of the eventual underwater profile thus reflects a dynamic equilibrium resulting in part from the feedback between toe erosion and vertical erosion. It follows, therefore, that an understanding of the processes and controls on erosion of the nearshore profile is essential to the development of models for predicting coastal bluff recession.

The purpose of this paper is to present the initial development of a simple computer simulation model for nearshore profile evolution in a cohesive till. Two sets of model tests are evaluated: the first examines the evolution of a profile over a relatively long time; the second compares the predicted erosion rates over profile shapes derived from the field to actual rates measured at two field sites.

Field Sites

The field sites are located at the southwestern end of Lake Ontario between 5 and 15 km east of the city of Hamilton. The coast is characterised by till bluffs 2 to 5 m high. At the eastern site (Grimsby) the till is exposed over almost all of the nearshore profile to depths of more than 10 m, with only a veneer of sand and isolated boulders (Davidson-Arnott and Askin, 1980). At the western site (Stoney Creek) a sand prism extends out to about 200 m. Both sites are exposed to a maximum fetch of over 200 km towards the ENE. Sediment supply is small, estimated to be about 3000 m^3 (Coakley and Boyd, 1979). The Halton till in which the profiles are developed is dense (bulk density approximately 2200 $kg \cdot m^{-3}$), and the water content is less than 20% dry weight. Underwater, the exposed till surface is generally stiff (vane shear strength ranges from 50 to 100 kPa), though occasionally areas have been observed where a 1 to 2 cm thick surface layer exhibits a very much reduced strength due to softening (Davidson-Arnott, 1986).

Since October 1984, bed elevation changes have been monitored at six points along a profile at Stoney Creek in water depths ranging from 1 to 7 m using an acoustic procedure (Rukavina and Lewis, 1979) and by direct diver measurements. Precision of the elevation data is on the order of 1 to 2 cm. The two sites on exposed till at depths of 6 and 7 m experienced net vertical erosion of 4 cm and 6 cm, respectively, from October, 1984 to December, 1987. These figures agree well with long-term vertical erosion rates of between 1.5 and 2.4 $cm \cdot y^{-1}$ deduced for the same locations by comparing the 1913-15 hydrographic survey with that of 1986.

At Grimsby, measurements of the subaqueous erosion rate were carried out using a modified micro-erosion meter (Askin and Davidson-Arnott, 1981) at stations along two profiles spaced 30 m apart out to a depth of 6.3 m. The technique has a precision of 0.1 cm. Average erosion rates measured over the period July 1980 to September 1984 ranged from 1.5 $cm \cdot y^{-1}$ in depths of 6 m to over 3.5 $cm \cdot y^{-1}$ at a depth of 2 m (Davidson-Arnott, 1986).

Till Erodibility Determination

The relationship between the applied shear stress and erosion rates of cohesive tills was investigated in a rotating cylinder apparatus (Zeman, 1984, 1986). The tests were conducted on 0.1 m dia., 0.1 m long cylindrical samples carefully trimmed from larger field samples, which were obtained by divers from the toe area of the bluffs. The tests were performed on samples of till from the Stoney Creek site.

The laboratory results show that the till can be characterised by a linear relationship between the applied shear stress, τ, and the measured erosion rate, $\bar{\varepsilon}$ (Fig. 1). This plot cannot be used for the estimation of the critical shear stress, τ_{crit}, for the Halton Till samples because the regression line intersects the abscissa to the left of the origin. The τ_{crit} values were therefore defined as the lowest shear stresses at which measurable erosion took place. These values ranged from 0.53 Pa to

2.28 Pa, with an average of 1.71 Pa (Coakley et al., 1986). The linear relationship for the Halton till is:

$$\bar{\varepsilon} = 0.120 + 0.386\,\tau \qquad (r^2 = 0.899) \tag{1}$$

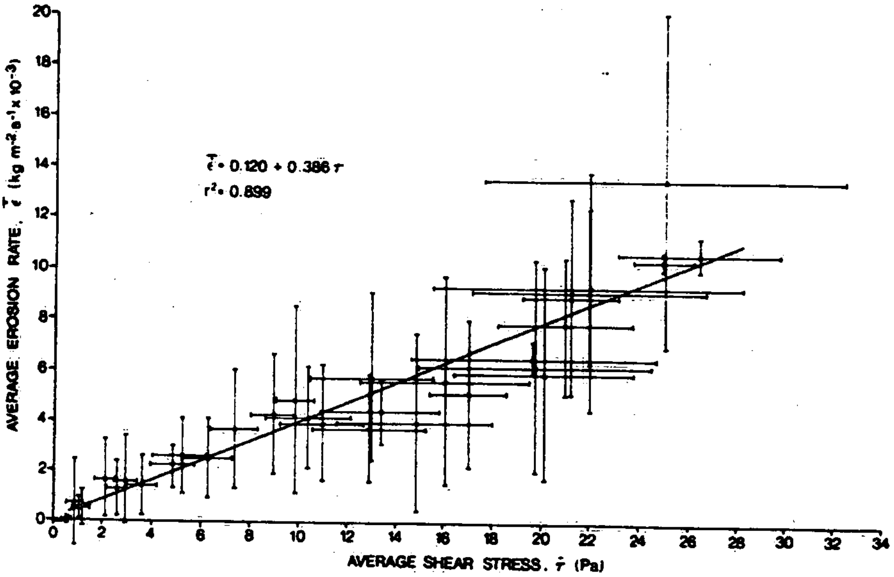

FIGURE 1. **Relationship between shear stress (τ) and erosion for Halton till, Lake Ontario. Horizontal and vertical scatter bars correspond to two standard deviations.**

Under the assumption that the till is fully saturated, the relationship between $\bar{\varepsilon}$ and h_d (the vertical downcutting distance) is given by the equation:

$$h_d = \frac{\bar{\varepsilon}}{\rho_w}\left[1 + \frac{1 - G_s}{G_s(w+1)}\right] \tag{2}$$

where ρ_w is the density of water, G_s is the specific gravity of solids and w is the natural water content.

Description of Model

The simulation uses a FORTRAN program designed to run on an IBM-AT microcomputer. The profile to be used in the simulation must be in the form of an array of depth/distance values. These can be calculated from a given slope angle for a simple, planar profile, or an actual digitized profile can be read into the program from a file. This initial profile, along with a reference water level and an hourly wave climate to act on the profile are all that are required as input. The deep-water wave climate used in the simulation was hindcast using the technique of Fleming, Pinchin, and Nairn (1986) from wind data recorded at the western end of Lake Ontario for the four-year period of profile measurements at Grimsby, i.e., 7/80 to 9/84. Linear wave theory is used at each grid point (depth) on the profile, first to transform the deep-water wave by refraction and shoaling (assuming a piece-wise plane sloping profile - a reasonable assumption for the two field sites), and then to calculate the orbital motion at the bottom. The orbital velocity, U, is calculated at intervals of 0.04 times the wave period, and is later used in calculating the instantaneous bed shear stress at each interval.

The flow is assumed to be laminar or rough turbulent based on the wave Reynolds number:

$$Re = U \cdot a / v \qquad \text{(Kamphuis, 1975)}$$

where U and a are the orbital velocity and amplitude, respectively, and v is the kinematic viscosity. The friction factor (f_w) is then computed at each grid point. For laminar conditions (i.e., $Re < 10^4$),

$$f_w = 2/\sqrt{Re} \qquad \text{(Kamphuis, 1975)}$$

For $Re > 10^4$, rough turbulent flow is assumed and the approximation proposed by Swart (1974) is used:

$$f_w = \exp\left[5.213\left(\frac{k_s}{a}\right)^{0.194} - 5.977\right] \qquad (3)$$

k_s is the bed roughness determined empirically for the local Halton till (Coakley _et al_., 1986). The shear stress is then calculated:

$$\tau = \frac{1}{2} \rho_w f_w U^2 \qquad (4)$$

If τ equals or exceeds τ_{crit}, the amount of erosion is calculated using equation (1). The program then loops again through the shear-stress calculation procedure for each increment of wave period, until the amount of erosion is summed over the entire wave period. The hourly erosion amount is determined by multiplying the sum obtained above for each wave period by the number of waves of that period in an hour. The amount of vertical erosion is then determined from equation (2).

The wave climate is read in as the number of hours of each wave height and period class. After the vertical erosion has been calculated sequentially at all the grid points, the process is repeated to simulate another hour of similar waves. When all the allotted time for one class of waves is completed, then another set of waves is used in the profile erosion loop.

Because wave-induced motions inside the breaker zone are not sufficiently understood, the model is limited to the profile outside the breaker zone. The shape of the profile landward of this grid point is treated as being fixed and so the vertical erosion at each grid point inside the breaker zone is assigned the same value as the last point outside the breaker zone.

RESULTS

Case 1. Figure 2 shows the evolution of a profile from a planar slope of 2 degrees using the wave climate hindcast for western Lake Ontario for the 4-year period July 1980 to September 1984. This record was repeated four times to simulate a total time of approximately 16 years of erosion. The simulated profile developed rapidly and soon assumed the recumbent-S shape characteristic of erosional profiles in cohesive sediments (Robinson, 1977; Boyd, 1986). There was a clearly defined point on the profile offshore of which there was no erosion, and erosion increased in a non-linear way shoreward to the breaker zone. The profile shoreward of the zero-erosion depth flattened with time, and if the simulation had continued, would have eventually formed an almost horizontal shore platform.

Case 2. Measured profiles from the two sites were used as the initial profile, and the same 4-year wave climate was applied. The results are shown in Figure 3. The result of erosion at both sites was a further flattening of the profile slope. Comparison of the calculated vertical erosion rates with those actually measured over comparable time periods are presented in Table 1.

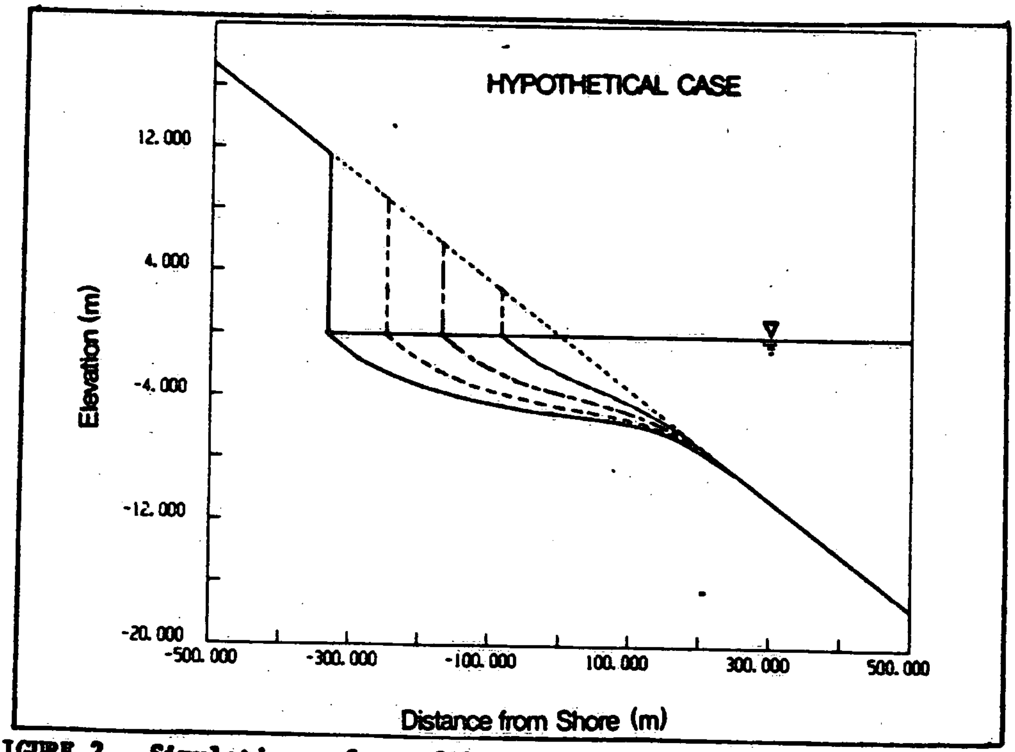

FIGURE 2. **Simulation of profile development in till over approximately 16 years (western Lake Ontario winds).**

TABLE 1. Comparison of predicted and measured vertical erosion.

Depth (m)	Vertical erosion rate ($cm \cdot y^{-1}$) Eastern profile Measured	Eastern profile Predicted	Western profile* Measured	Western profile* Predicted
2.3	3.5	35	-	-
3.8	2.4	19	-	-
4.7	1.8	14	-	-
5.6	2.0	7	-	-
6.0	-	-	1.2	4.0
6.4	1.1	3.5	-	-
7.0	-	-	2.0	2.0

* The period covered by these measurements does not coincide with that of the wave hindcast.

From Table 1 it is clear that the measured annual erosion rates are lower, by up to an order of magnitude, than those predicted by the model. The overestimation by the model is greatest in shallow water, and it should be noted that erosion at the innermost site (depth 2.3 m) was inside the breaker line for some waves and therefore it is not expected that erosion was adequately modelled here.

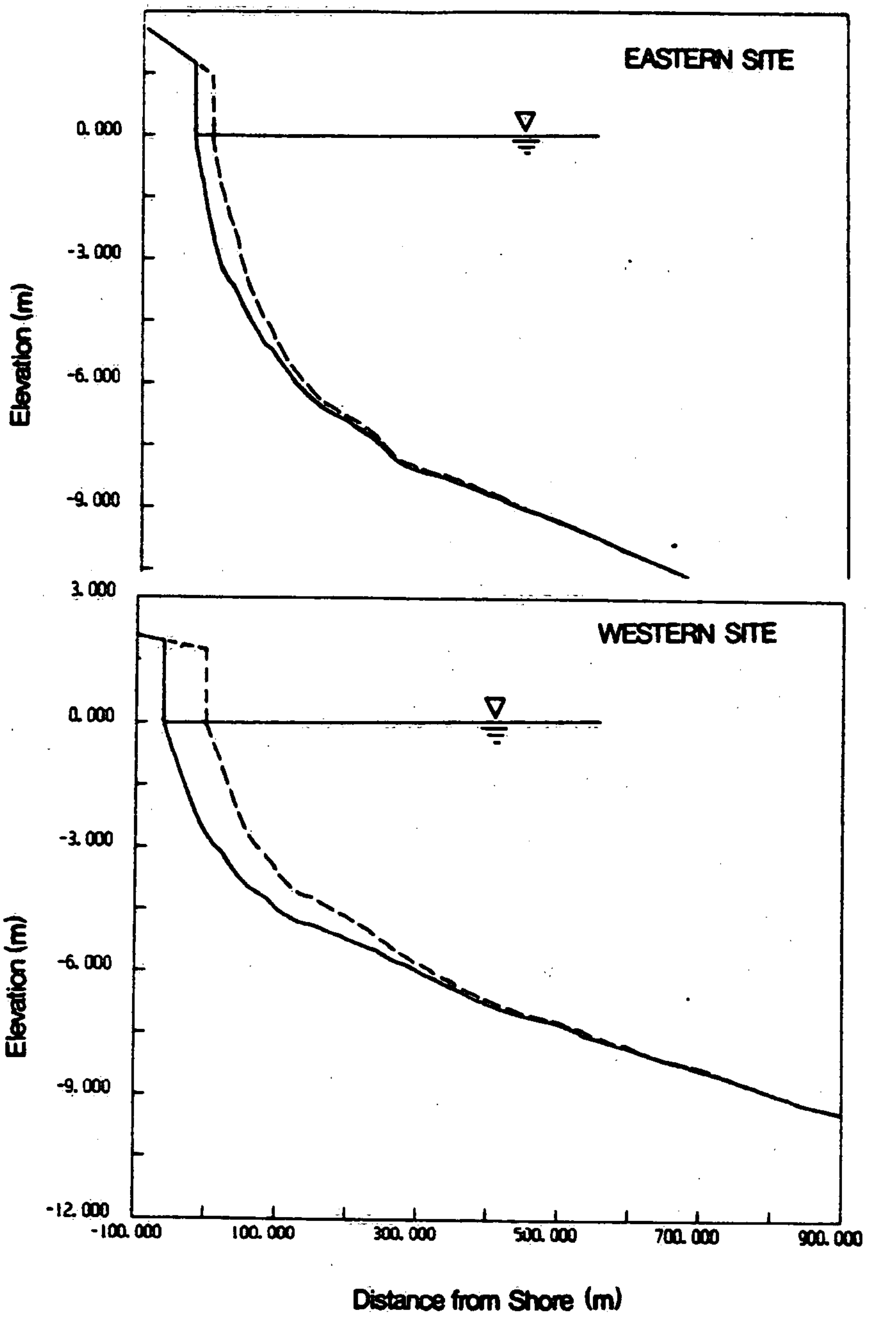

FIGURE 3. (a) Simulation of profile development at eastern site, 1980 to 1984
(b) Simulation of profile development at western site, 1980 to 1984
The dashed line represents the initial profile.

DISCUSSION

As a first attempt at simulating the complex processes controlling the evolution of an erosional nearshore profile based on measured substrate

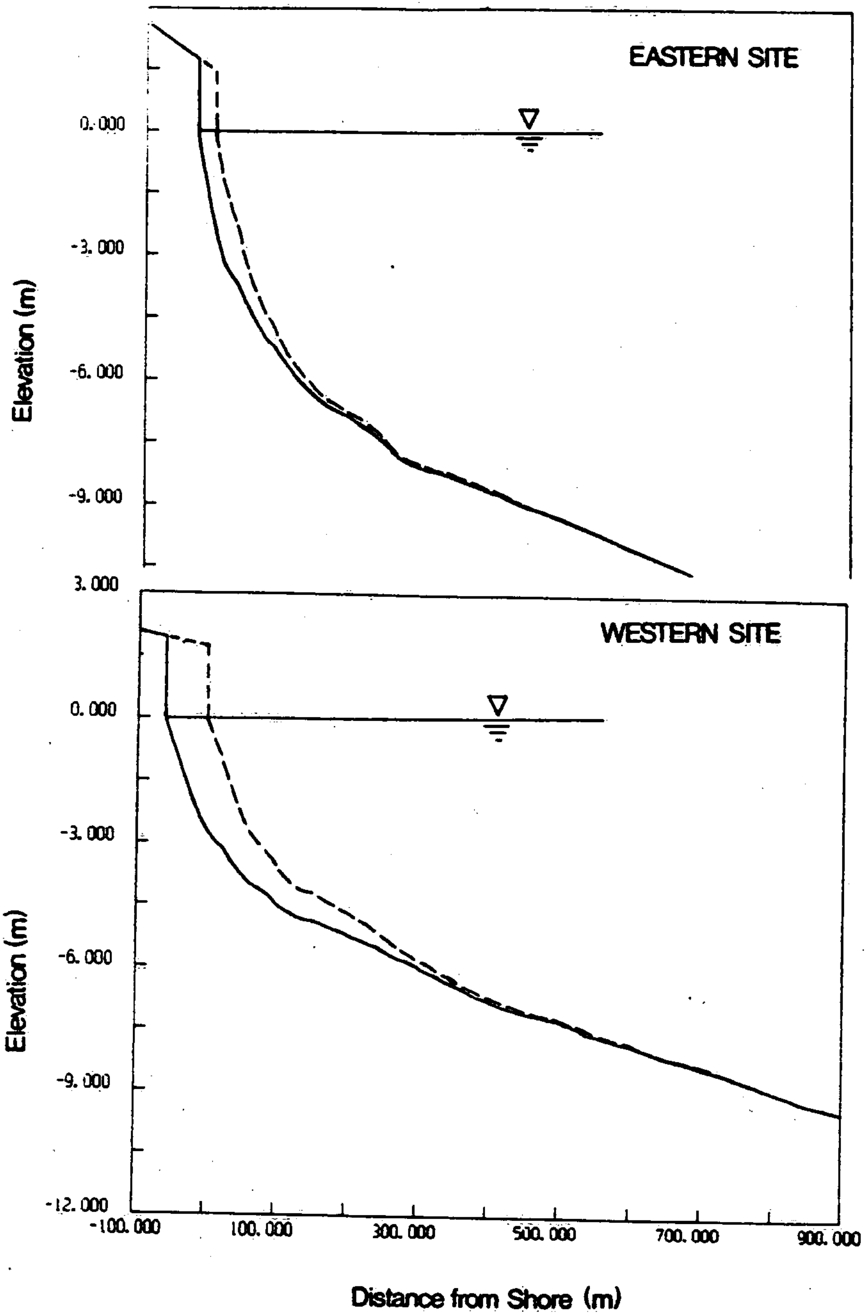

FIGURE 3. **(a) Simulation of profile development at eastern site, 1980 to 1984**
(b) Simulation of profile development at western site, 1980 to 1984
The dashed line represents the initial profile.

DISCUSSION

As a first attempt at simulating the complex processes controlling the evolution of an erosional nearshore profile based on measured substrate erodibility, the model presented shows promise. It reasonably reproduces the flattening of the profile with time that is characteristic of mature nearshore areas, such as parts of the Great Lakes. Furthermore there appears to be a trend toward reduced rates of erosion with time, as the profile becomes broader and the depth at each grid point increases. The overestimation of erosion rates in two actual profiles is not overly surprising at this initial stage, and suggests that key model components (e.g., wave climate of the ε versus τ relationship) need to be re-examined, or that other process-related factors, such as sand cover or shore ice, must be included in order to obtain better agreement with field results. This will be the subject of future model developments.

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