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COASTAL PROCESSES ON SOFT SHORES

by

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February 1983

Management Perspective

This report illustrates the difficulty in measuring recession rates of shores deficient in granular soils. It is suggested that the information on recession rates is more useful if reported as the integral giving recession as a function of time. A model to relate the wave energy to the recession is proposed which is substantiated with available data on the north shore of Lake Erie.

As lakes and reservoirs have the potential of having their level regulated, the consequences of regulation on shore recession may require evaluation. In Lake Erie, future withdrawals of water may affect shore developments and recession rates. The model provides a means to assess change which up to this point is not available.

T. Milne Dick
Chief, Hydraulics Division
March 1983

Perspective de gestion

L'auteur a voulu montrer la difficulté de mesurer les vitesses de recul des rives mal pourvues en sols granuleux. Il estime que l'information sur les vitesses de recul est plus utile lorsqu'elle est présentée en tant qu'intégrale donnant le recul comme fonction du temps. L'auteur propose un modèle pour relier l'énergie des vagues au recul et ce modèle s'appuie sur les données disponibles concernant la rive nord du lac Érié.

Comme il est possible de régulariser le niveau des lacs et des réservoirs, il faudrait peut-être évaluer les conséquences de cette régularisation sur le recul des rives. Dans le cas du lac Érié, les retraits d'eau pourraient affecter l'évolution des rives et les vitesses de recul. Le modèle prévoit un moyen d'évaluer le changement, ce qui n'existait pas encore jusqu'ici.

T. Milne Dick
Chef de la Divison hydraulique
Mars 1983

COASTAL PROCESSES ON SOFT SHORES

by

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Abstract

The characteristics of shores which erode rapidly are described and the processes are outlined.

Results of annual topographic surveys of a section of Lake Erie northern shore are used to illustrate the difficulty of obtaining measurements of shore recession rates. Annual rates of shore recession are shown to vary considerably both as a function of time and of location.

A model is proposed which gives the recession of the toe of the bluff as a function of the work done by waves. Some verification of the concept is obtained but other information is contradictory. The data available do not permit an evaluation of the effect of a sand bed near the bluff.

Résumé

On décrit les processus qui causent la récession rapide de la ligne de côte.

Par les moyens des levés topographiques annuels de la côte, on a illustré la variabilité des vitesses de recul en fonction de temps et d'espace.

Un modèle est développé qui donne une relation entre le travail accompli par les vagues (c'est-à-dire l'intégral du flux d'énergie) et le recul de la base de la falaise pendant la même période de temps. La forme du modèle est verifiée partiellement par les observations: mais malheureusement il y a quelques mesures qui son contradictoires à la forme mathématique. Également, les données disponibles ne permettent pas une analyse qui determinerait l'influence d'un lit du sable près de la falaise.

INTRODUCTION

Shore recession, especially where it is rapid, endangers properties and buildings which are considered significant by planners or by the community. In addition, shore developments are now widely recognized as possibly causing alteration to the shore regime. Environmental assessments of projects required by legislation now would like studies that give quantitative evaluations rather than qualitative opinions.

It is therefore becoming more important that the relationships between the waves, currents and sediment be adequately described. Most shores studied in the coastal engineering literature are mainly composed of sand but, in Canada, there are shores which are poorly supplied with sand. Such a shore is found along the northern boundary of Lake Erie.

Some conversations with Mr. K. L. Philpott about erosion in Lake Erie, combined with the ongoing research on Lake Erie by the National Water Research Institute (NWRI), stimulated an increasing interest in trying to improve the quantitative relationships between the eroding processes and the resulting recession.

IDEAL SHORE MODELS

The reaction of a shore to an obstruction may be imagined for three types of ideal shores. In Fig. 1 are shown the effects of an obstruction on a rocky shore, a sandy shore and a silty or clayey shore.

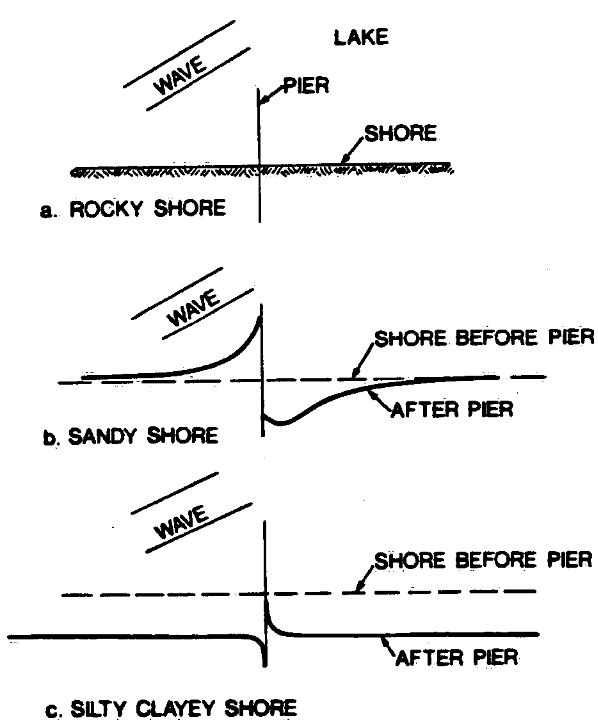


Figure 1. Reaction of ideal shores to an obstruction.

1a. Rocky Shore. This shore is all rock and, over a short period of time, the change in the shore is so small it may be thought of as zero. It is obvious therefore that the side effects of the structure are virtually zero.

1b. Sandy Shore. This shore, commonly characterized by beaches, dunes and offshore bars is very dynamic. It responds rapidly to an obstruction and the effects of structures on the adjacent shore, such as erosion and accretion may be significant. This type of shore has been studied extensively.

1c. Silty or Clayey Shore. This shore may be called a soft shore. It contains no granular material and therefore there are no beaches. The rates of erosion depend on wave energy and the resistance to erosion of shore strata. The shore does not respond to man-made developments because there are no beaches with the exception of some local effects owing to alteration of the wave and current pattern.

Comparison of these ideal shores shows that the only shore type which reacts to a barrier is the sandy shore. In fact the presence of sand-sized material seems to be a key variable to the response of shores to a change in regime.

In real life, natural shores may contain elements of all three types. The north shore of Lake Erie, for example, consists predominantly of clayey and silty bluffs with minor occurrences of rocky, sandy or gravelly shores. It follows that the shore behaviour should tend towards type three unless the presence of a relatively small volume of sand has a very strong influence.

SOME TYPICAL FEATURES

The soft shores of Lake Erie have typically a steep eroding bluff face with a smooth offshore slope. An idealized profile is shown in Fig. 2. This bluff is a very active zone and undergoes continual change. At the toe of the bluff, waves continually remove material which eventually leads to slope instability and landslides. The nearshore slope is usually covered by a layer of sand which varies in volume but rarely is sufficient to form a protective beach. Sand is often virtually absent.

Surveys by Zeman and Thompson (1982) show clearly that the bluff continually undergoes changes of slope morphology. Landslides and slips are often triggered by toe erosion but are also caused by other processes. Groundwater levels are important as well as slope geomorphic processes. Because of these other factors, the rate of recession as determined by the observed position of the toe or the bluff crest is subject to great variability. Moreover, as the bluff slope material slips downward, the waves are often not acting directly on in situ strata but on remolded debris which has moved from a higher location down onto the wave cut zone.

Before the process of erosion and recession can be tackled either deterministically or statistically, some standardization of measurement is quite desirable. Unfortunately, although the concept of recession rate is easily imagined, obtaining representative measurements is not so simple.

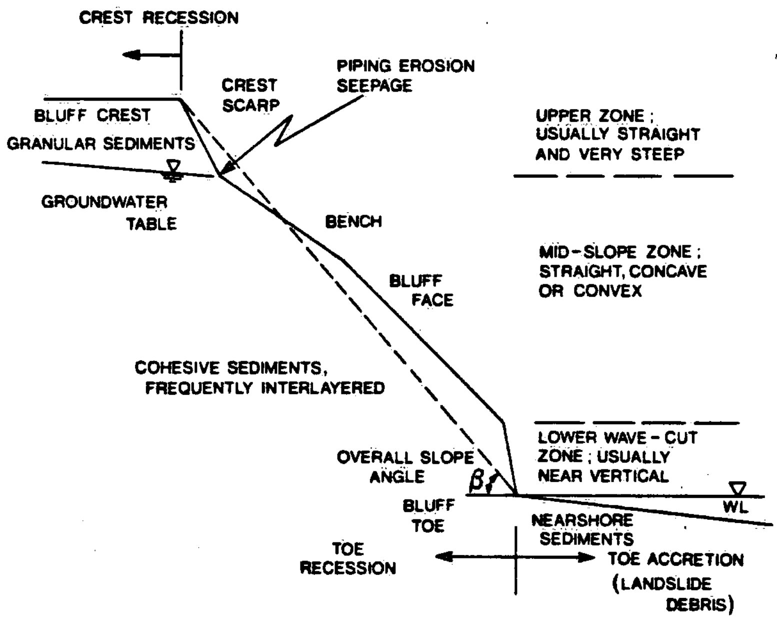


Figure 2. Typical bluff profile, central Lake Erie north shore.

RECESSION MEASUREMENTS

In the Great Lakes area, historical information on shore recession and accretion has been compiled by numerous agencies in order to assess the severity of erosion problems, to define areas of high erosion risk and to delineate structural setbacks in undeveloped areas. Principal difficulties with obtaining recession rates in engineering studies are at least threefold:

a) temporal variability of recession rates;
b) spatial variability of recession along the shore and;
c) accuracy of methods, air photographs, maps and charts used to obtain rates of shoreline change.

Temporal Variability

An assumption that recession rates on soft shores are constant in time is not supported by measurements that are available. Detailed measurements of Birkemeier (1981) and Carter and Guy (1978) indicate seasonal accelerations and decelerations within a single year, with peak recession occurring in the late fall (November and December) and in the spring (March and April). Seasonal peaks in recession generally coincide with storms before major freeze up and just after ice breakup (Birkemeier, 1981). Increased groundwater discharge and higher then usual water tables contribute significantly to bluff recession in the spring months. Variability of annual recession rates is documented both from regional erosion surveys (Boyd, 1981) and from detailed site investigations (Zeman and Thompson, 1982). The annual rates vary particularly in areas where the shore retreats by rotational slumps and gullying. Short-term rates fluctuate in response to lake level changes (Seibel, 1972; Berg and Collinson, 1976; Hands, 1976; Quigley et al., 1977; Birkemeier, 1981). Through recent investigations it has become clear that high rates of recession may occur also during low lake levels (Quigley et al., 1977; Birkemeier, 1980; Zeman and Thompson, 1982) and that other factors than average lake level should be considered for the interpretation of recession rates.

Even when a fairly long reach east of Port Burwell is analyzed systematically with cross sections at intervals of 250 m, and then averaged, there are distinct differences in the mean erosion rates (Table 1).

TABLE 1. Average Recession Rates for 7-km Long Reach East of Port Burwell. The rates were measured at 28 cross sections spaced at intervals of 250 metres.

Years		Toe Recession Rate	Crest Recession Rate
From	To	(m yr^{-1})	(m yr^{-1})
1913	1937	3.85	3.68
1937	1945	3.66	6.13
1945	1951	4.81	4.32
1951	1959	3.20	4.98
1959	1964	4.62	7.56
1964	1968	4.60	7.93
1968	1973	5.85	4.93
1973	1976	6.70	7.48

For the above reasons, any measurements of recession rates obtained over a short time period should be treated with caution, especially when projections into the future are attempted. Short-term rates are in general less reliable than long-term averages. Historical data give long-term rates but as they are usually derived from old maps and charts there may be some doubt about the location of the shoreline. Often it is impossible to determine if a map depicts the edge of bluff or the water's edge. Long-term changes occurring over a geological time period of hundreds and thousands of years are mostly unknown. These changes can be unidirectional as well as cyclic. Slow tilting of the basins by differential crustal uplift due to the retreat of the Late-Wisconsin glacier ice should be considered in assessments of very long-term trends. Other long-term effects are

Holocene climatic changes and man-induced modifications of the shoreland, e.g. deforestation at the time of early colonial agricultural development. These effects can be detected from variable sedimentation rates of postglacial basin muds and the geochronology of offshore sediments (Lewis and Anderson, 1976; Zeman, 1979a) but the relationship to shore recession is not determinable at the present time. In many areas, extensive construction of shore-protection structures is the principal cause of the overall decrease in recession rates (Zeman, 1979b; Carter and Guy, 1980).

A procedure which seems to result in less confusion is to obtain data as detailed as possible and then report the recession in the form of a cumulative curve, which characterizes the short-term as well as long-term trends (Fig. 3). As shown in Fig. 3, toe recession rates and crest recession rates at the same location can be strikingly dissimilar. Both toe and crest recession rates should be therefore measured and clearly distinguished.

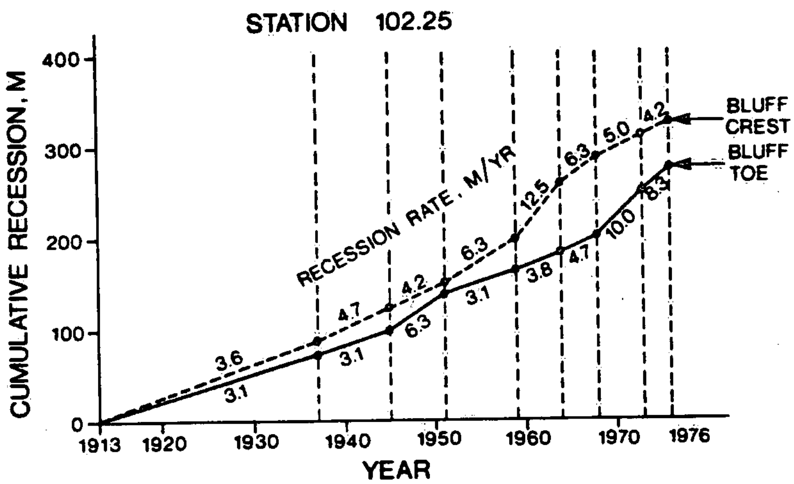


Figure 3. Cumulative plot of shore recession (data from Zeman and Thompson, 1982).

Recession rates have been frequently determined at arbitrarily-spaced survey lines, which are usually oriented perpendicularly to the shore. Measurements are then taken as representative of the stretch of shore between adjacent survey lines. The problem of optimum spacing of survey lines was examined by Seibel and Maresca (1974) for two sites on southeastern Lake Michigan.. They computed the average rate of recession using four different spacings between survey lines. Their conclusion was that, in order to obtain a "representative" rate, spacing should not exceed 250 m for the first site and 38 m for the second site. Detailed topographic surveys near Port Burwell on the Lake Erie north shore (Zeman and Thompson, 1982) showed that 250-m spacing, suggested as an upper bound by Seibel and

Maresca (1974), is too large for this stretch of shore. Due to the presence of rotational slides and gullies, high spatial variability exists even between lines that are 50 m apart (Fig. 4).

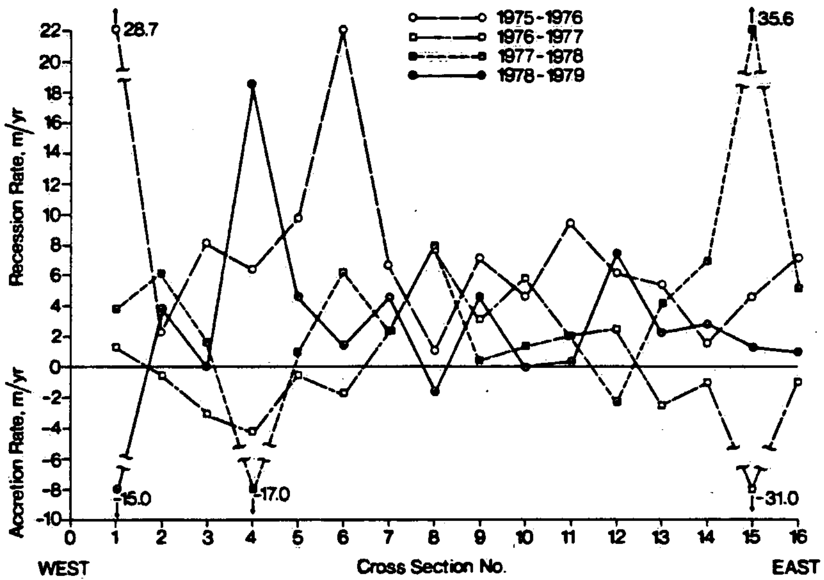


Figure 4. Toe recession rates at NWRI study site from 1975 to 1979. Cross sections are 50 m apart (after Zeman and Thompson, 1982).

Spatial variability along the shore is not smoothed out by increasing the time interval as illustrated in Fig. 5. The long-term rates were obtained from available township surveys and aerial photographs. The error in rate is about ±0.5 m/yr for each point. Gelinas (1974) seems to have less spatial variation and his error is estimated to be ±.25 m/yr. The plotting of continuous shoreline traces, instead of discrete measurements, was strongly advocated by Carter (1974). Continuous plots of recession and accretion can then be related to shore structures, distribution of beaches, shore stratigraphy, nearshore slope bathymetry and other factors.

Spatial variability should be also considered in computations of volumetric erosion, for which volumes are frequently estimated from two-dimensional profile changes. A more accurate technique is to determine volumetric erosion from successive contour maps (Weaver, 1979; Zeman and Thompson, 1982). In the latter study, volumetric erosion was computed both from digitized contour maps and from two-dimensional profiles that were spaced 50 m apart. Annual volumes of eroded material were found to differ within ±25% of the more accurate values.

Errors, Precision and Accuracy

Apart from problems of spatial and temporal variability, various constraints exist on the reliability of measured recession rates.

Accuracy of rates determined from maps and air photographs is tied to their scale. For example, for an air photograph at a scale of 1:20,000, the smallest field distance measurable is in the order of 4-10 m (Tanner, 1978). In general, scales below 1:25,000 are not appropriate for measurements of shore recession or accretion, particularly for areas where changes in shore position are small. Further errors can be introduced due to inaccurate maps, radial distortion and tilt of air photographs, different lake levels on successive maps and charts, vegetation, overexposure or sun reflection on air photographs, lack of suitable reference points and human errors in measurements. Error limits inherent in determination of recession rates should be carefully estimated and reported. Precision of measurements may be increased by the use of projecting-plotting equipment, rulers with a vernier dial, magnifying lenses and replicate measurements.

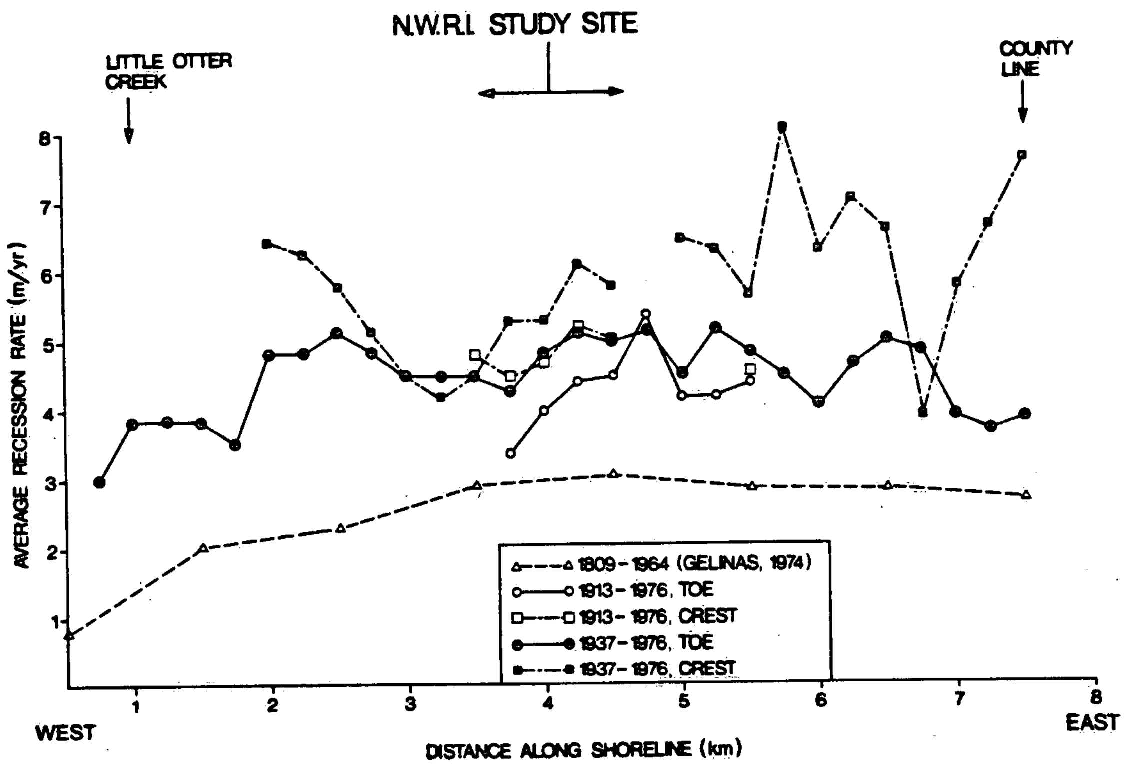


Figure 5. Spatial variability of long-term recession rates east of Port Burwell, Ontario (after Zeman and Thompson, 1982).

MODEL FOR SHORE RECESSION

A simplified bluff profile with the relevant variables is shown in Fig. 6.

The object of the model is to state the rate of linear shore recession as a function of sediments forming the bluff stratigraphy, the wave energy and the geometry. As shown before, the process of linear recession is very unsteady because the bluff frequently fails and slides. Basically, the waves erode the bluff at the water levels and continuously remove the debris which falls into the lake. The equation for the erosion and transportation rate may be written approximately

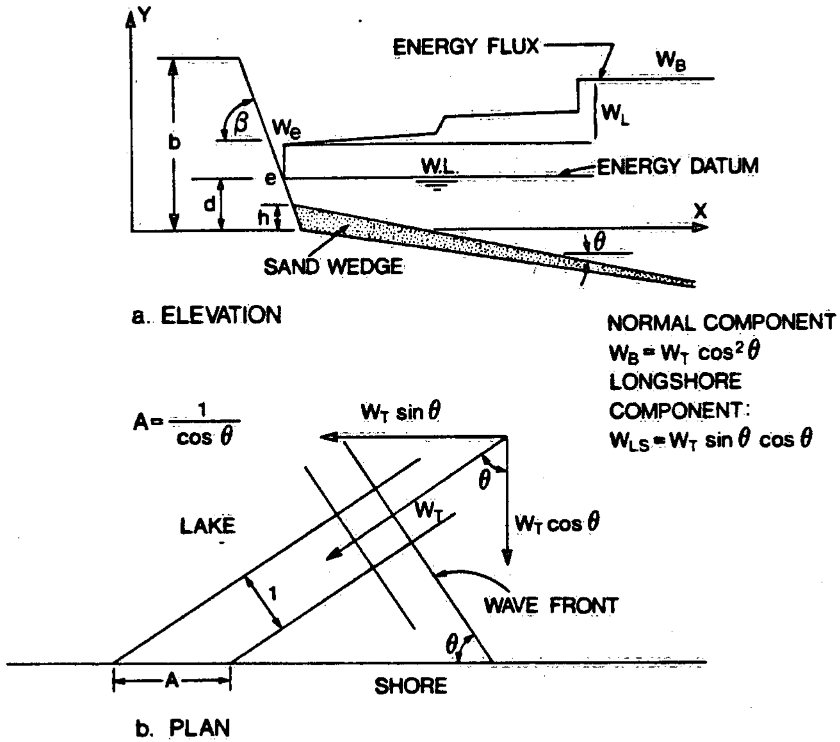


Figure 6. a) Model bluff and foreshore profile;
b) Wave energy flux distribution.

$$\dot{V} = b\dot{x} \qquad (1)$$

where $\dot{V}$ is the bluff volume eroded per unit of time per metre of shore;
b is the bluff height;
$\dot{x}$ is the bluff horizontal recession.

Note that the volume V in Equation 1 does not include the erosion of the foreshore slope. Obviously, the foreshore continues to erode because the depths offshore increase and clearly at one time the depth of the foreshore was close to the depth d at the toe of the bluff (Fig. 6). Usually d is very small. Because the deepening process continues, then a sand wedge near the shore must at times be fluidized by wave action in order for the erosion to continue.

The energy causing the erosion is provided by the waves. The waves cause both the erosion of the bluff and of the foreshore but for the model only the energy causing bluff erosion is considered. Wave energy approaching the shore is accounted for by dissipation through wave breaking, bottom friction and reflection. The timing and manner in which energy is converted depends very strongly on the bottom configuration and the sea state.

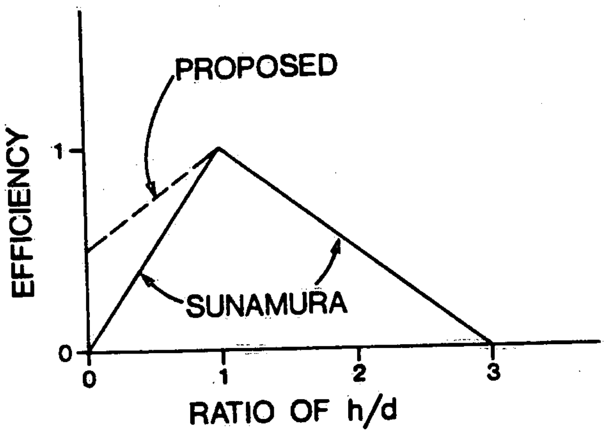


Figure 7. Sunamura's relationship between efficiency of shore recession and relative beach elevation.

The energy flux equation is illustrated in Fig. 7 and gives

$$W_e = W_B - W_L$$

where W_B is the energy flux <u>normal</u> to the bluff orientation just before breaking in Watts;
W_L is the loss of energy passing from the breaker to the bluff;
W_e is the energy flux normal to the bluff available for erosion.

If the waves break at an angle θ to the shore orientation, Fig. 6, then

$$W_B = W_T \cos^2 \theta \tag{3a}$$

$$W_{LS} = W_T \cos \theta \sin \theta \tag{3b}$$

where W_T is the wave energy flux per unit length of wave crest;
W_{LS} is the longshore component of W_T.

In very shallow water near the bluff, the behaviour of the wave is tightly controlled by the depths and the bottom slopes. The type of breaker is also a function of the bottom geometry and depths. A plunging breaker will dissipate energy in the foreshore but a spilling type will carry more energy to the bluff face. If breaking does not occur on the face of the bluff, then the wave will tend to reflect with possibly low erosive effects. It seems therefore that the effect of the waves on the bluff face may be greatly influenced by the last few metres of the foreshore.

The mechanism of soft cliff erosion has been extensively studied by Sunamura and he identified some important mechanisms in his model tests (Sunamura, 1982). He showed that not only do the depths near the bluff control the breaking mechanism and vortex formation as the waves break on the bluff but that the sand wedge is also mobilized to increase the abrasion and erosion rate. In fact he goes on to show that the rate of recession is controlled by the volume of the sand wedge and its height. His relationship for the effect of the sand is given in simplified form in Fig. 7. This function f(h/d) may be taken as an efficiency term or converting term because it represents the portion of the wave energy converted to erosion of the bluff. Sunamura's artifical material, a mixture of Portland cement and sand, which he used in his model tests, did not erode until the shear stresses induced by the wave currents exceeded a limiting value. Consequently, when h/d equalled zero, no erosion occurred in his tests because no sand was present. For tills and glaciolacustrine clays, erosion occurs whether or not there is sand available. Therefore Fig. 7 shows a proposed modification to account for erosion in the absence of sand.

Introducing Sunamura's efficiency term and postulating that the sediment erosion is a function of wave energy flux, it follows that,

$$\dot{V}_e \propto W_e f(h/d) \qquad (4)$$

where V_e is the volume eroded by waves.

Before statement 4 may be linked with Equation 1, a proportionality constant and a term to convey the erodibility of the strata are required. There are two possible routes to follow. The first is to relate a value of erodibility to a property of cohesive sediment forming the bluff. Vallejo (1980), relying on Flaxman (1963), proposed an index which is a function of the unconfined compressive strength (q_u) and gave some data to support the view that the rate of recession is a function of q_u. If Vallejo's approach were used then Equation 4 becomes

$$\dot{V}_e = A\, W_e\, f(h/d)\, I \qquad (5)$$

where I is an index derived from the erodibility of the sediments; A is a proportionality constant.

In this approach, the index I must include all the strata in the bluff and must also include the effects of remolding.

Flume tests by Rohan et al. (1980) give some indication of the difficulty in computing I. They tested the erosion of firm to very stiff sensitive clays by flowing water. The erosion of undisturbed clays was negligible until the shear stress exceeded 8 Pa. Remolded portions of the samples however eroded much more easily at shear stresses as low as 0.2 Pa. Although remolding of Lake Erie tills and clays would have probably less effect, nevertheless the process is possibly quite significant. Choosing a representative index based on the sediment properties is obviously difficult and could result in wide variations in the constant A in order to compensate for the poor representation of the erodibility by I.

In view of the uncertainties of developing an index I by any means, it is proposed to use the second alternative and define erodibility e by Equation 6. That is

$$\dot{V}_e = W_e \, f(h/d) \, e \qquad (6)$$

where e is the erodibility of the shore.

Equation 6 should also provide a reasonable basis for model development as soil properties can always be explored relative to values of e.

Combining Equations 6 and 1 and assuming $\dot{V}_e = \dot{V}$, then the recession rate is given by,

$$\dot{x} = \frac{W_e}{b} \cdot f(h/d) \, e \qquad (7)$$

It has already been observed that integrating recession rate data seems to give a better perspective.

It is therefore further proposed that Equation 7 be integrated to give

$$x = \int_{T_1}^{T_2} \frac{W_e}{b} \cdot f(h/d) \, e \, dt \qquad (8)$$

Direct verification of the model is not available but some observations may be made.

Gelinas and Quigley (1973) compared erosion rates with the wave energy flux near the point of breaking. They did not attempt to separate the flux into a normal and longshore component and regression analysis gave

$$\dot{x} = 0.28 + 0.96 \, W_T$$

with a correlation coefficient of 0.79. Obviously the wave energy flux (W_T) is a major influence on x as one would expect.

Baird (1980) postulated a decay function for the wave energy flux normal to the shore. He used long reaches and averaged the foreshore

WAVE ENERGY AT TOE OF BLUFF FOR REACH 18
(after Baird,1980)

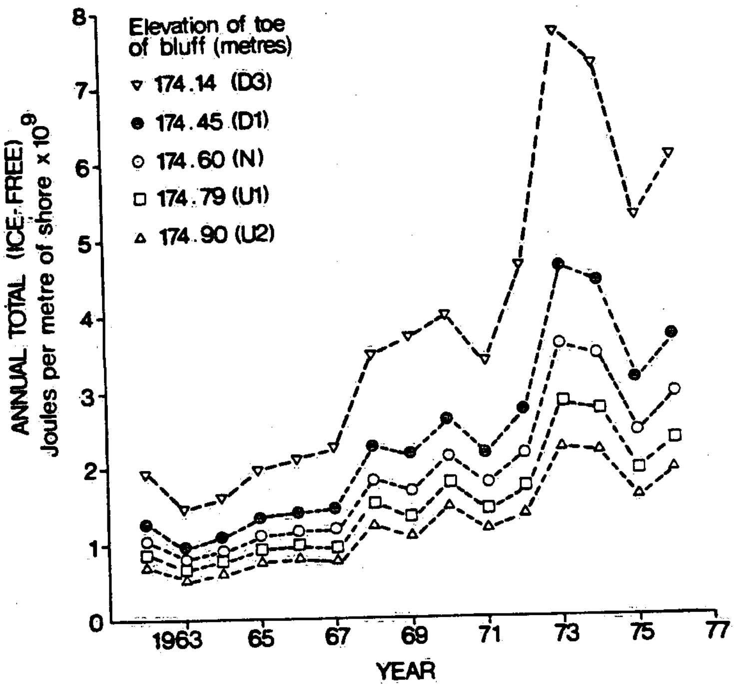


Fig. 8. Wave energy at toe of bluff for reach 18 (after Baird, 1980).

to be a plain surface at a fixed slope. He computed W_e from weather and water level records at hourly intervals for various toe elevations and then summed up the wave energy flux for each year over a period of 14 years. His computed values are shown in Fig. 8.

Zeman and Thompson (1982) measured the rates of recession for the same period over a portion of the same reach. Their data for the average recession of the 7-km long reach are given in Table 1.

Equation 8 may be approximated as follows:

$$x = A \int_{T_1}^{T_2} W_e \, dt \qquad (9)$$

where A contains f(h/d), e and b. Using the data mentioned above, results are plotted on Fig. 9. Remarkably a series of straight lines for this limited data is obtained, which despite the few data points testifies quite strongly that the recession is a function of work done by the waves near the bluff. Clearly Equation 9 has different values of A depending on the elevation of the toe but, as far as correlation of W_e with average annual toe recession is concerned, the elevation of the toe is not critical.

As the correlation of W_e and x shows little scatter, there is no apparent effect from f(h/d). However, probably f(h/d) does not vary greatly over the relatively long time periods used for Fig. 9. Unfortunately, the f(h/d) is the only factor which is influenced by a shore structure. It is therefore obvious at this stage nothing may be deduced of a quantitative nature on the effect of f(h/d) and the presence of sand. Data which would permit an evaluation of the effect of f(h/d) is required before deductions may be made of the effect of intercepting littoral drift on the rate of recession.

Zeman and Thomson (1982) correlated x with bluff height b and plotted the results on Fig. 10 which also shows similar data by Quigley (1976) and Gelinas (1974). The regression analysis shows that x is proportional to b whereas the model, based on physical reasoning, indicates that x is inversely proportional to b.

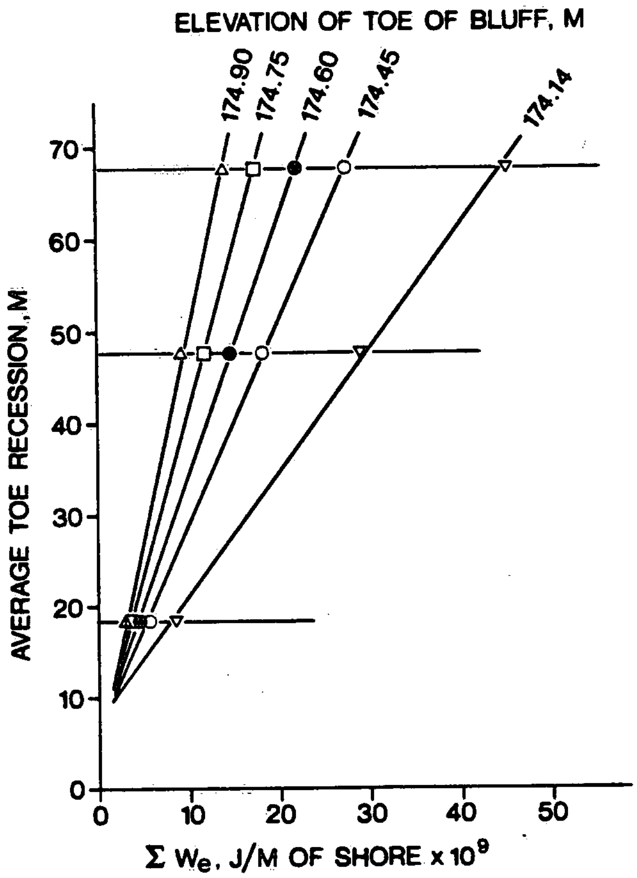
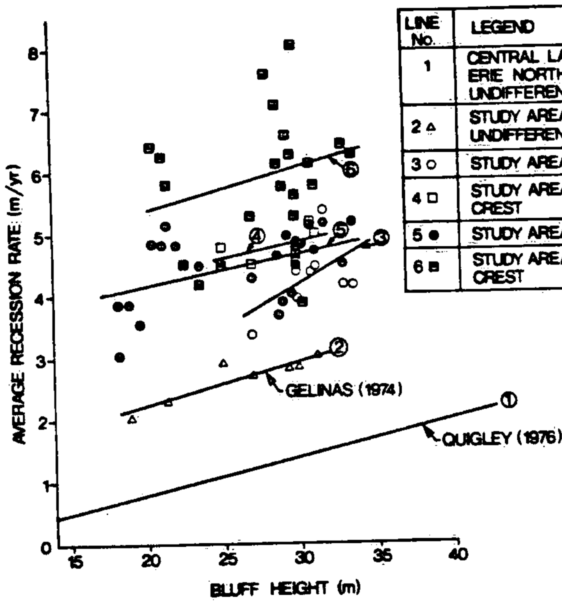


Figure 9. Plot of average toe recession as a function of work done.

The regression analysis, giving $x \alpha b$, is not a strong correlation and there is considerable scatter. Nevertheless, if the observation that $x \alpha b$ is true, then, for Equation 8 to also be true, the value of e must be affected by b because of remolding and the supply of debris. A strong possibility exists therefore that remolding and slumping are important processes for shore recession.

This observation forces a reevaluation of the basic recession equation and that it should be modified so that the recession rate is



LINE No.	LEGEND	TIME INTERVAL	CORRELATION COEFFICIENT
1	CENTRAL LAKE ERIE NORTHSHORE UNDIFFERENTIATED	~1810 -1964	0.5
2 △	STUDY AREA UNDIFFERENTIATED	1809-1964	0.9
3 ○	STUDY AREA, TOE	1913-76	0.5
4 □	STUDY AREA, CREST	1913-1976	0.5
5 ●	STUDY AREA, TOE	1937-76	0.4
6 ■	STUDY AREA, CREST	1937-1976	0.3

Figure 10   Correlation of recession rate with bluff height (after Zeman and Thompson, 1982).

made up of two terms. The first term relates only to the geotechnical and geomorphic processes of the bluff, the second relates to the active wave energy causing instability and removal of sediment. Equation 9 may then be expressed in general terms as

$$x = A + \int_{T_1}^{T_2} \frac{W_e}{b} f(h/d)\ e\ dt \qquad (10)$$

where   A is a function depending on the geotechnical and geomorphic slope processes.

Although the plot of Equation 9 in Fig. 9 does have a positive intercept on the Y axis, giving credence to Equation 10, the evidence is not yet strong enough to abandon Equation 9 for Equation 10.

Lastly, no data based on shore observations are yet available to examine the role of the sand wedge and the f(h/d). Unfortunately, it is the only term affected by the contruction of a pier, Fig. 1, and consequently is a key variable for any quantifiable environmental assessment. If the f (h/d) behaves as contended by Sunamura, then a groyne or pier blocking sand transport could reduce the recession rate instead of increasing it: a result dramatically opposed to the normal sandy shore behaviour.

CONCLUSIONS

1. Soft shores, composed of clay and till, have recession rates which vary greatly in space and in time.

2. Integration of the recession rate to give recession provides a better description of the process.
3. There is probably a linear relationship between the work done by the waves on the shore bluff and the distance the bluff recedes.
4. In order to develop a model suitable for quantitative estimates of the effect of structures on shore recession, the influence and effect of nearshore sand deposits must be ascertained.

RECOMMENDATIONS

Research to obtain methods for estimating erodibility and to find out the role of sand volume in the nearshore zone is required.

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