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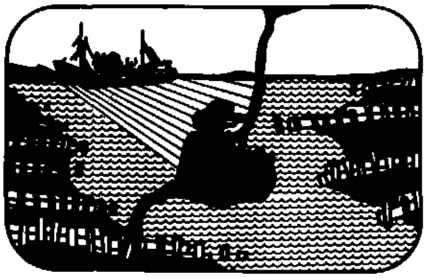

Soil Mechanics Aspects of Shoreline Erosion

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Abstract
Shoreline bluff retreat is influenced by the interaction of shoreline-wave hydraulics, cliff geology-morphology and soil mechanics. One important variable is lake level, since a rising level moves the wave attack towards shore, steepens the cliff front and alters the slope failure mechanisms from a slow, flattening process controlled by effective stresses to a short term toe failure mechanism controlled primarily by geometry and undrained shear strength.

Three major morphological types of retreat are considered: 1) the non-eroding cliff that is gradually flattening to its long term, stable, angle of repose, 2) the eroding, unvegetated cliff of nearly constant profile which is retreating due to a combination of toe erosion, frontal toppling and sheet sloughing, and 3) the eroding cliff that shows cyclic changes in profile in response to major, cyclic landslides. All three types are illustrated by examples from the north shore of Lake Erie and related to the erosion model proposed by Gélinas and Quigley (1973).

Résumé
Le retrait des falaises littorales est influencé par l'interaction des vagues en eau peu profonde, de la géologie et morphologie des escarpements et des propriétés mécaniques des matériaux. Un facteur important est le niveau de l'eau dans les lacs puisqu'une augmentation des niveaux déplace la zone d'attaque par les vagues vers le rivage, rendant ainsi le talus plus raide et fait évoluer les mécanismes de rupture d'un processus d'aplanissement contrôlé par les contraintes effectives jusqu'à un mécanisme de rupture contrôlé surtout par la géométrie et la résistance non-drainée. Trois types morphologiques de retrait se rencontrent surtout: 1) des pentes où l'érosion est absente qui s'aplanissent jusqu'à un angle de repos stable à long terme; 2) des pentes soumises à l'érosion, dépourvues de végétation, à profil plus ou moins constant et qui reculent par combinaison d'érosion à la base, d'éboulement frontal et de désagrégation en feuilles; 3) des falaises fortement érodées qui montrent des changements cycliques de profil à la suite de glissements majeurs cycliques. Ces trois types sont illustrés par des exemples relevés le long de la rive nord du Lac Erié et sont expliqués par le modèle d'érosion proposé par Gélinas et Quigley (1973).

Introduction
Shoreline erosion or retreat rates are controlled by the complex interaction of shoreline-wave hydraulics, cliff geology-geomorphology and soil mechanics. An important variable is lake level since a rising level moves the attack by breaking waves towards shore, markedly altering the coastal geomorphology and accelerating the rate of erosion. The purpose of this paper is to describe the soil mechanics aspects of the retreat of shoreline cliffs using as examples the many forms of cliff failure that exist along the north coast of Lake Erie. Since it is intended to present many of the failures in technical detail in subsequent publications, this presentation is descriptive and general. The paper is intended to be a companion paper to that presented by Haras *et al.* as part of this same Symposium.

General Concepts
Shoreline cliffs might be considered to be of three main geomorphological types, namely: 1) the non-eroding cliff that is gradually flattening to its long term stable situation without removal of toe debris, 2) the eroding cliff that retains a fairly constant shape while retreating at a fairly constant rate in response to continuous toe erosion, and 3) the eroding cliff that is rapidly steepening due to aggressive erosion at the toe that will result in cyclic failure and cyclic changes in cliff morphology.

The flat, type 1 cliff develops during periods of low water level or behind protective beaches. The type 2 cliff develops when a critical equilibrium develops between cliff soil mechanics and wave erosion and normally would represent "slow" retreat during "normal" water levels. The cyclic, type 3 cliff develops during periods of high water level and rapid erosion such as has existed for the past six years (1969-1975) or in response to soil softening and cyclic slope failure of the long term, effective stress type. In all of the above three geomorphological types, time plays a crucial role in determining the actual shape of the cliff front at any point in time.

Since the soil mechanics and toe erosion are interrelated, a brief review of erosion rates in our type area (the Lake Erie north shore) will be presented first. Examples of failure types and mechanisms will then be presented.

Erosion rates vary greatly from west to east along the Lake Erie north shore between Rondeau and Long Point as shown in Figure 1 from Gélinas and Quigley (1973). Although there are many interrelated variables controlling the rate at a given location, the dominant control is the amount of wave energy that strikes the shoreline and attacks the toe. As shown in Figure 2 also from Gélinas and Quigley (1973) the relationship between the 150 year erosion rate and breaking wave energy is approximately linear although there are marked deviations from this relationship at certain locations. Within this stretch of eroding coastline, the morphology of the bluffs also varies remarkably in response to changes in both the geology and the soil mechanics aspects of failure.

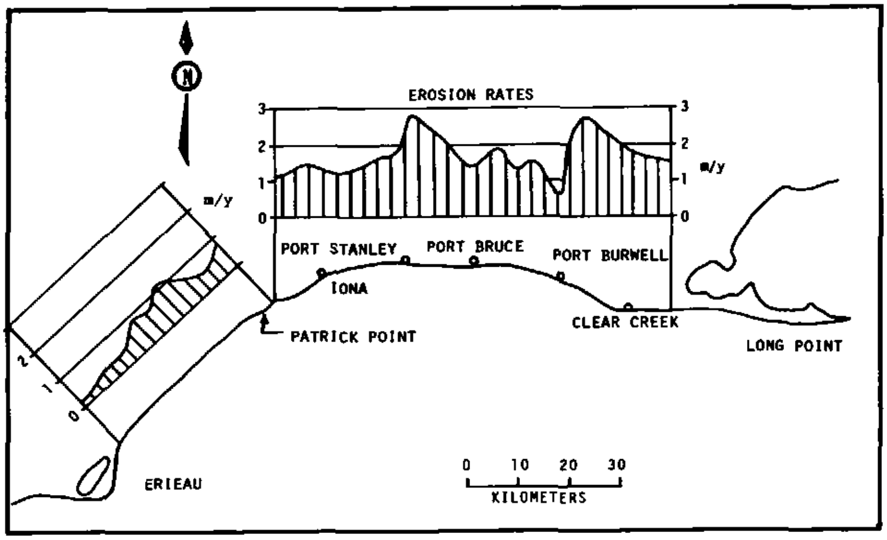

Figure 1
Shoreline erosion rates in central Lake Erie north shore, 1810-1964 (after Gélinas and Quigley, 1973).

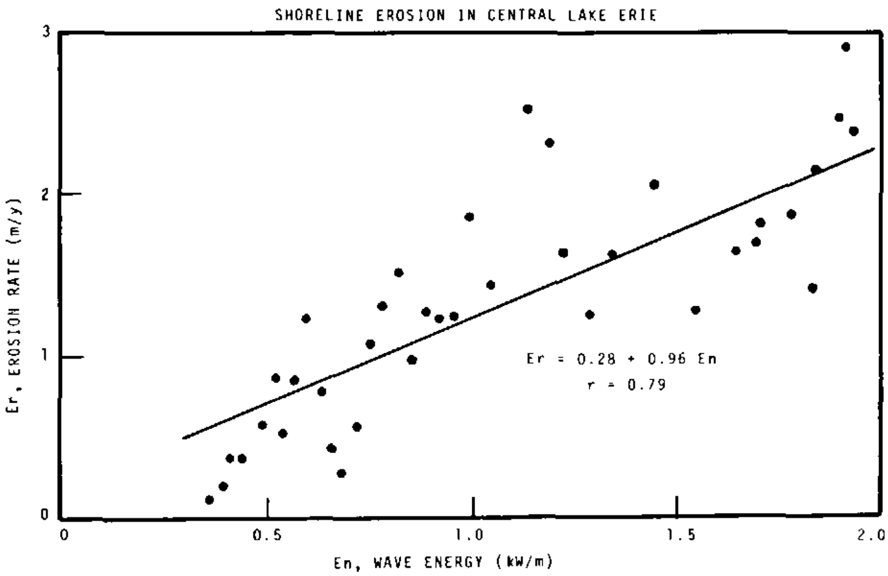

Figure 2
Relationship of 150 year erosion rate and calculated breaking wave energy (after Gélinas and Quigley, 1973).

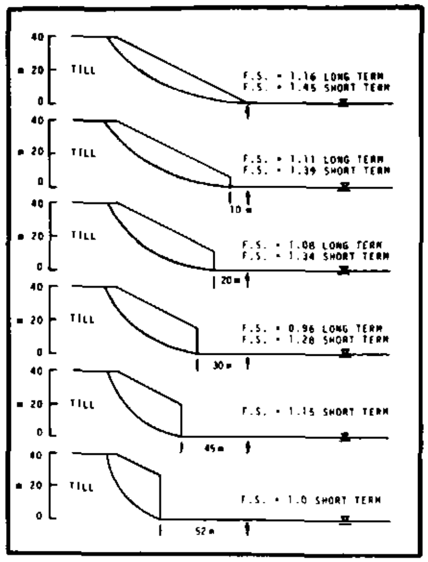

Figure 3
Changes in shorecliff morphology and factor of safety with increased toe erosion due to a rising lake level (after Gélinas and Quigley, 1973).

In Figure 3 the effects of increasing toe erosion and bluff steepness on both the short and long term factors of safety are shown for a typical cliff of clay till having a height of 40 m. The short term factor of safety represents the situation for intact clay having its original undrained strength whereas the long term factor of safety is calculated using drained strength parameters or completely softened soil. If the rate of toe erosion is slow enough that softening occurs in the slope such that the factor of safety is reduced to unity a failure of the long term type will occur. In other words, given enough time, all three of the lower profiles represent potential long term failure situations for the slip circles shown.

Soil Mechanics Aspects and Examples

The uppermost profile in Figure 3 represents the long term stable type 1 slope which results from landslides and creep of an initially unstable slope. These slope flattening processes are illustrated in Figure 4 adapted directly from Hutchinson (1973). The rate of slope flattening is much faster early in the life of the slope when high shear stresses exist and softening along shear planes is fairly rapid. As the slope angle decreases, a creep situation develops and the rate of flattening decreases greatly as illustrated in Figure 5, also adapted from Hutchinson (1973). Although Hutchinson's data were obtained from extensive studies on abandoned coastal cliffs of London clay which contains considerable montmorillonite, the same processes are operative on any abandoned cliff. Such type 1 slopes exist west of Port Burwell where originally steep, wave-cut cliffs have been protected by large beaches west of a long harbour jetty. In Figure 6, the 1971 profile of a flattened slope studied by Gélinas (1974) is presented along with the probable cliff about 1900 prior to jetty construction. The present slope is still creeping (flattening) slowly especially during spring periods of high ground water level.

Type 2 cliffs (those of fairly constant slope during continuous toe erosion) are found in the western end of the study area just west of Patrick Point. In this area, the bluffs are about 27 m high and are characterized by two types of coexisting slope profiles as shown in Figure 7. The flatter slopes (about 37°) occur as scallops in the cliff front and seem to represent slightly wetter areas

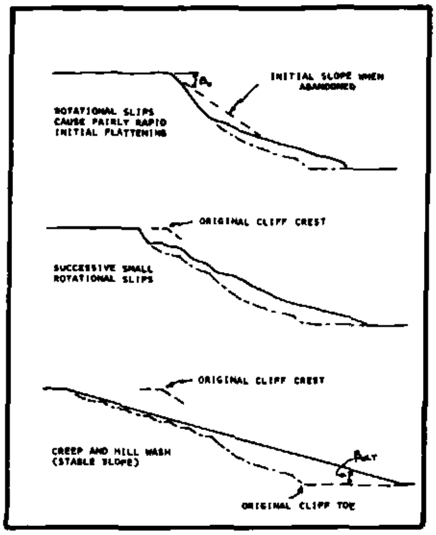

Figure 4
Flattening stages in abandoned cliffs of London Clay (after Hutchinson, 1971).

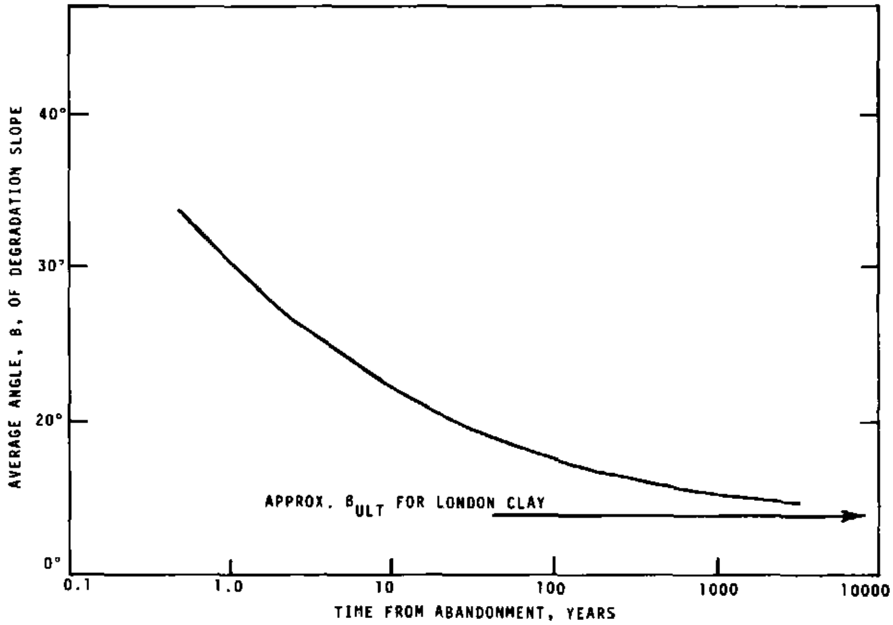

Figure 5
Rate of flattening of slopes containing London Clay (after Hutchinson, 1971).

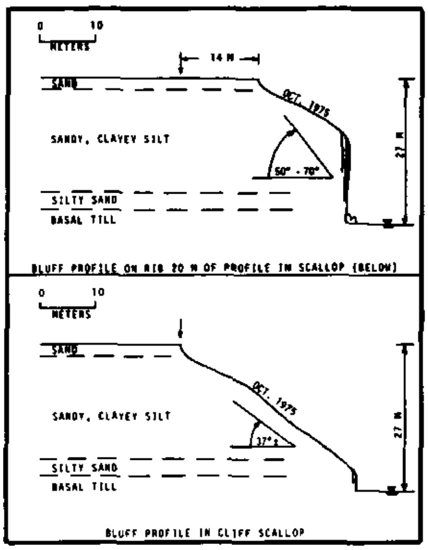

Figure 7
Companion profiles west of Patrick Point showing erosion processes of toe erosion, toppling and surface slaking (little or no evidence of overall instability).

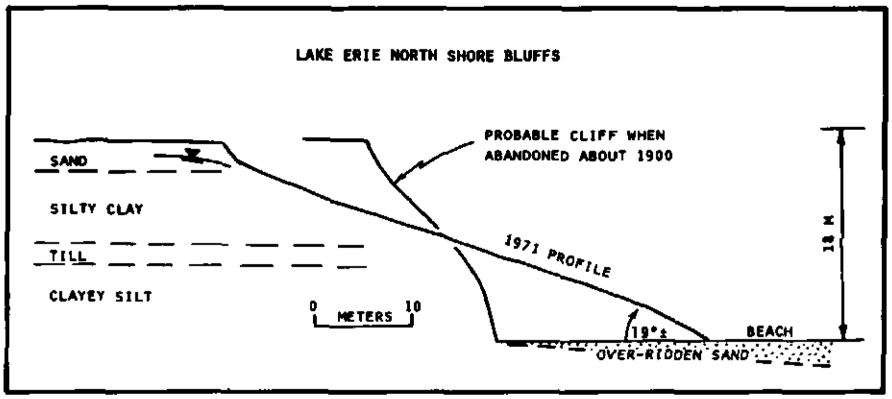

Figure 6
Cliff profiles at beach, Port Burwell.

than the steeper slopes (50° to 70°) which form ribs between the scallops. Steep profiles also exist over long lengths of the bluffs in areas only slightly serrated with scallops and gullies.

From a theoretical point of view, these cliffs are identical to those in the lowest profile in Figure 3 even though they are not so high. Should toe erosion cease, they would flatten to a type 1 slope given enough time. As shown in Figure 1, the long term erosion rate in this area is 0.5 to one m per year. Although quite slow, this is still too rapid a rate of retreat to permit softening and reduction of the safety factor to unity thus enabling a landslide to develop.

The retreating or eroding process in this area is an interesting combination of repeated surface desiccation followed by wetting and sloughing. This process is illustrated in Figure 8 which clearly shows that erosion of clay tills by moving water is negligible until the water content is reduced by desiccation to a percentage slightly below the shrinkage limit. In the case of the till studied by Gélinas (1974) this corresponds to a water content of about 13 per cent compared to in situ values of about 20 per cent. Since the clay cliffs in the area of Patrick Point face southward, they are particularly susceptible to desiccation by the sun followed by sloughing erosion either in sheets during subsequent rainstorms or at the toe due to spray wetting by waves on impact with the cliff.

In Figure 7, tension cracks are shown in the illustration and these represent an

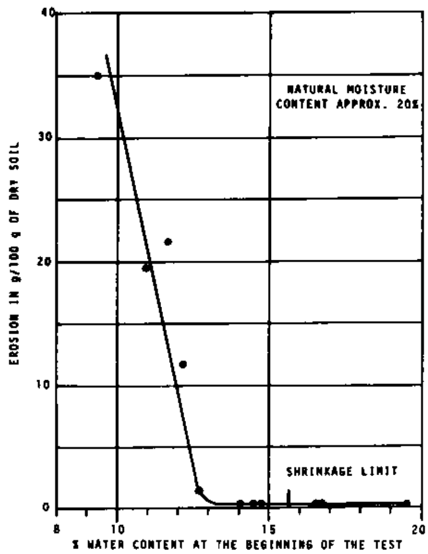

Figure 8
Erosion of Port Stanley Till (directly from Gélinas, 1974).

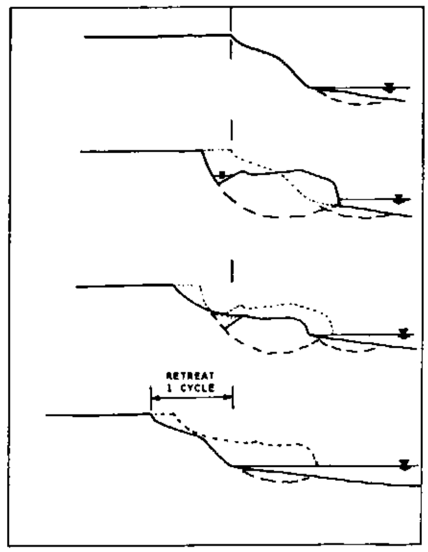

Figure 9
Stages of London Clay cliff erosion, one cycle (adapted from Hutchinson, 1971).

additional mechanism of erosion consisting of local undercutting of the toe followed by subsequent tension cracking and toppling.

A further variation in bluff morphology is caused by shallow gullies and tile drains which issue over the cliff tops creating cirque-like depressions extending back beyond the normal cliff edge. The growth mechanism of these features appears to be the previously described process of desiccation followed by rain-wetting and sloughing of sheets of very soft, remoulded, clay soil. These exit onto the shoreline and are similar to the under-consolidated mud flows described by Hutchinson and Bhandari (1971).

The type 3, cyclic type of erosion markedly influenced by landslide development occurs at several locations along the Lake Erie north shore. This type of continuous erosion has also been admirably described by Hutchinson (1973) again for London clay cliffs as shown in Figure 9. The process basically involves failure of a steep slope (top profile in Fig. 9) such that the displaced mass of soil acts as a counterbalancing force for the slope. Erosion gradually removes this landslide debris until a new intact profile identical to the top profile is created. During the time interval for this erosion, the soil in the slope has softened and a new failure occurs. The process constitutes one cycle of a continuing process of erosion.

It is important to note that softening need not occur to have the above cyclic process develop on a shoreline. If the short term factor of safety is less than one when the counterbalancing debris is eroded away, the slope will fail due to its own weight without softening.

It is also important to note that a cycle of erosion need not remove all of the debris in order for the next failure to occur. Such a conditon exists on the Erie north shore south of Iona as illustrated by the two profiles in Figure 10. In this area, the shoreline is marked by landslides at most locations so that a major step appears in the slope nearly all of the time. Failure of a slope steepened by toe erosion creates a retreat scallop in the crest of the bluffs and pushes the toe off-shore as illustrated by the lower profile. The adjacent cliff 100 m east shown by the upper profile represents an earlier failure now steepened to the point of incipient failure. It will in turn create a new scallop in the bluffs extending back beyond that of the lower profile.

The presence of the silty sand stratum just below midslope accelerates softening of the tills which are comparatively soft in the first place since they are believed to have been laid down beneath a partially buoyant ice sheet.

These particular slopes are representative of the middle profiles in Figure 3 since they have long term safety factors of less than unity and short term safety factors greater than unity.

The time period of a failure cycle is very difficult to determine since toe erosion rates will vary with changes in water level. However, at the Iona site represented in Figure 10, the long term erosion rate is about one m/year and an average slide seems to involve a 20 m scallop in the shoreline. Therefore, one could predict a recurrent failure at 20 year intervals on the average.

Stepped shoreline profiles may be caused by a variety of stratigraphic controls and the interested reader is referred to Barton (1973) for a description of horizontal slips activated by talus loading.

Many other failure modes exist along the Lake Erie north shore and are currently receiving extensive study. Two of the most important are the high velocity, cyclic slides that occur east of Port Stanley and the sand piping failures east of Port Burwell. The former leave carpets of slide debris extending several hundred feet offshore of the slide area. The latter are characterized by high speed gully development in sands overlying clays and are currently being studied by Mr. A. J. Zeman of the Canada Centre for Inland Waters. Both types will no doubt be presented in detail in future publications.

Summary

The soil mechanics aspects of shoreline erosion have been described in general terms using examples from the literature and from current studies of till bluffs along the north shore of Lake Erie. The slopes have been categorized into three major types, as follows:

Type 1 - Abandoned or protected slopes in the process of flattening to their long term angle of repose.

Type 2 - Slopes of constant morphological shape or profile that retreat slowly in response to toe erosion, toppling, and sheet erosion by slaking and sloughing.

Type 3 - Bluff slopes of variable profile related to cyclic landsliding in response to both steepening by toe erosion and internal softening of the soils in response to changes in effective stress.

Detailed consideration of the mechanics of failure of the various morphological processes are beyond the scope of this paper but will be detailed in future publications.

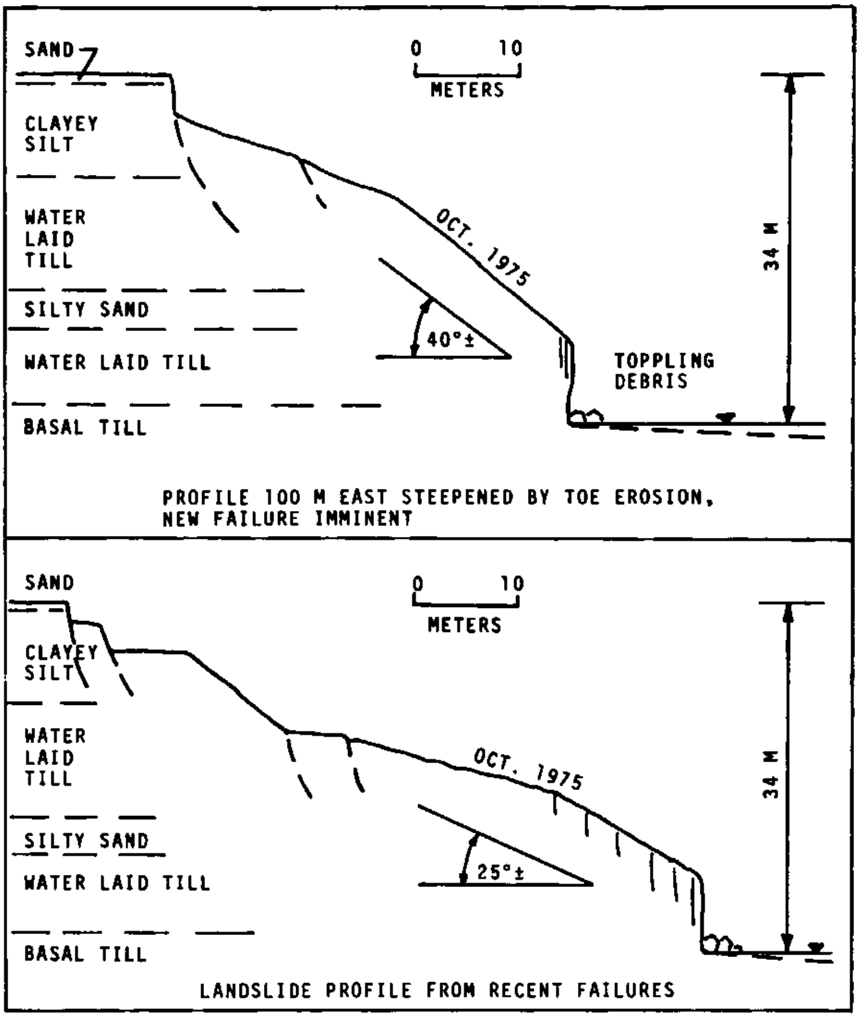

Figure 10
Companion profiles south of Iona, showing cyclic pattern of failure, steepening by toe erosion and new failure.

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