Shoreline Erosion and Landslides in the Great Lakes

Erosion et Stabilité des Berges des Grands Lacs

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SYNOPSIS Stability of coastal bluffs is examined in order to determine the mechanics of bluff recession and the long-term trends in the evolution of coastal slopes. Six active bluffs in two locations on the western shore of Lake Michigan are monitored for erosion-sliding processes in an integrated program of field and laboratory investigation and stability analysis. Landslides constitute only one part of the overall bluff recession process. The key factors in failure and retreat appear to be the wave action at the bluff toe and the degradation of the bluff face by solifluction and surface runoff. The effective stress analysis of slope stability provides a reliable method for predicting bluff recession in those bluffs where the rotational sliding is the main process of slope evolution. Two different models of slope evolution are established for the bluffs monitored. An understanding of the slope evolution is required for an evaluation of engineering and management solutions for the problems created by retreating coastal bluffs.

INTRODUCTION

Near record high water levels in the Great Lakes during the early 1970's contributed to accelerated erosion along the highly developed shoreline of Lake Michigan in eastern Wisconsin. Extensive sliding took place along the high bluffs that border the lake for much of this region, resulting in property damage, reduction in property values, and concern about the personal safety of residents living close to the edge of the bluffs. The study presented herein forms a pilot project with the purpose of gaining an understanding of the complex processes causing bluff retreat. The findings and the methods of this study will be used in a subsequent major project which will cover extensive segments of the Wisconsin shoreline and provide the data base for the evaluation of engineering and management alternatives in developing the state's coastal zone management policy.

The problem of coastal bluff recession presents certain unique traits with respect to its nature as well as the solutions involved. Consequently, it requires a novel approach and the modification of conventional procedures. The most significant aspect of coastal bluffs is that the slope geometry is not static; rather, it continually changes with time as a consequence of toe erosion and bluff face degradation. In the Great Lakes the water levels fluctuate continually and, consequently, the rate of toe erosion varies with time; however, it can be extremely rapid when the lake water levels are high. Therefore, the nature and rate of change in the geometry of the natural coastal slopes become of concern to the civil engineer unlike the usual situation where it is only of concern to the geomorphologist.

Solutions to the problems created by coastal slumping and shoreline retreat are also varied in nature and require an adjustment in the usual engineering approaches and attitudes. Engineering solutions in terms of protective structures against toe erosion and slope stabilization at a grand scale are neither economically feasible nor environmentally desirable. When the problem is considered at the state or regional level, it becomes apparent that solutions will probably fall into two major categories:
(a) engineering alternatives involving various corrective and preventative measures and
(b) management alternatives involving various forms of non-structural solutions. For an evaluation of engineering and management alternatives the engineer has to determine what stage of evolution the bluff is going through and establish realistic recession rates.

GEOLOGY AND LOCATION

Much of the shoreline of Lake Michigan in eastern Wisconsin is an area of high, steep bluffs developed in unconsolidated glacial deposits. Most of these deposits are fine-grained sediments containing high percentages of clay. In many areas the bluffs contain both glacial tills and glacio-lacustrine deposits. The glacial tills contain varying amounts of coarse material but consist mainly of reworked reddish brown lacustrine silts and clays. The glacio-lacustrine deposits contain little or no coarse material and commonly are stratified. Scattered lenses of sand and gravel may also be found in these bluffs. The two sites of the investigation are located in this geological setting on the western shore of Lake Michigan near the cities of Kewaunee and Port Washington.

FIELD INVESTIGATION

On the basis of an extensive ground survey and photoreconnaissance of a substantial portion of Wisconsin shoreline of Lake Michigan, and the reports of individuals, the two sites near Kewaunee and Port Washington were selected. Intensive observation of the erosional processes was conducted over a period of three years covering 200 to 300 meter segments of the shoreline. Three control stations were established in each of the sites and designated as A, B and C.

Subsequent to the site selection, the following work was undertaken:

1. Ground photographic record of bluff face and beach was established at various time intervals for qualitative assessment of the erosion-slumping processes.

2. Shore-vertical bluff profiles from waterline to bluff top were measured. This information on bluff geometry is used for slope stability analysis and for quantitative determination of changes in bluff morphology.

3. Surface samples were collected from various strata exposed on bluff face for a preliminary classification of earth materials and determination of site geology.

4. Boring operations on top of bluffs were performed. From the bore holes, relatively undisturbed soil samples were obtained for the determination of shear strength of the materials involved.

5. Piezometers were installed in the bore holes in appropriate layers to monitor the ground water.

6. Metal stakes 60 cm in length were driven normal to the bluff faces at regular intervals with initial penetration of 30 cm. Their relative movement and depth of penetration were monitored at appropriate time intervals in order to establish the contribution of weathering and slope face degradation in modifying slope geometry.

The last stage of the field work involved monitoring of the bluffs and piezometers at appropriate time intervals.

LABORATORY INVESTIGATION

Engineering index tests (grain size analysis and Atterberg limits) were performed on all samples for the classification of earth materials. The comparison of boring and bluff face samples indicated that the surface samples provide a reasonably accurate account of bluff stratigraphy in these generally active and steep slopes. The only exception to this is when extensive sheet flow of softened material on bluff faces due to weathering and disintegration occurs. The stratigraphy of the six control bluffs is indicated on the slope profiles given in Figure 1 and the corresponding index properties and strength parameters are listed in Table I. The liquid limit had an average value of 32% (range: 20-42%) and the average plasticity index was 11% (range: 2-18%) for 36 samples tested. The drained strength parameters of the cohesive soils (c' and ϕ') were established from consolidated undrained triaxial tests with pore pressure measurements on undisturbed samples.

A study on soils of similar geological origin utilizing both drained direct shear and consolidated undrained triaxial tests with pore pressure measurements indicated close agreement of data from both tests (Edil, 1974). The same work also indicated that there was not a significant reduction in strength at large strains and these materials generally exhibited isotropy with respect to the strength response. The drained angle of internal friction for these glacial soils is quite consistent and varies between 30° and 35°; the associated drained cohesion intercept values are generally low (less than 20 kN/m^2). These values compare well with other data on soils of similar origin (Edil, 1974; Edil, 1975). The undrained strength characteristics for the same soils were determined from a consideration of the results of unconfined compression tests performed on undisturbed samples at natural water contents and of the field test data. The values of the undrained shear strength, s_u are also given in Table I and they reflect the in-situ variations in strength. The strength parameters for cohesionless soils were determined from the laboratory direct shear tests at field densities estimated from a knowledge of the standard penetration numbers and overburden pressures.

STABILITY ANALYSIS

The stability of natural slopes is usually considered as a long-term problem. The coastal bluffs considered herein are not maintaining a constant geometry with time, and they are in constant evolution due to the combined effects of toe erosion and slope face degradation. Toe erosion in general tends to decrease the stability, whereas slope face flattening may tend either to increase or to decrease it, depending on the slope geometry.

Comparison of Drained and Undrained Failure

The stress path technique can be used to determine the critical mode of failure in a qualitative manner (D'Appolonia, Alperstein and D'Appolonia, 1967). Consider a soil

TABLE I. Soil Properties

Soil Designation	Soil Description	Group Symbol*	w_L	I_p	ϕ'	c' (kN/m^2)	s_u (kN/m^2)	γ** (kN/m^3)
A	Fine sand with gravel	SW			29°	0	0	17.3
B	Brown clayey silt	ML	20	2	35°	8	40	20.3
C	Brown silty clay	CL	30	9	31°	20	95-130	20.7
D	Fine sand	SP			30°	0	0	17.3
E	Brown silty clay	CL	34	14	33°	20	90-265	21.2
F	Fine sand	SW			32°	0	0	18.8
G	Gray clayey silt	ML	36	3	35°	8	95	20.3
H	Silty sand	SM			30°	0	0	17.3
I	Reddish brown clayey silt	ML	19	10	32°	10	25	22.5

* According to the Unified Soil Classification ** Bulk Unit Weight

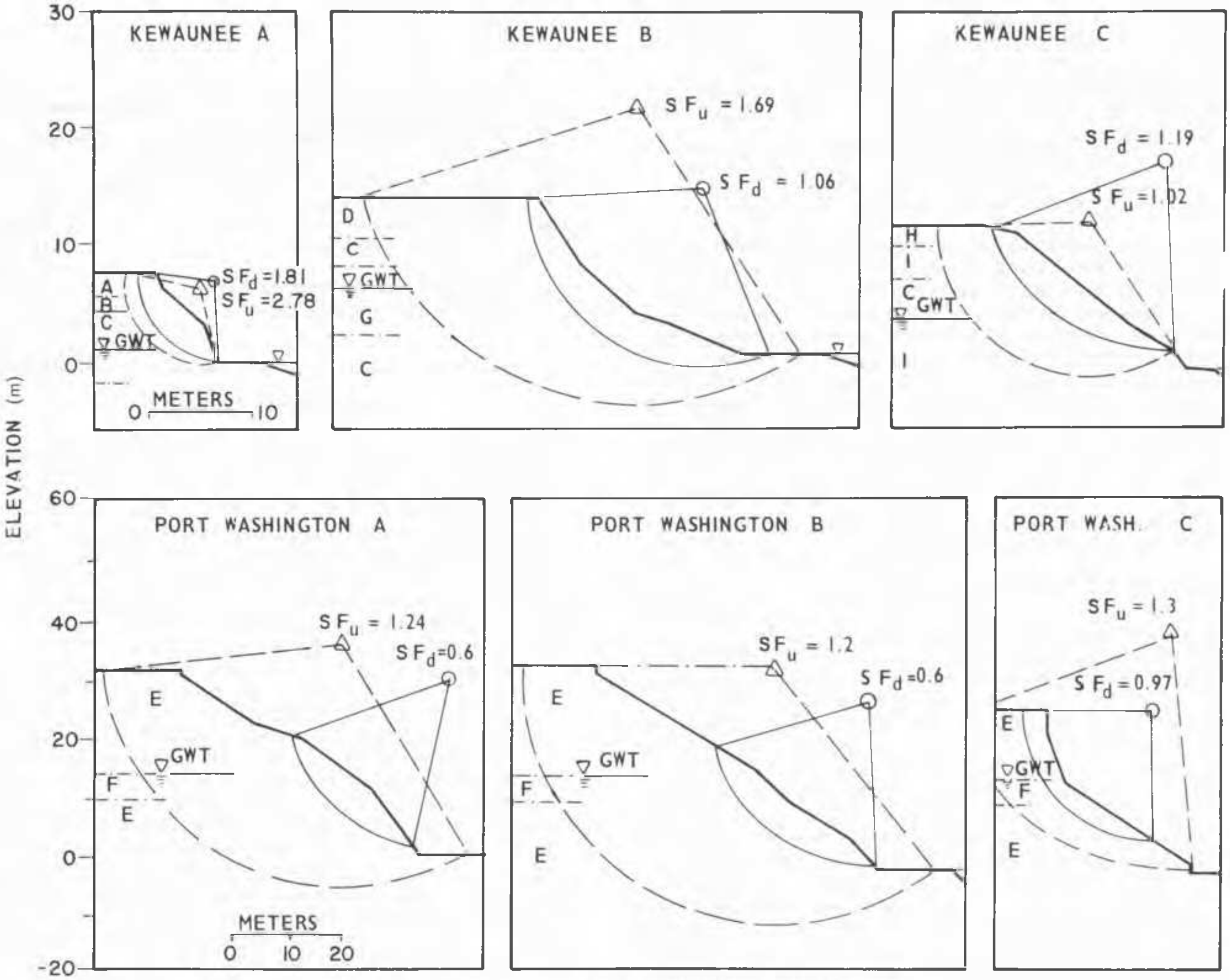

Figure 1. Geology and Stability Conditions

element near the toe of the slope. Toe erosion will cause a decrease in total lateral stress which will decrease the average principal total stress and increase the shear stress on the soil element. If the erosion takes place rapidly, the pore pressure decreases during this rapid unloading. However, subsequent to the erosion, the soil will begin to swell, and the pore pressures will begin to increase to the initial values determined by natural ground water conditions. Thus the effective stresses and the strength of the soil will decrease with time. This situation becomes much more critical in the case of overconsolidated clays because of the relatively low values of Skempton's A parameter for such soils. For the stiff clays encountered in the bluffs considered, the values of A at failure varied mostly between -0.15 and 0.60. Therefore, the stability should be evaluated in terms of effective stresses and assuming drained conditions. If this safety factor is maintained greater than unity during the erosion and afterwards, the slope cannot fail.

Initial Stability of Bluffs

Stability analyses herein were made using the ICES-LEASE computer program (Bailey and Christian, 1969) based on the modified Bishop method (Bishop, 1955). The long-term stability of the six control bluffs is analyzed using the drained strength parameters and the measured pore pressures and the resulting safety factor is designated as SF_d. The stability using total stresses and the undrained strength parameters is also determined and the resulting safety factor is designated SF_u. These safety factors and the corresponding slip circles are determined for the 1974 profiles of the control bluffs as established at the initiation of this investigation and the results are presented in Figure 1. The effective stress analysis resulted in lower safety factors in comparison to the total stress analysis in general. The only exception to this was the case of Kewaunee C where a very soft soil (designated I) with a Skempton's parameter A equal to 0.9 was present. The Kewaunee bluffs were generally safer than the Port Washington slopes where the SF_d values were found to be less than unity.

SLOPE DEVELOPMENT

Interpreting the development of natural slopes through time is a problem in soil mechanics and geomorphology, complicated by the need to determine the nature of the change in slope form, the rate of change, and the variety of form introduced by the influence of processes, stratigraphy, soil type, climate, and vegetation (Brundsen and Kesel, 1973). Because of the long time usually needed for slope development, slope studies are based on theoretical models of evolution, the use of scale models or repetitive measurements of rapidly evolving slopes. The change in the forms of the control slopes considered herein is taking place at varying rates but generally all very rapidly. The method of repetitive measurements and the interpretation of changes by superposed analysis is the approach adopted in this study.

Bluff Zones and Processes

In order to achieve an understanding of slope evolution, one needs to consider the slope processes. In this discussion, the bluffs are divided in three zones as depicted in Figure 2: (a) the toe zone reaching up to about one third of the total height; (b) the intermediate zone; and (c) the top zone extending down at a steep angle and usually less than one third of the total height. The various processes which modify these zones are also indicated on Figure 2. Two processes can be identified as the most important factors in initiating various forms of mass movement: (a) toe erosion due to wave action and (b) face degradation mainly due to solifluction and spring waters. These two processes are responsible for triggering rotational landslides and/or translational slab studies.

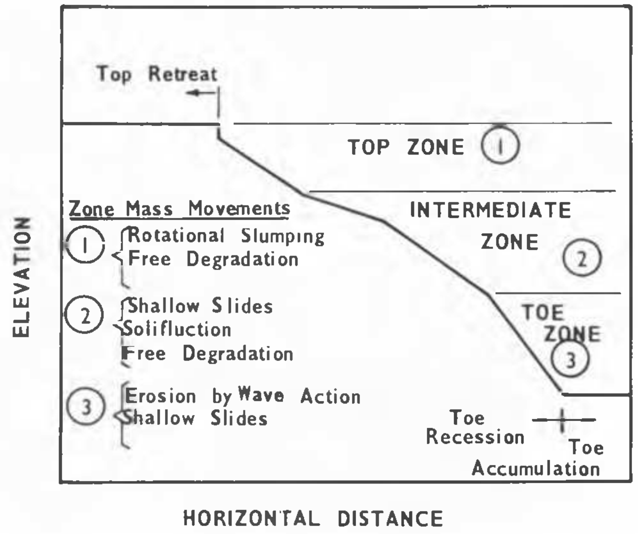

Figure 2. Bluff Zones and Mass Movements

Toe Movements

The toe movements of the six control bluffs are determined using the profiles measured at different times and presented in Figure 3 in terms of accumulations and recessions as a function of time. Accumulation results from the deposition of material due to slumping and solifluction; recession is primarily due to removal by wave action. In Kewaunee B and C, the major process is solifluction which is the sheet flow of softened material on bluff face subsequent to frost action and this is reflected in the toe movements. In spring months of 1975, ice melting resulted in flow of material parallel to the bluff face and accumulation at the toe. During the summer and fall months of 1975, the material starts to retreat due to the relative change in the magnitudes of solifluction and toe erosion rates. In winter months no appreciable change takes place due to the protective ice formed on the beach zone. Kewaunee B and C are subject to extensive solifluction because the materials in the lower half of the bluffs consist of clayey silts. In Kewaunee A, the early recession of the toe was interrupted recently by the mud flows on this steep bluff due to the spring waters drained out by the top sand layer.

Port Washington A and B are subject to steady toe erosion with the exception of winter months when protective ice forms on the beach. The average rate of toe recession is in excess of 2 meters per year. Port Washington C is in a more advanced stage of its evolution, two massive rotational slides took place during the one and a half year period of observation, resulting in net accumulation of material at the toe. The removal of material certainly takes place, however, at a slower rate than it is supplied by the slides in the top zone.

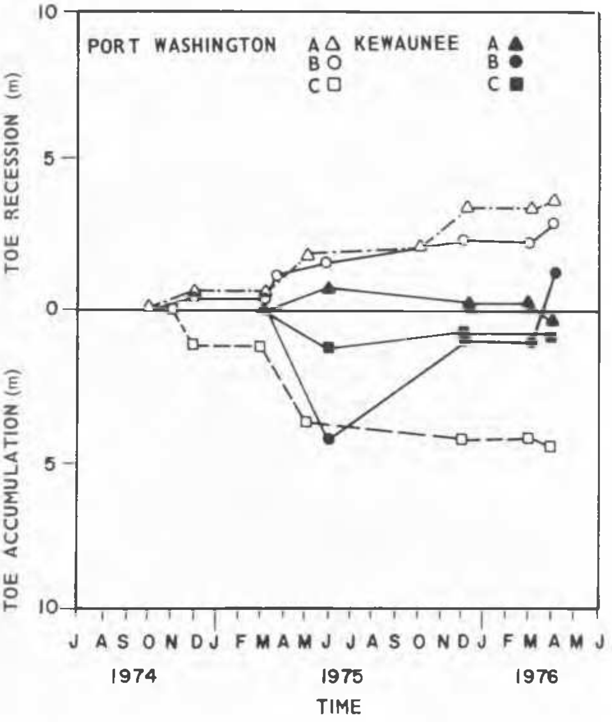

Figure 3. Toe Movements with Time

Top Recession

During the period of observation only Port Washington C exhibited significant top recession. The other bluffs are presently going through changes in their intermediate and toe zones with little or no recession at the top zone. The slope profiles of Port Washington C, as measured at different times, are presented in Figure 4. The November, 1974 profile was first modified at lower slope by local slumping due to toe erosion in early spring (March, 1975). The loss of support at the lower slope and spring rainfall caused a massive slide by May, 1975 with a retreat of bluff top about 2.5 meters. This profile was maintained throughout the winter months and early March, 1976 during a spring thaw, a second slide was activated taking another 6 meters off the bluff top. The active sliding removed close to 10 meters of property in a period of approximately 12 months from the city park located on top of the bluff and encroached on a road requiring its relocation. The top zone of the bluff maintained a steep, near 65°, slope throughout all stages of sliding, whereas the lower portion of the slope accumulated the sliding mass at an angle of repose roughly equal to 30° to 35°

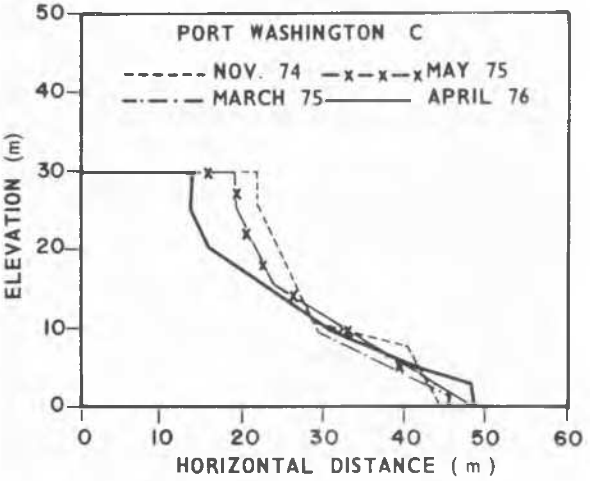

Figure 4. Bluff Top Recession

The progress of slope retreat was predicted based on the effective stress stability analyses performed on each successive profile using the drained strength parameters and measured pore pressures. These analyses indicate successfully both the possibility of coming failures and the general location of the slip surfaces. The calculated and measured values of the top retreat are compared in Figure 5.

Pattern of Failure

The three control bluffs in Port Washington are closely located and have similar heights and soil conditions. However, Bluff C is extremely active with slides in the top zone whereas A and B are relatively inactive. Bluff C is at a more advanced stage of its evolution with respect to A and B. In Figure 6 the original profile of bluff A is subjected to successive failures using the ICES-LEASE computer stability program each time using the new profile resulting from the previous failure. Five successive failures, involving initially lower zones and gradually progressing upwards, result in a profile which closely approximates the initial profile of C as measured in 1974. Therefore, it is expected that bluffs A and B will go through the suggested evolutionary stages and reach the stage of C and finally follow the evolution observed in C in 1975 and 1976. This postulate is valid, certainly, if the present lake levels persist and the removal of sliding material at the toe continues in the same manner. Any deviation from this would tend to interrupt the evolutionary process. The reason that Bluff C is in a more advanced evolutionary stage is possibly due to the differences in toe erosion rates. Even though a net accumulation is indicated in Figure 3 for C, and net recessions for A

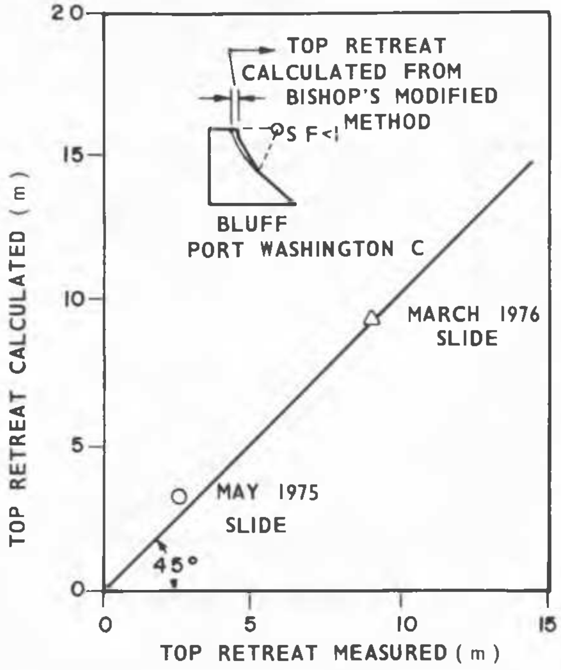

Figure 5. Predicted and Measured Top Retreats in Slides

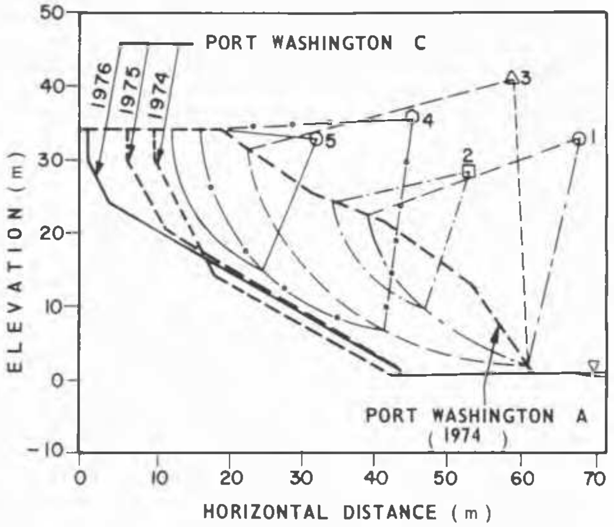

Figure 6. Pattern of Failure and Slope Evolution

and B, the actual shore process is probably more active in C due to a recent lake shore fill constructed next to Bluff C with a strong riprap erosion protection. This causes a disturbance in the otherwise smooth shore segment with increased turbulence and erosional activity right at the toe of Bluff C. The higher toe recession rates may be overshadowed by the accumulation of slided material.

SLOPE EVOLUTION MODELS

On the basis of the field observations and the analyses presented herein, it is possible to propose the modes of slope evolution in Kewaunee and Port Washington bluffs. The bluffs in each of these sites are following somewhat different patterns. In the moderately high bluffs of the Kewaunee site, solifluction and mud flows in terms of translational slab slides parallel to the bluff face are operative with resultant parallel or non-parallel retreats as depicted in Figure 7 schematically. In Port Washington's relatively high bluffs, rotational slides working their way from the toe up to the bluff top are prevalent in the first phase. The first phase changes a convex bluff profile to a concave one with a steep top and flatter lower portion (composite slope).

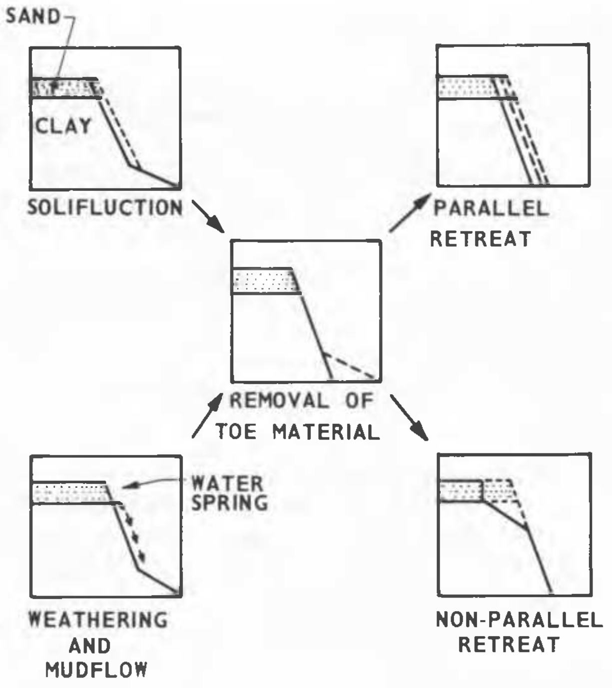

Figure 7. Slope Evolution Model for Kewaunee Bluffs

A bluff which reaches the end of the first phase begins to retreat in the top zone in terms of rotational slides as depicted in Figure 8. This second phase terminates with a uniform slope when an equilibrium is established with the removal of toe materials. At the present time, it is not possible to establish the long-term rates at which these evolutionary processes are taking place because of the short duration of the field investigation and the insufficient time-interval aerial photographic data.

CONCLUSIONS

On the basis of the analysis presented, the following conclusions and observations can be made:

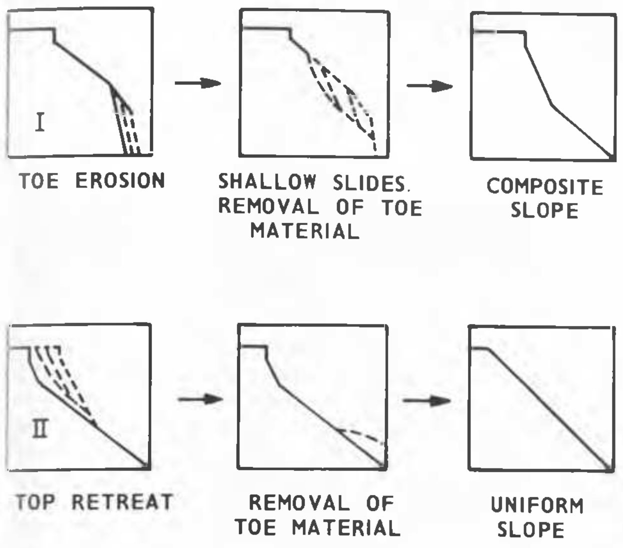

Figure 8. Slope Evolution Model for Port Washington Bluffs

1. The safety factor of the coastal bluffs against sliding varies with time. Since the slope geometry is not constant but is rapidly changing, the primary question becomes one of predicting the nature and rate of this change.

2. The short-term changes can be best studied by periodic profiling and interpreted by an understanding of the processes involved. The long-term trends require the interpretation of recession rates as obtained from a photogrammetric study of air photos taken over longer intervals of time.

3. The most important processes in initiating changes in slope geometry are toe erosion by wave action and physical degradation on the bluff face. These processes, in turn, trigger rotational slides, solifluction and mud flows which modify the slope geometry greatly and eventually cause the retreat of the bluff top.

4. By studying the profiles of bluffs, the net toe erosion and top retreat can be determined. However, by itself neither of these is sufficient to understand and interpret the slope evolution and its rate.

5. By analyzing the stability of natural bluffs and in determing the shape of the sliding surface, the effective stress analysis using the modified Bishop method and the drained strength parameters and measured pore pressures, provides a viable and realistic procedure. The bluff top recession, predicted on the basis of this procedure and the measured values in the field compared well.

6. It is observed that two different evolutionary processes are taking place in the bluffs of the two sites studied, one involving rotational and the other translational slides. Deep-seated rotational slips involving the complete bluff are not present. It is possible that variations of these processes are operative at other sites along the shoreline. Therefore, a method of classification with respect to slope evolution could be desirable.

7. Unless the processes which cause the slope evolution are known, it is not possible to design the proper corrective measures, i.e., protection against toe erosion or mass failure.

ACKNOWLEDGEMENTS

This project was funded by the National Oceanic and Atmospheric Administration's Office of Sea Grant, U.S. Department of Commerce through an institutional grant to the University of Wisconsin. The cooperation of the Wisconsin Division of Highways and the Wisconsin Geological and Natural History Survey in furnishing the samples is acknowledged. Special recognition is given to Mr. Norman H. Severson for his invaluable assistance throughout the project.

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