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THE EFFECT OF LAKE-LEVEL FLUCTUATIONS ON THE GEOMORPHIC EVOLUTION OF THE LAKE MICHIGAN BLUFFS IN WISCONSIN

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ABSTRACT

The purpose of this paper is to describe the effect of lake level fluctuations on the geomorphic evolution of coastal bluffs on the Lake Michigan shore in Wisconsin. Recent field stuies of morphologic features along approximately 100 km of bluff revealed six major kinds of bluffs. Twelve bluff profiles were measured two to three times per year in the field between 1974 and 1980, and additional bluff profiles were estimated at various times from 1937 to the present using air photographs.

The results from the short-term field measurements indicate that bluffs composed primarily of cohesionless sediment recede in parallel fashion. Bluff profile shape remains fairly constant as the rates of bluff toe and bluff edge erosion are nearly equal. The magnitude of failures on these bluffs is relatively small. On cohesive bluffs where adequate protection against severe toe erosion is present (wide beach, shallow nearshore water depths), parallel recession also occurs. In cases where cohesive bluffs are not well protected from intense toe erosion, the bluff toe and bluff edge erode at significantly different rates (non-parallel recession), and recession is caused by much larger failures. Lake level changes cannot be directly correlated with changes in bluff profile shape.

Evaluation of bluff change since 1937 indicates that the bluffs that show parallel recession over a short time period steepen and become more gentle in response to rising and falling lake levels. Also, bluff profile changes on these bluffs are relatively synchronous from profile to profile and failures tend to be small scale. Longer-term changes on those bluffs that show non-parallel recession over a short time period (cohesive bluffs, intense toe erosion), however, are not synchronous from profile to profile and cannot be correlated to lake level changes. Geomorphic change is caused by episodic large scale failures.

INTRODUCTION

As a coastal bluff erodes, its morphology also changes. The geomorphic changes taking place on a bluff are a result of a combination of passive and active factors in the environment. Passive factors are those inherent in the geologic medium; bluff stratigraphy, the engineering properties of bluff deposits, and bluff height. Active factors include things such as wave erosion, groundwater, wind erosion, and processes associated directly with precipitation (rainsplash, sheetwash). Temporal and spatial differences in these factors result in differences in failure mechanism, thus differences in bluff evolution.

Over the long term, wave action is the major factor causing changes in bluff form. Water level ultimately controls the intensity of wave erosion. The effect of water level and wave erosion on bluff morphology can be increased or decreased by various factors such as shoreline orientation, offshore bathymetry, and beach width. Thus, although water level along a particular coast is the same everywhere at one time, it can have different effects at different locations due to variability of the above factors.

The purpose of this study was to determine the effect of short and long-term lake-level changes on the geomorphic evolution of the coastal bluffs on the Lake Michigan shore in Wisconsin. Lake Michigan is an interesting area for study because lake levels are not controlled, lake levels have been measured since 1860, and have fluctuated almost 2 m during this time, and bluff stratigraphy and bluff height are quite variable along the shoreline.

METHODS OF ANALYSIS

Present-Day Bluff Morphology

Definition of the present-day bluff morphology provides a starting point from which recent geomorphic change can be evaluated. Morphological features of bluffs were examined along 100 km of bluff along Wisconsin's Lake Michigan shoreline (fig. 1). This investigation revealed the six major kinds of bluffs summarized in table 1. The aerial extent of these groups is shown in figure 1.

Recent Changes in Morphology

Once the variability in the present-day bluffs was established, it became possible to try to evaluate the effect of fluctuating lake levels on bluff evolution. Bluff changes have been documented over a 3- to 6-year period (considered short-term fluctuations) at four locations shown on figure 1. A total of 12 bluff profiles were measured 2 or 3 times a year at the four locations between 1974 and 1980.

Documenting changes in bluff morphology over a longer time is more difficult because no field measurements were possible. Selected profiles measured in the field were located on a series of air photographs dating back to 1937. The angle of the bluff could be estimated because bluff height was known and the horizontal distance from the bluff edge to the beach could be measured. By detecting changes in the tone of the photograph, it was also possible to determine the relative shape of the profile (that is, convex or concave, or combination). These photos were periodically viewed in stereo as a check for determining bluff shape. An average bluff top recession rate for a particular bluff reach was taken from Mickelson and others, 1977 and approximate bluff profile changes through time were then reconstructed. A more complete description of the method is provided by Peters (1982).

Lake-Level Fluctuations

Changes in bluff morphology have been evaluated with respect to historic water-level fluctuations in Lake Michigan (fig. 2). Note that the earliest air photographs available are from 1937, a time of relatively low water level. Since that time Lake Michigan has gone through two major high-water periods (the early 1950s and the 1970s and a major low-water interval in the late 1950s and early 1060s.

DOCUMENTED CHANGES IN BLUFF MORPHOLOGY

Evaluation of Profile Measurements

Bluff recession data for 9 out of the 12 profiles measured since 1974 are summarized in table 2. Three profiles at Notre Dame were not included because there was no change in morphology over the monitoring period. The Notre Dame site is within bluff group D, whose morphology is dominated by deep-seated rotational failures. Bluffs in this group are largely vegetated, suggesting that the slumps are very old. The geomorphic evolution of bluffs in group D will not be discussed further in this paper, because there appear to be no significant changes in these bluffs since 1937.

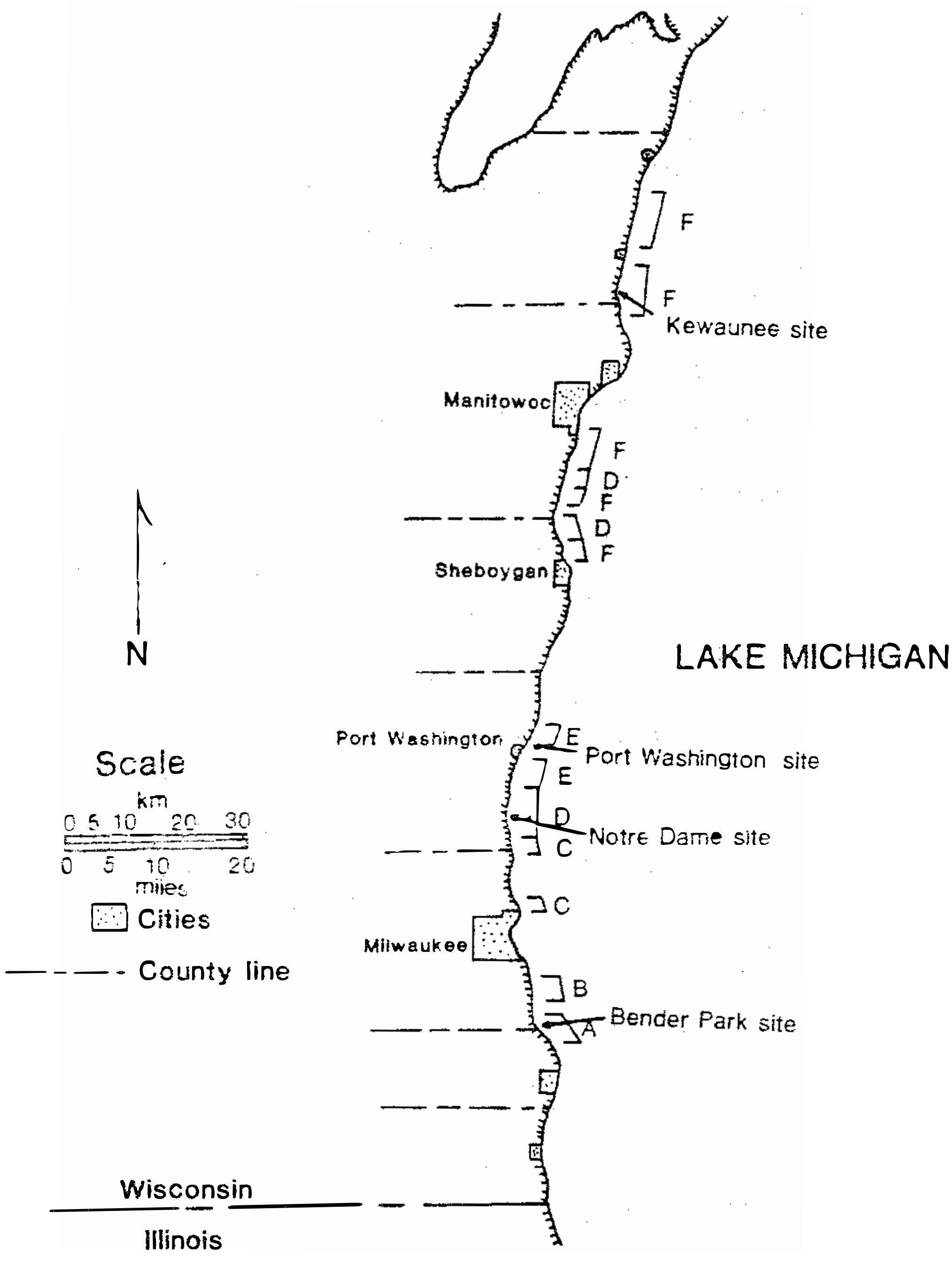

FIGURE 1.--Map of study area showing locations of bluff groups (A-F) and profile monitoring sites.

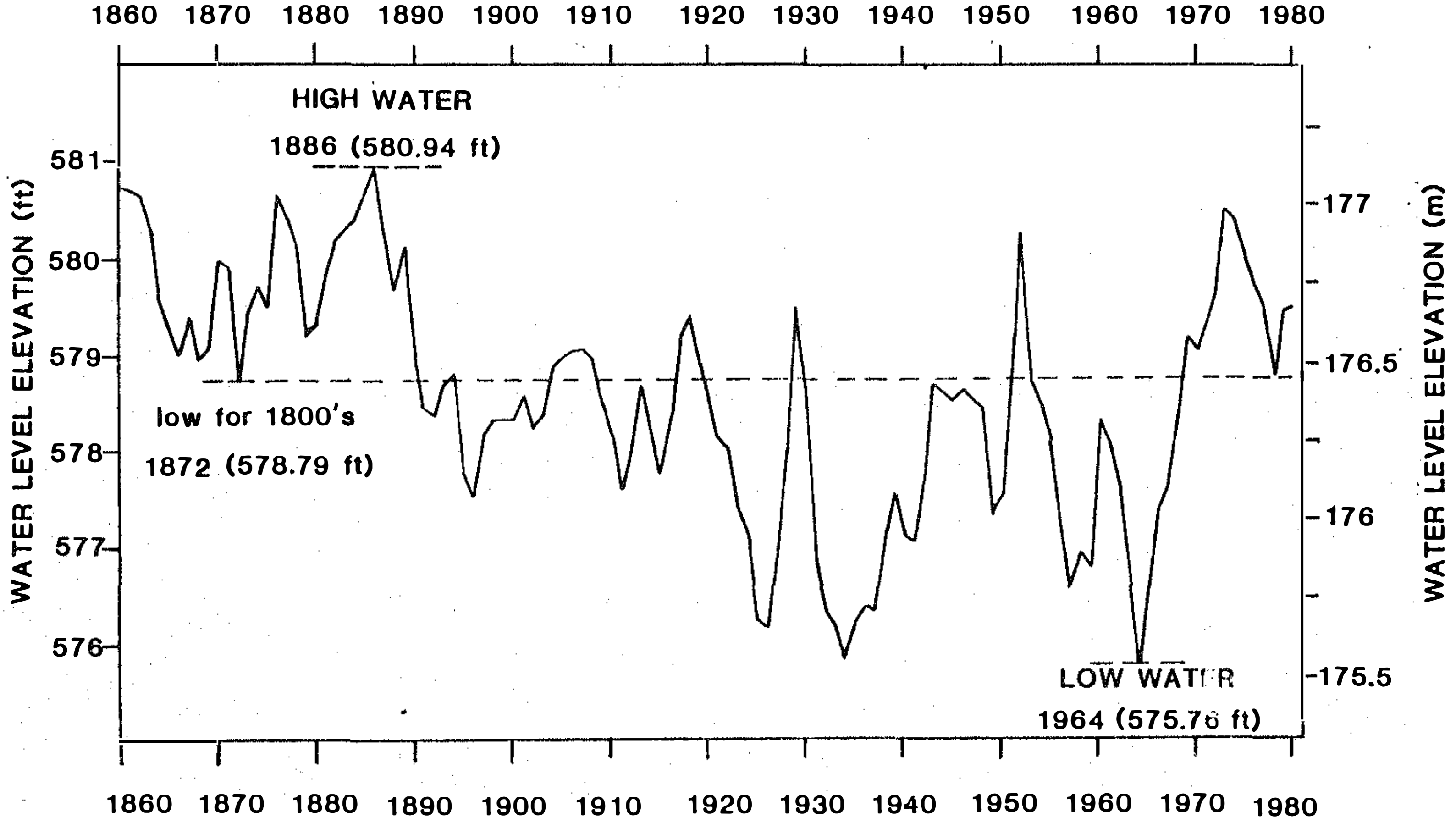

FIGURE 2.--Lake Michigan water levels, 1860-1980. (Source: U.S. Department of Commerce).

Group	Bluff Height	Bluff Angle	Nature of Bluff Face (plan view)	Bluff Profile Shape (x-section)	Other Comments
A	Medium to very high (14 to 37 m)	Generally steep (greater than 35°) except where protected	Variable; often highly scalloped top; sharp, well defined ridges.	Highly variable; ridges between gullies are commonly strongly convex with very steep lower bluff, but concave or straight bluff profiles common in gullies; compound (convex and concave) slopes where large slumps are present.	Till or glaciolacustrine units top and bottom with sand layer in middle; bluffs are subject to intense wave erosion and are unstable.
B	High (21 to 27 m)	Very steep (generally greater than 40°)	Mostly low relief, especially in upper bluff; some gullies in lower bluff.	Mostly straight or concave.	Cohesionless (sand and silt) material at top, cohesive (till or glaciolacustrine) sediment at bottom.
C	High to very high (24 to 37 m)	Moderate (30 to 35°)	Broad scallops, low relief.	Gently convex or straight.	Till or glaciolacustrine sediment throughout except for sand lens in middle; bluff not subject to intense wave erosion.
D	Very high in Ozaukee Co. (30 to 40 m), medium in Sheboygan Co. (12 to 18 m).	Low (about 25°)	Variable but generally low relief because slopes are mostly grassed or wooded due to old deep seated slumps now stabilized.	Compound, generally "stair-step" profile shapes	Till or glaciolacustrine sediment top and bottom with sand layer in middle; morphology dominated by deep seated slumps.
E	Medium to very high (18 to 37 m) lower to the north.	Moderate to steep (30 to 45°).	Broad scallops.	Generally straight or slightly convex.	Stratigraphy same as group D; toe erosion is intermediate between groups A and C.
F	Low to medium (6 to 20 m).	Very steep (greater than 40°).	Mostly low relief, but some scalloping in higher bluffs where cohesive sediment is present.	Mostly straight or concave, some convex where cohesive units are present.	Mostly cohesionless sediment to the south; more cohesive sediment to the north.

TABLE 1.--Summary of characteristics of bluff groups discussed in text.

TABLE 2.--Results of short-term bluff recession measurements.

Profile	Bluff Ht. m	Years Monitored	Recession (m)		Average Recession Rate (m/yr)	
			Top	Bottom	Top	Bottom
Bender Park 1	36	3.3	-1.8	-9.3	-0.6	-2.9
Bender Park 3	32	3.1(toe) 3.5(top)	-16.8	+1.5	-4.8	+0.5
Notre Dame 1	36	2.8	-3.0	-4.9	-1.1	-1.7
Port Wash. 1	27	5.7	-15.8	+2.8	-2.8	+0.5
Port Wash. 2	30	2.9	-3.3	-0.6	-1.2	-0.2
Port Wash. 3	31	2.7	0	-1.2	0	-0.5
Kewaunee 1	7	5.3	-2.6	-1.4	-0.5	-0.3
Kewaunee 2	14	5.8	-2.0	-2.4	-0.3	-0.4
Kewaunee 3	10	2.8	-0.5	-2.2	-0.2	-0.8

The results from the remainder of the profile measurements suggest two principal modes of bluff evolution. The first, which has been termed non-parallel recession (Vallejo, 1977), is defined as having bluff-edge and bluff-tow recession rates that are significantly different. This type of bluff recession occurs on bluffs composed primarily of cohesive sediment that undergo intense wave erosion. The best examples of this type of retreat are the Bender Park 3 and Port Washington 1 profiles. Bluff profile changes at Port Washington 1 are illustrated in figure 3. The bluff edge appears to be adjusting to bluff steepening that occurred prior to the first (1974) measurement (in 1974). Over the 6-year period the bluff toe actually shows a net accretion of material.

The second type of recession which has been called parallel recession (Vallejo, 1977), is defined as having bluff toe and bluff edge recession at about the same rate. This type of recession appears to be characteristic of bluffs composed primarily of cohesionless materials (sand or gravel). The Kewaunee bluffs, best illustrated by profile Kewaunee 2 (fig. 4) show parallel recession. In this case, bluff profile shape remains relatively constant and rapidly adjusts to wave erosion. Parallel recession is also suggested by the Port Washington 2 profile (fig. 5), although it is a cohesive bluff and is close to Port Washington 1. However, the intensity of wave erosion at the bluff toe of Port Washington 2 is much less than that of Port Washington 1 because a seawall adjacent to profile 1 has caused waves to refract directly toward the base of that profile.

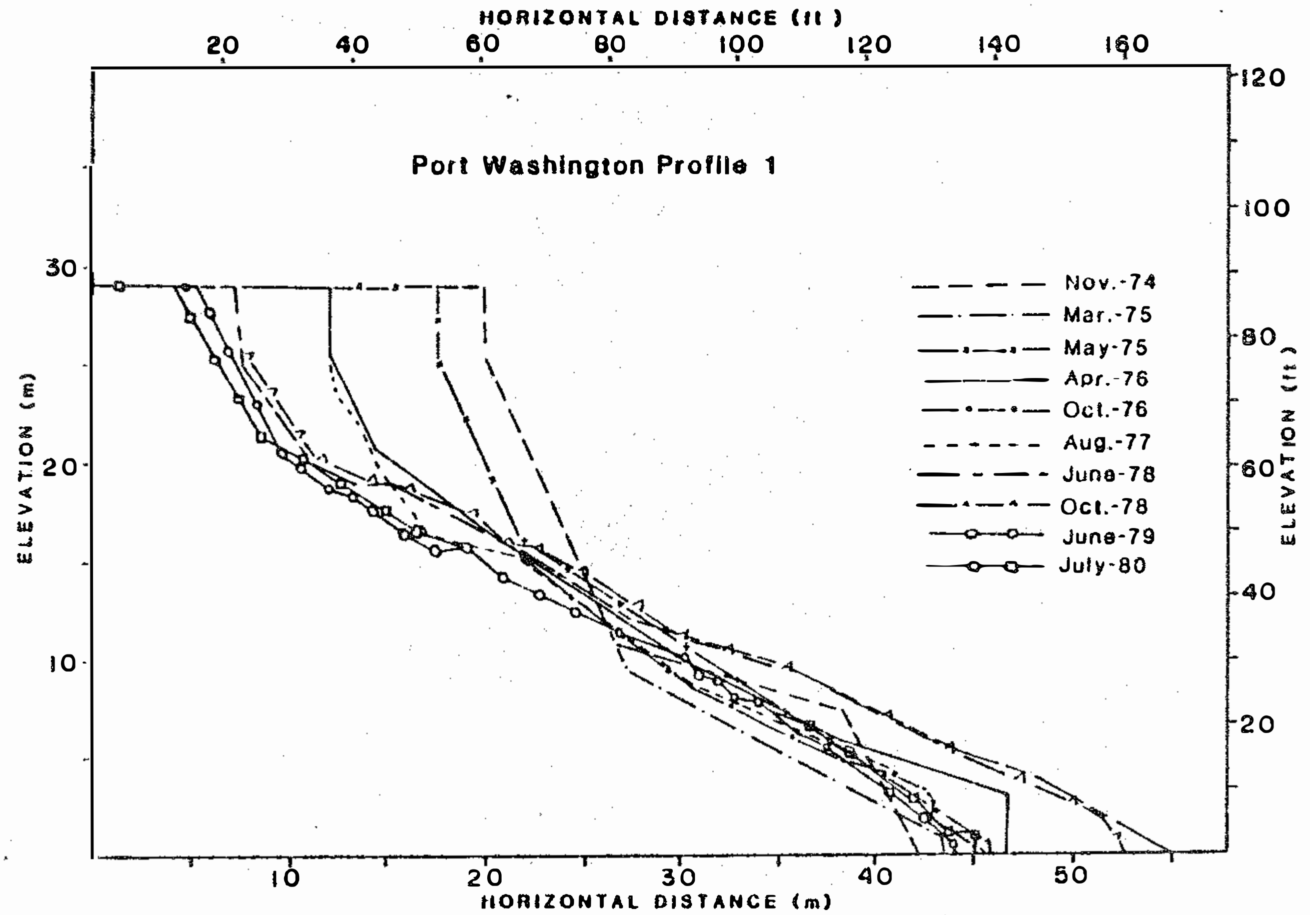

FIGURE 3.--Port Washington Profile 1, bluff profile changes, 1974 to 1980.

This difference in the behavior of nearby profiles is primarily the result of differences in beach width and offshore bathymetry, and therefore the amount of wave erosion taking place at the base of the bluff. Our measurements of bluffs between 1974 and 1980 show no direct correlation with lake-level changes. This lack of correlation is because a certain rise in water level has different effects in different places. At locations where the beach is narrow, a small rise in water level may lead to erosion of the bluff toe. The same increase in water level might have no effect at another place. Therefore, I will use the term "high effective lake level" to mean a lake level at which toe erosion is potentially taking place and "low effective lake level" to mean lake level low enough that the erosion is limited, even during storms.

Evaluation of Geomorphic Changes Since 1937

The results of the long-term analysis indicate that the geomorphic changes on the Lake Michigan bluffs depend on a combination of stratigraphy and effective lake level. Three combinations of these two factors are most common.

(1) Cohesionless sediment alternating, high and low effective lake level.

(2) Cohesive sediment alternating, high and low effective lake level.

(3) Cohesive sediment continually high, effective lake level.

The first of these is illustrated by most of bluff groups B and F (table 1). Changes in bluff angle on these

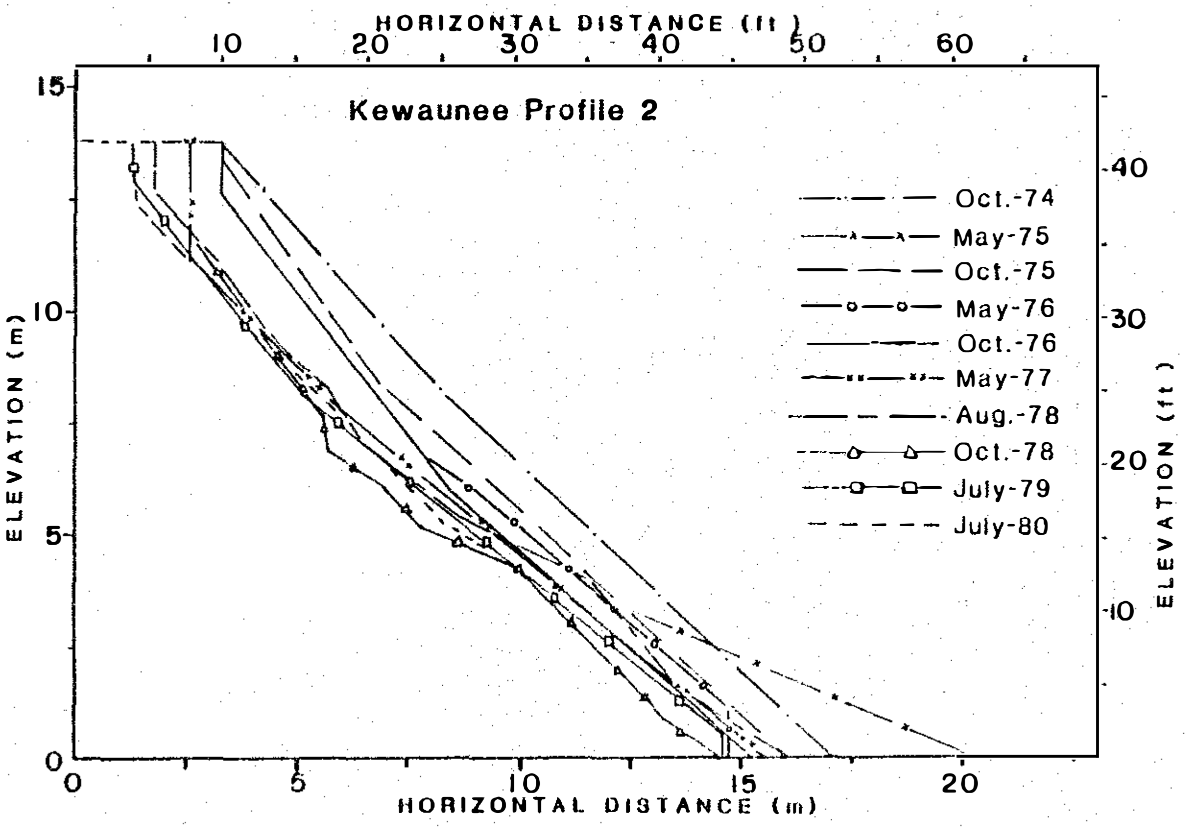

FIGURE 4.--Kewaunee Profile 2, bluff profile changes, 1974 to 1980.

bluffs can generally be correlated directly to changes in lake level. Figure 6 is a graph of bluff angle through time for group F, the symbols representing individual profiles within the group. A comparison of these changes to lake-level fluctuations over the same period (fig. 2) indicates that bluff angles were steepest during periods of high water and were lower during periods of low water. Unfortunately, no air photographs of these bluffs in the early 1950s were available. However, results from the late 1950s suggest a declining trend in bluff angle from the 1950s into the 1960s. It appears that regardless of the intensity of wave erosion at present or in the past, changes in bluff morphology are relatively synchronous from profile to profile. Differences in bluff angle between measuring points are not large, suggesting that small-scale failures (small slides and slumps, solifluction, sheetwash) are the principal means by which geomorphic change occurs. No large-scale mass movements are evident.

The second of these combinations of factors, cohesive sediment and alternating high and low effective lake levels, is illustrated by bluff group C and most of bluff group E. Bluff angle changes through time on bluff group C are shown in figure 7. Like the previous case, bluff angle changes are relatively synchronous from profile to profile, and bluff angle appears to have steepened and declined as lake level rose and fell.

The third case, that of high effective lake level and cohesive sediment, is represented by most of bluff group A, which includes the Bender Park bluffs, and the bluff at the Port Washington 1 profile, which is in group E. Bluff angle changes through time on some of the bluffs of group A are shown in figure 8. No clear correlation between lake level and bluff angle can be established here, in contrast to the previous two cases. In fact, some of the higher bluff angles occur during periods of low water, and vice versa.

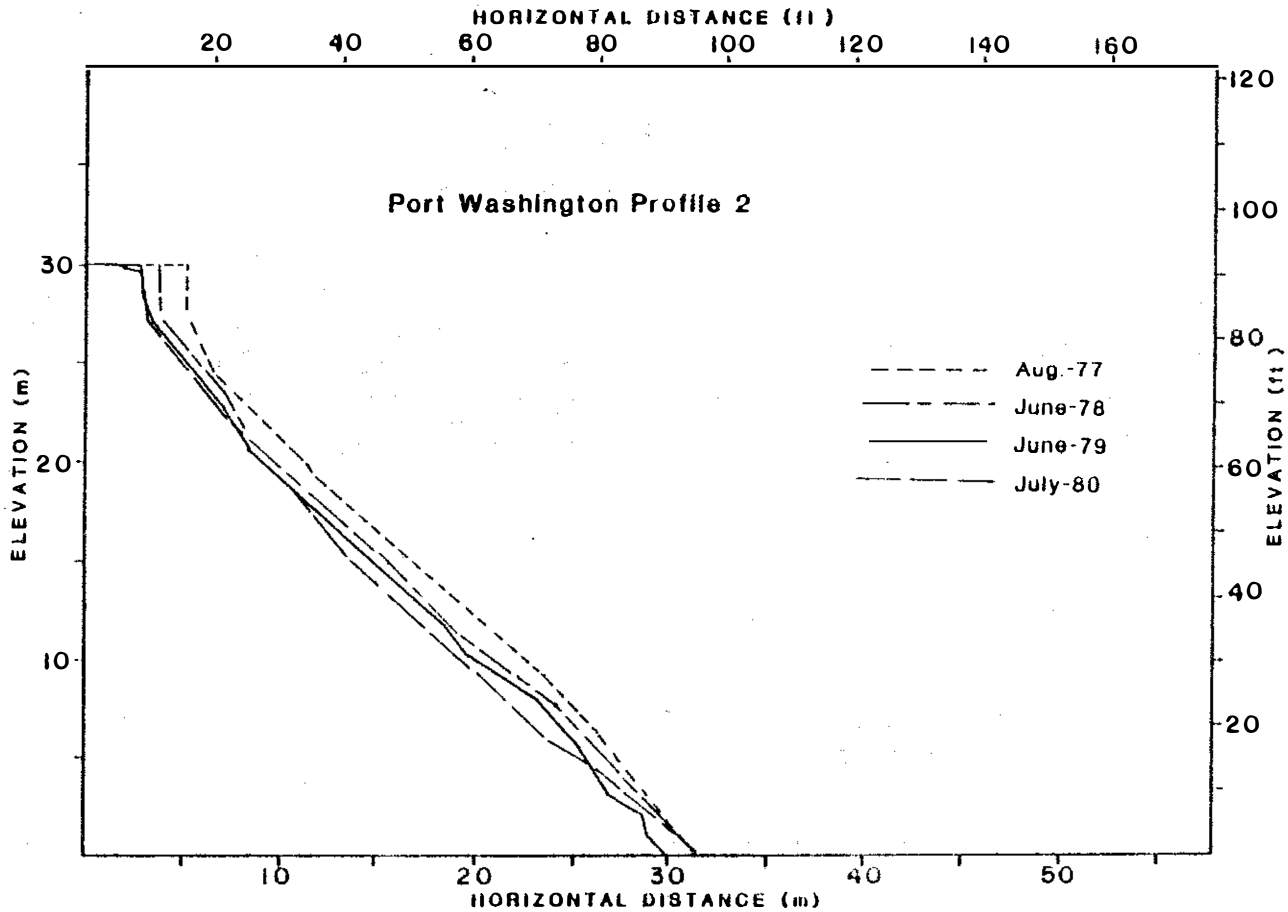

FIGURE 5.--Port Washington Profile 2, bluff profile changes, 1977 to 1980.

Significant changes in bluff angle between some of the measurements suggest that large scale failures have occurred. Figure 9 shows the approximate bluff profile changes through time for one of the profiles in fguure 8. It is evident that a large-scale slump occurred sometime in the mid-1960s.

DISCUSSION

Modes of Bluff Evolution

The results from the short-and long-term bluff monitoring suggest that there are two major modes of bluff evolution. The first is characterized by bluffs that respond directly to changes in lake level through time; that is, bluff angle steepens and declines in response to rising and falling lake level.

Bluffs that are composed largely of cohesionless material such as sand fall into this category. These include most of the bluff profiles in groups F and B. On truly cohesionless bluffs (where the effective cohesion intercept (c' = 0) scale failures cannot occur. The influence of the c' parameter on bluff geometry is discussed in detail in Edil and Haas (1980) and Edil and Vallejo (1980). Although the profiles in groups F and B mentioned above are not truly cohesionless, their geomorphic evolution is such that they can be treated as cohesionless.

Bluffs of group C and most of group E also appear to retreat in a nearly parallel fashion or respond to short-term changes in lake level. Despite the generally cohesive nature of the materials in these bluffs, no large

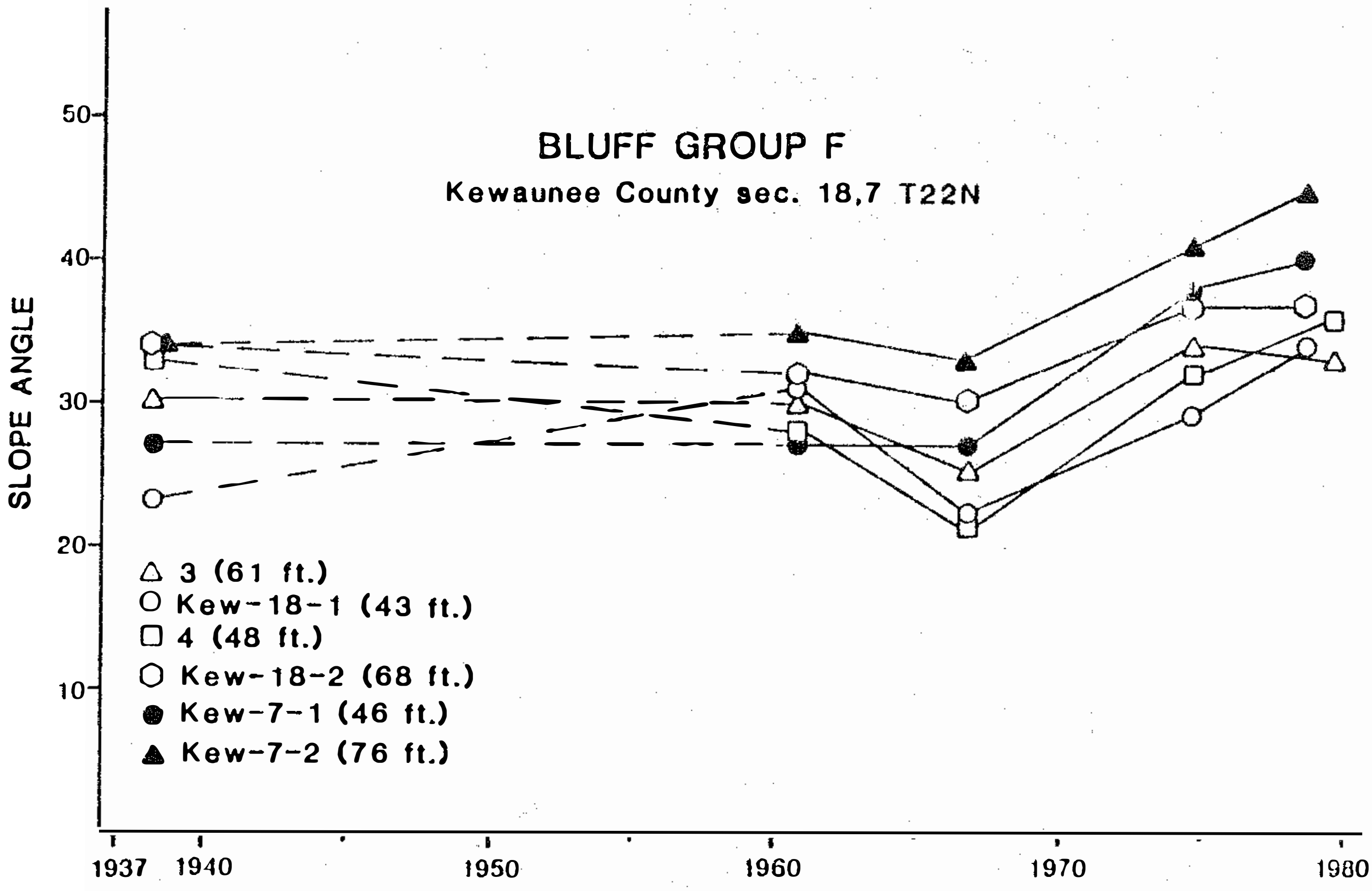

FIGURE 6.--Bluff group F, Kewaunee County, bluff angle changes through time. Bluff heights in parentheses.

scale failures have occurred throughout the monitoring period. Because effective lake level has generally remained low, it is likely that wave erosion has occurred at a sufficiently slow rate that weathering on the bluff slope could keep pace with it. Freeze-thaw and wetting and drying break up the cohesive sediment so that it can eventually be transported downslope by shallow slides and slope wash. In this manner bluff angle could vary without any large scale failures occurring. This mode of geomorphic evolution was described by Hutchinson (1973) for some of the bluffs composed of the London clay.

The second mode of bluff evolution is one marked by periods of gradual change in bluff morphology interrupted by episodes of large-scale mass movement. This occurs only on cohesive bluffs where effective lake level is continuously high. It appears that geomorphic change occurs in this manner regardless of lake level fluctuation as long as effective lake level remains high. Over the short term, these bluffs are characterized by nonparallel recession (see, for example, fig. 5).

Threshold Lake Levels

These results suggest that the geomorphic evolution of coastal bluffs is governed in part by the existence of threshold lake levels that, when exceeded, initiate some significant geomorphic change. This concept of a threshold is basically the same as that advanced by Schumm (1973) for defining landform evolution.

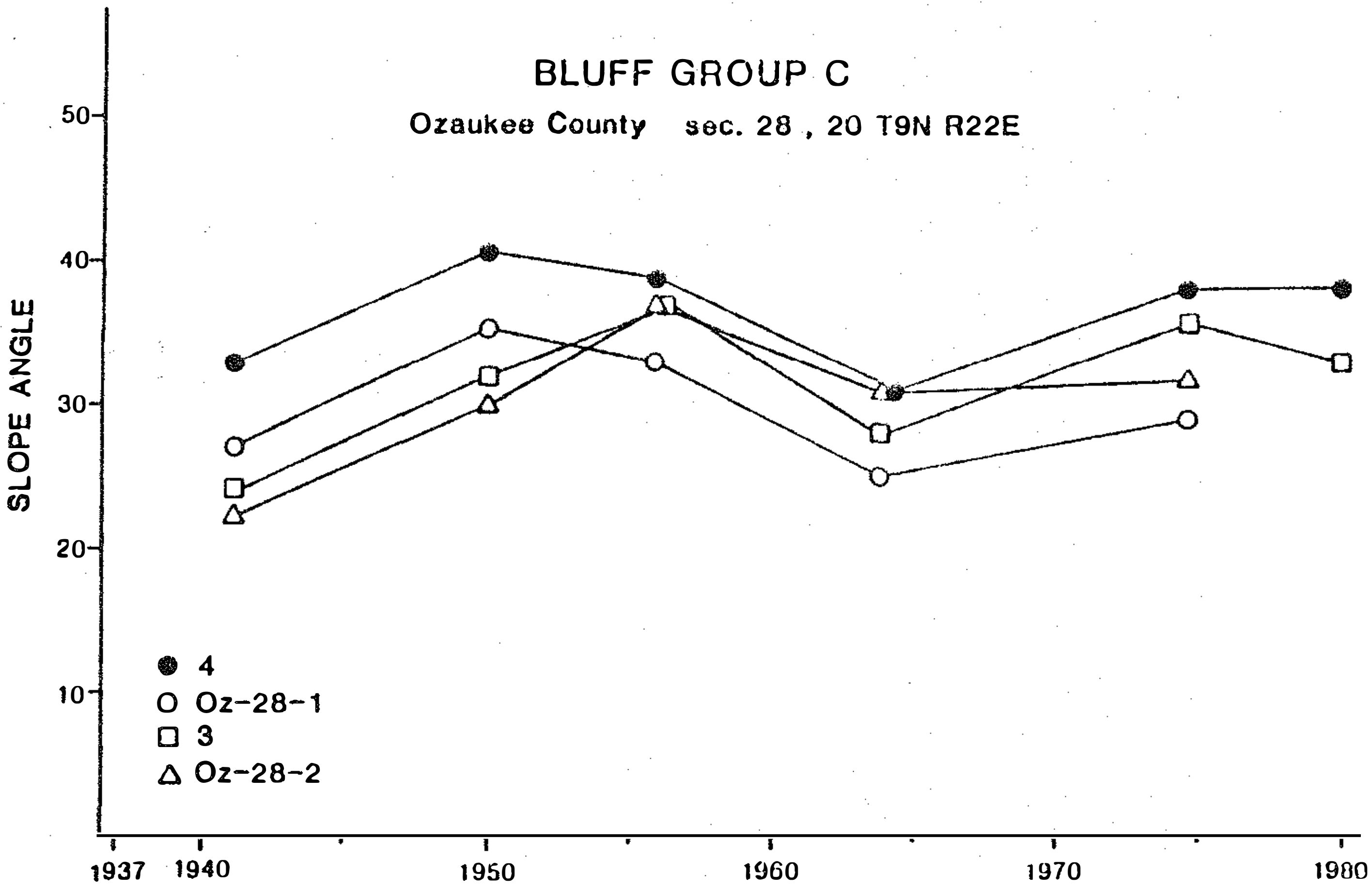

FIGURE 7.--Bluff group C, bluff angles through time.

There is some lake level below which bluff-toe erosion will not occur because waves do not strike the base of the bluff. In this case waves do not remove material from the base of the bluff and the bluff face behaves like any inland slope.

Evidently, for high bluffs composed of cohesive material, there is another, higher, threshold. On these bluffs, if water level rises sufficiently high, cutting at the base of the bluff causes oversteepening. This, in turn, leads to large-scale slumping followed by smaller-scale slumping that takes place high on the bluff. This progression of events takes place irrespective of water level change after the initial oversteeping has taken place.

The upper lake-level threshold is only relevant for cohesive bluffs, because bluffs composed primarily of cohesionless sediment are not susceptible to large scale bluff failures. Neither of these thresholds is a single lake level throughout the coastal zone in Wisconsin because of variations in beach width, offshore bathymetry, and shore orientation.

The results suggest that once the upper lake-level threshold is exceeded, the bluff angle steepens to an angle above which large scale mass movement is likely. For the high bluffs in Milwaukee and Ozaukee Counties, the bluff angle above which slumping occurs is about 45°. For the lower bluffs in Sheboygan County, the data are less abundant but it appears that 50° is a minimum value. If bluff angles on

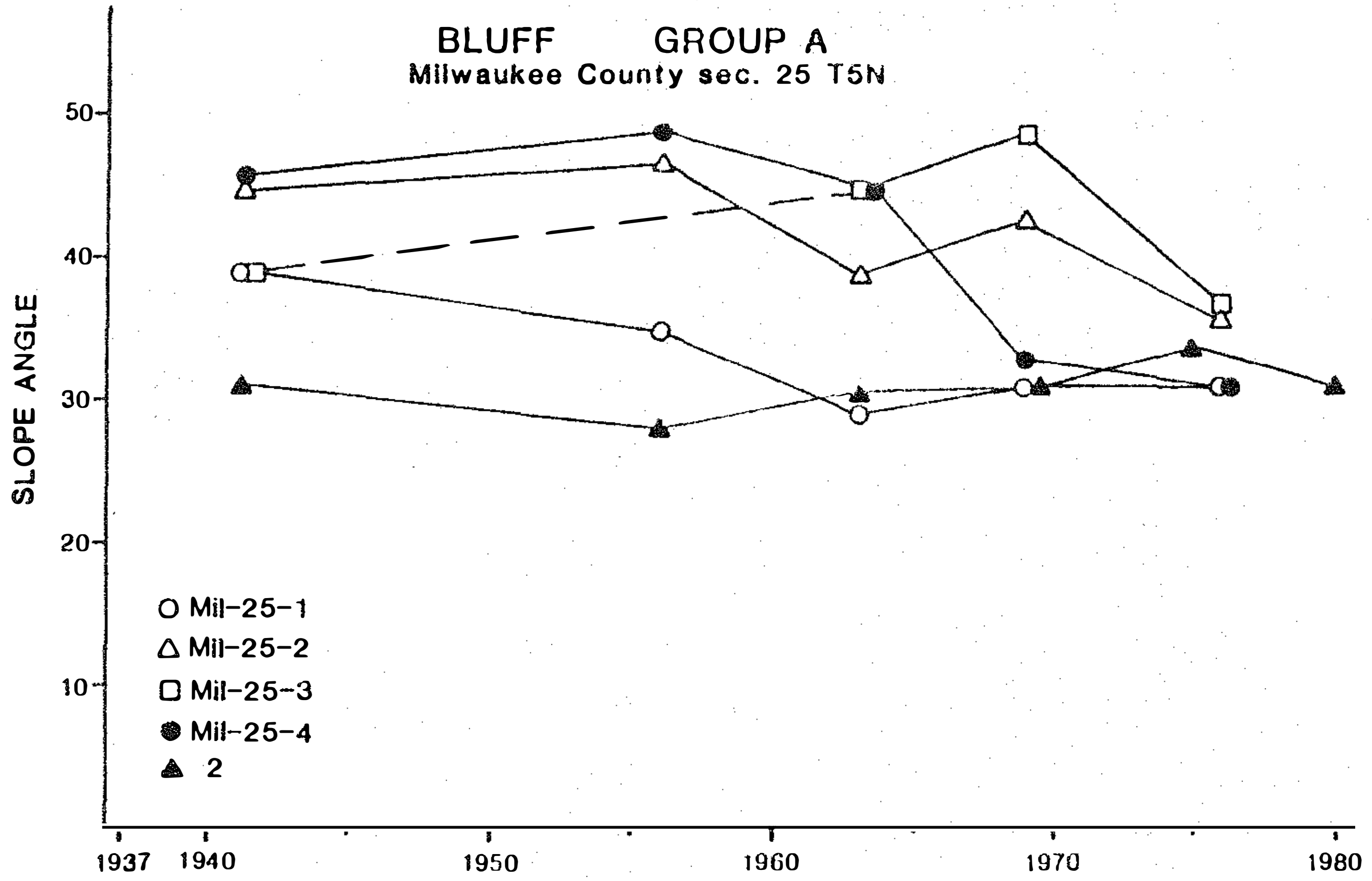

FIGURE 8.--Bluff group A, bluff angle changes through time.

these bluffs do not exceed these values, large scale mass movement will not occur. These observed angles agree fairly well with those predicted by slope stability charts developed by Vallejo and Edil (1979).

Lake Level and Bluff Response Models

My perception of the effect of lake-level fluctuations on bluff evolution is represented graphically in figures 10 and 11. In the case shown in figure 10, lake level is maintained between the two thresholds discussed above. In other words, lake level fluctuates but never drops below the level where some erosion of the bluff toe takes place and is never above the level at which major steepening of the bluff takes place. Bluff angle varies directly with lake level, with a short time lag between peak lake level and peak bluff angle. Short term fluctuations in bluff angle, such as those shown by the short term monitoring, are superimposed on the longer term fluctuations. Time periods between peak bluff angles correspond to periods between peak water levels. During the 1900's these intervals have varied from approximately 10 to 25 years. This type of geomorphic evolution takes place on non-cohesive bluffs and some cohesive bluffs where oversteepening due to wave erosion does not occur.

Geomorphic evolution on cohesive bluffs is represented in figure 11. When lake level is between the two thresholds geomorphic change is the same as that shown in Figure 10. When the upper lake level threshold is continuously exceeded, however, the bluff will steepen and eventually fail as a

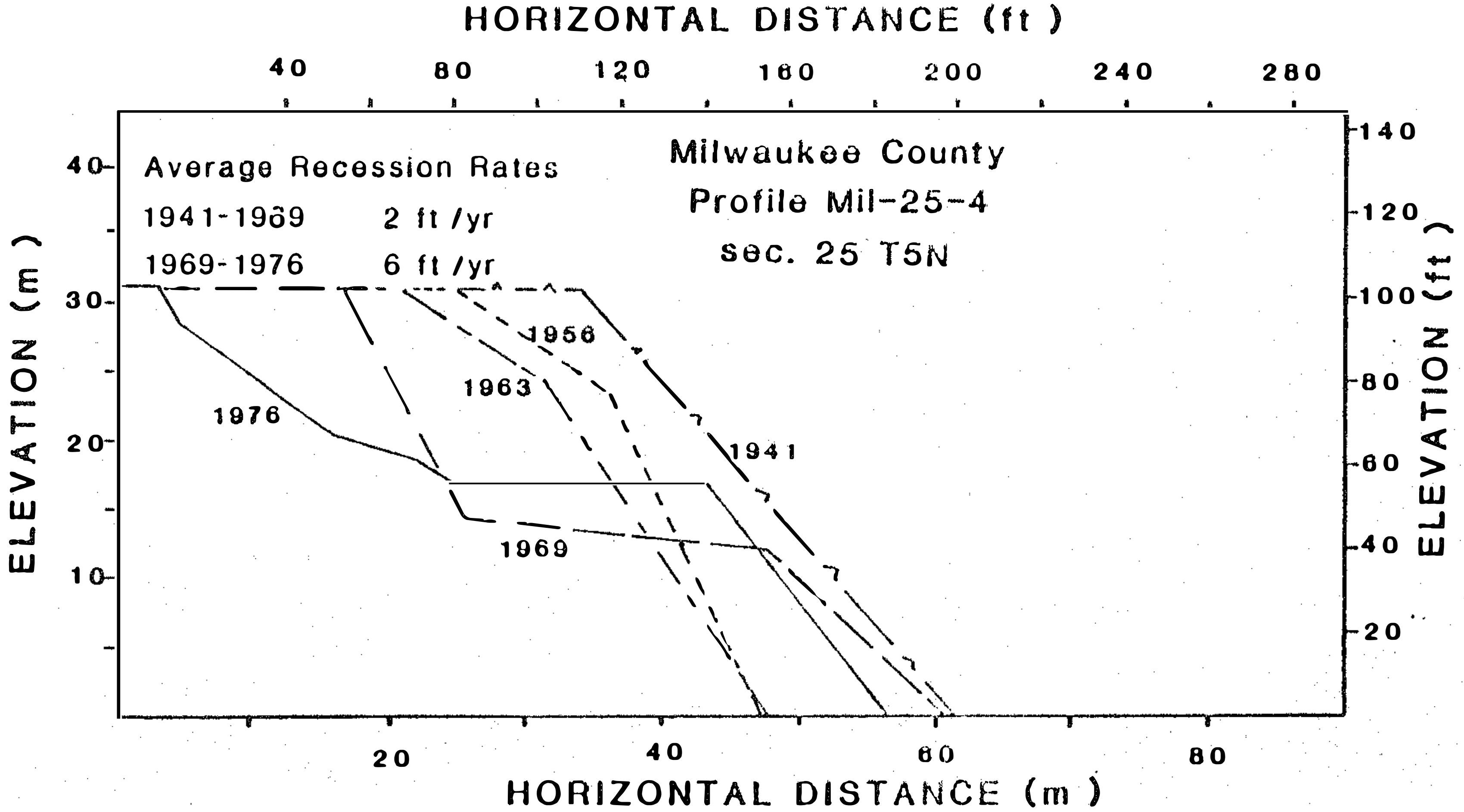

FIGURE 9.--Profile Mil-25-4, approximate bluff profile changes through time. This is an example of a group A bluff.

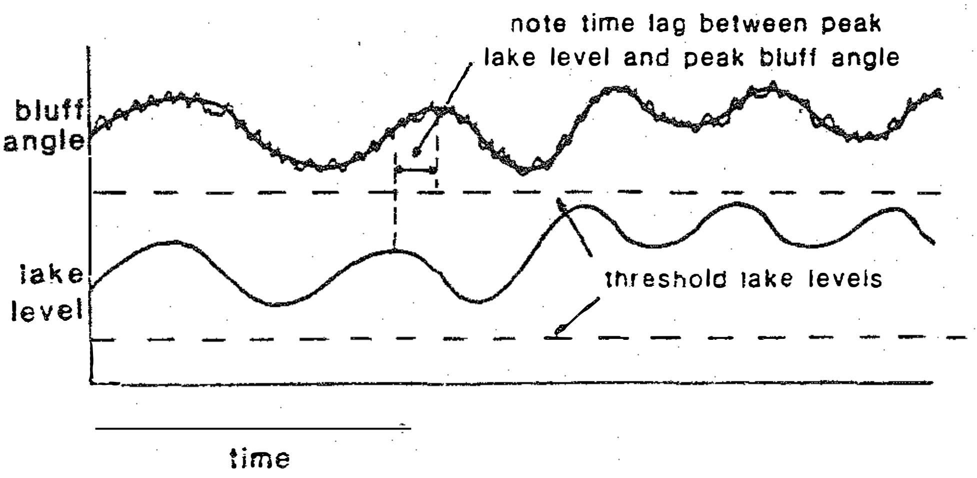

FIGURE 10.--Sketch showing the proposed relationship between water level and bluff angle when water level is high enough to cause erosion at the base of the bluff but low enough so that oversteepening does not occur.

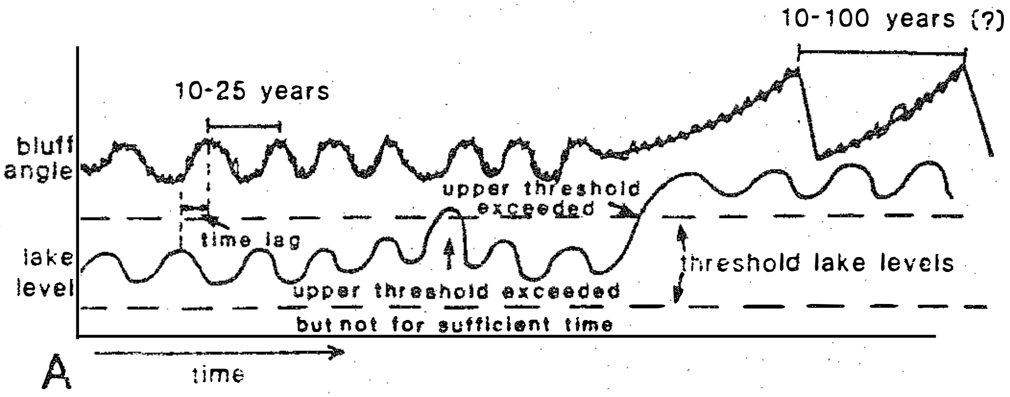

FIGURE 11.--Sketch showing the proposed relationship between lake level and bluff angle on cohesive bluffs that experience a sustained water level high enough to cause oversteepening.

large slump. This sequence of periodic mass movement probably continues as long as the upper threshold continues to be exceeded. One complete cycle of this sequence has not been documented for the Lake Michigan bluffs. However, based on known recession rates of bluffs undergoing this type of geomorphic change, the time between major failures varies from about 10 to 100 years, depending on the bluff height and the recession rate of the toe.

SUMMARY

Geomorphic evolution of the Lake Michigan coastal bluffs in Wisconsin can be described by relatively simple models relating the degree of wave erosion through time with bluff stratigraphy. On bluffs composed of cohesionless sediment, bluff angle steepens and declines in response to rising and falling lake levels. Geomorphic change will be caused only by shallow slides, flow and slopewash. On bluffs composed primarily of cohesive sediment, bluff angle varies as described above only if the lake remains at a level where the amount of material being removed by waves at the toe of the slope is roughly equal to the amount coming down the slope. In environments where the lake is higher, the rate of bluff toe erosion will begin to exceed the rate of erosion on the bluff, resulting in over steepening and eventual large scale mass movement. This sequence probably repeats itself if the lake remains sufficiently high. This high lake-level threshold is not a single lake level everywhere along the shoreline, but varies depending on factors such as shore orientation, offshore bathymetry, and beach width.

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