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Erosion, Slope Stability, Prediction of Future Recession in Actively Eroding Slopes

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ABSTRACT: Evolving slopes are those slopes subject to active erosion processes such that their morphology, thus their stability, is changing rapidly i.e., in human-time scale rather than geological-time scale. There may be several erosion processes but the most influential ones are related to the interactions with an external body of water such as wave action on coastal cliffs and bluffs (defined as steep slopes due to active erosion) such as along the shorelines of oceans, lakes, and reservoirs. The cost-effective solutions often are a combination of both stabilization and management approaches to minimize the impact. These concepts are presented based on the author's 35 years of experience observing and dealing with the bluffs along the shorelines of the Great Lakes (specifically Lakes Michigan and Superior). These lakes are subject to large lake level fluctuations and high waves, thus significant wave erosion takes place reshaping the bluffs and often leading to landslides. The state of knowledge with respect to shore erosion and associated bluff stability issues is presented including the available methods of predicting rate of erosion and determining bluff stability along with the controlling factors. The approaches to mitigating coastal recession are described. Finally, the environmental and ecological impact of coastal structures, which is gaining significant attention recently, is highlighted.

1. INTRODUCTION

Evolving slopes are those slopes subject to active erosion processes such that their morphology, thus their stability, is changing rapidly i.e., in human time scale rather than geological time scale. There may be several erosion processes but the most influential ones are related to the interactions with an external body of water. The interactions may be in the form of wave action on coastal cliffs and bluffs (defined as steep slopes due to active erosion) such as along the shorelines of oceans, lakes, and reservoirs. The current action is important along river and canal banks and bluffs. Finally, rapid drawdown (i.e., sudden drop of external water level), although not primarily an erosion process, impacts reservoir, canal, and levee slopes. The evolving slopes often extend over large distances longitudinally and cannot be dealt with strictly following traditional site-specific engineering approaches and structural solutions to mitigate the impacts. The cost-effective solutions often are a combination of both stabilization and management approaches to minimize the impact. These concepts are presented based on the author's 35 years of experience observing and dealing with the bluffs along the shorelines of the Great Lakes (specifically Lakes Michigan and Superior). These lakes are subject to large lake level fluctuations and high waves, thus significant wave erosion takes place reshaping the bluffs and often leading to landslides. Nearly 65 percent (10,444 km) of the 16,047-km-long Great Lakes shoreline is designated as having significant erosion; about 5.4 percent (860 km) of it is critical. The geology of the Great Lakes shoreline is shaped largely by the movement of glaciers. The Great Lakes formed behind retreating ice sheet when large quantities of ice melted. Re-advances of various ice lobes formed the glacial tills and lake sediments that form the shoreline of the Great Lakes today. The records of water levels in the Great Lakes over the last century indicate that water levels fluctuate up to about 2 m with a period of 15-20 years in addition to daily and seasonal fluctuations. These fluctuations, coupled with other factors such as storm activity and shoreline configuration, give rise to varying rates of shore erosion and instability of coastal bluffs (Figure 1), which culminate in coastal recession and economic loss. The shore erosion problem requires different strategies in different parts of the lakes depending on local circumstances (both physical and socio-political). In some areas prediction of future shoreline recession and providing setbacks for development to minimize economic loss may be appropriate and in some other areas coastal protection and bluff stabilization approaches may be required.

Figure 1. A coastal landslide on western Lake Michigan shoreline

2. SHORE EROSION

Coastline recession in the United States has caused millions of dollars in damage to structures and property, and threatens to produce significant future damage (Platt 1994, Heinz Center 2000). Coastal bluff erosion processes can generally be classified into two categories: subaerial and subaqueous (Hampton *et al*. 2004). Previous studies of subaerial bluff processes have characterized bluff slope stability (Vallejo 1977, Edil and Vallejo 1980, Edil and Haas 1980, Edil and Schultz 1983), bluff face erosion (e.g., Buckler and Winters 1983, Jibson *et al*. 1994, Reid 1985), and bluff toe erosion (e.g., Carter and Guy 1988, Meadows *et al.* 1997, Amin and Davidson-Arnott 1995). Research on subaqueous processes includes that on direct wave impact, horizontal retreat of bluff toe materials, and "downcutting", which is schematically described in Figure 2. In particular downcutting in the nearshore and foreshore is an irreversible process along cohesive and bedrock coastlines (Davidson-Arnott and Askin 1980, Kamphuis 1987, Sunamura 1992). Depending on water levels and the thickness of overlying sand, downcutting sometimes occurs relatively continuously compared to bluff recession and affects nearshore bathymetry, which in turn affects the wave energy reaching the shoreline and, potentially, the bluff toe (Davidson-Arnott 1986, Kamphuis 1990, Davidson-Arnott and Ollerhead 1995). Wave action at the bluff toe removes failed and eroded material that would otherwise act to stabilize the bluff. Waves can further erode intact bluff-toe material, creating a steeper bluff profile and promoting further slope failures and face erosion or undermining coastal structures. Thus, continuing erosion and recession of coastal bluffs depends on waves removing material from the base of the bluff. Variability in both wave action at the bluff toe and the processes acting on the bluff face affect recession rates (Swenson *et al.* 2006). In areas where there is a shore protection structure (e.g., revetment), lake-bed downcutting can undermine such a structure.

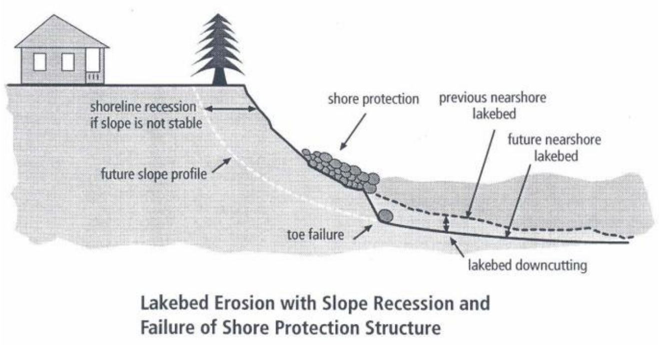


Figure 2. Schematic description of downcutting in cohesive lakebeds (Keillor 2003).

Variations of climate, coastal morphology and lithology, and human activities can cause difficulties in predicting the spatial variability of recession rates. Since wave-induced erosion at the bluff toe is inevitably the chief agent responsible for evolving the bluff geometry, first the wave impact on coastal erosion needs to be explored. Currently, there are no rigorous analytical models based on the physics of the problem available to determine quantitatively the rate and amount of erosion for a given wave climate in a given coastal reach. Therefore, predictions of coastal bluff recession rates are often statistically based. Data from the field and/or laboratory are correlated with recession rates, typically determined from available aerial photos with stereopairs, to reveal significant relationships. For example, Gelinas and Quigley (1973) and Kamphuis (1987) correlated deep-water wave power with long-term bluff recession rates on Lake Erie. Using step-wise multiple regression analyses, temporal variation in erosion rates was related to beach profile changes and protective structures at the toe, while spatial variation was dependent on shoreline aspect and material strength. Along the southwestern shoreline of Lake Michigan, Brown *et al*. (2005) found bluff recession was related to average annual maximum wave impact height, an index of wave energy reaching the bluff toe. Overall, these previous studies have demonstrated some success correlating various factors with bluff recession rates. In particular, the combination of storm waves and high water levels has been shown to be an important contributor to bluff recession.

In a recent study bluff recession rates and beach and bluff lithology and morphology were characterized at 28 sites along the Wisconsin coastline of Lake Superior (Swenson *et al.* 206). Bluffs are composed of clay, sandy clay, clayey sand, sand, and sandstone, and range from 1.1 to 37.3 m in height. Beach composition at the sites varies from sand to a mix of sand and cobbles, to cobbles and boulders, and beach slopes are between 3 and 14°. Bluff-crest recession rates between 1966 and 1998, measured from aerial photographs, ranged from 0.07 to 0.57 m/yr. The photos analyzed were chosen based upon consideration of photo availability and long-term changes in lake levels. Epochs spanning high and low lake levels were chosen to investigate the effect of water levels alone versus water level coupled with storm activity on bluff recession. The position of the bluff top was digitized for each year using stereopairs to identify the bluff crest and recession distances were measured at 5 m intervals to ± 50 m on either side of the site.

Field measurements of wave runup at the study sites were conducted to verify wave runup estimated from available methods in the literature. Wave runup is the maximum vertical extent of wave uprush above the still water level on a slope (Hunt 1959). Wave impact height (WIH) is defined as the elevation of wave runup minus the elevation of a bluff toe (Figure 3). An index, cumulative wave impact height (CWIH), which accounts for the frequency, magnitude, and duration of waves impacting the bluffs, was used to assess the degree of correlation between this measure and bluff recession rates. CWIH is defined as the area under the curve with positive WIHs (Figure 4) because positive WIHs represent waves actually impacting the bluff toe. In contrast to the WIH by Brown et al. (2005), CWIH accounts for the magnitude, frequency, and duration of all waves impacting the bluff. The calculated CWIH is normalized with time to obtain an average CWIH per year ($\overline{\text{CWIH}}$) for the epoch of interest. $\overline{\text{CWIH}}$ was correlated with recession rates (i.e. bluff recession normalized to time) for the same epoch (a period defined by the availability of aerial photos to determine recession).

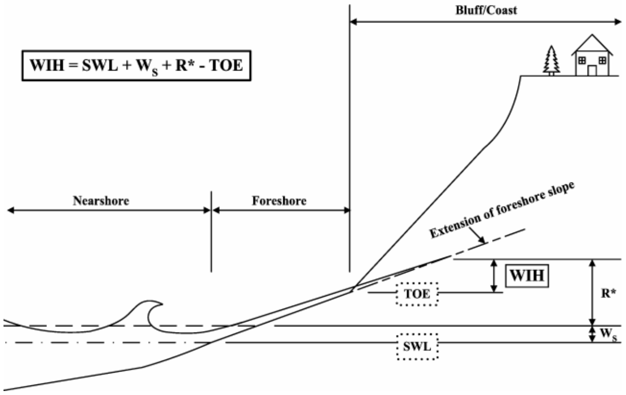


Figure 3. Schematic of wave impact height (WIH), elevation of the still water level (SWL), wind setup (W_S), wave runup in absence of bluff (R*), and elevation of bluff toe (TOE) (Swenson *et al.* 2006).

To hindcast CWIH at each site, historical data, including records of wave, wind, and water level, were used with the site characteristics measured in the field. Wave runup records were measured for deep-water wave conditions with significant wave heights of 0.2 to 4.8 m and dominant wave periods of 2.5 to 10.1 s. Foreshore and bluff profiles, nearshore bathymetry, and material types were used to characterize each study site. The observed wave runup at each site was compared with those estimated by five different wave runup empirical methods. It was found that the N&H (Nielsen and Hanslow 1991) relations provide the most consistent estimate of mean and 2% wave runup at the study sites.

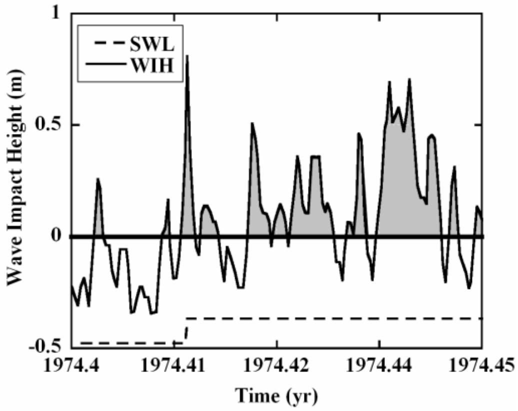


Figure 4. WIH and monthly mean still water level (SWL) versus time. The sum of the shaded areas or positive WIH is Cumulative wave impact height (CWIH) (Swenson et al. 2006).

The average yearly CWIH ($\overline{CWIH}$) for the 1966-1998 epoch was correlated with the recession rates from the same period. Reasonable correlations between $\overline{CWIH}$ and recession rates at sites throughout the study area were found when comparing bluffs of similar lithology and height as shown in Figure 5. These results suggest that bluff recession rates in this area are not only linked to wave impact at the bluff toe but also lithology, which affects a bluff's response to wave attack at the toe as well as other processes (e.g., gully erosion) that promote recession.

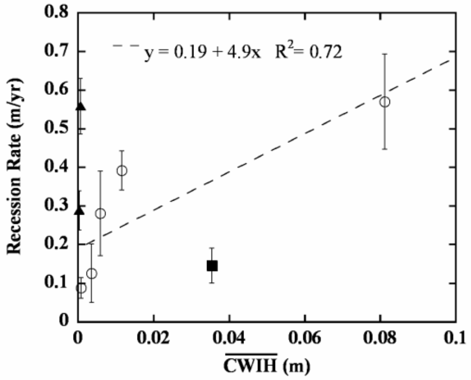
3. WATER LEVELS

The level of water in the Great Lakes has fluctuated significantly since 16,000 years before present (B.P.) when the area was entirely covered by ice. Modern long-term, mean water levels also fluctuate (up to about 2 m), resulting in extended periods of high or low water levels (15-20 years) (Figure 6a). Water levels fluctuate unpredictably over periods of hours, months, and years. Seasonal water level fluctuations of 0.35 meters are typical in Lake Superior (Figure 6b), with the highest lake levels occurring in late summer/early fall. The correlations shown in Figure 5 between recession rate and $\overline{CWIH}$ is over an epoch with the water levels as shown in Figure 6b. Therefore, any variations from the historical water levels can be expected to impact the recession rates. However, the impact of systemic water level rise or drop, such as that can be expected from global climate change, can be estimated from the relationships given in Fig. 4 for the southwestern Lake Superior by calculating the $\overline{CWIH}$ corresponding to the new water level.

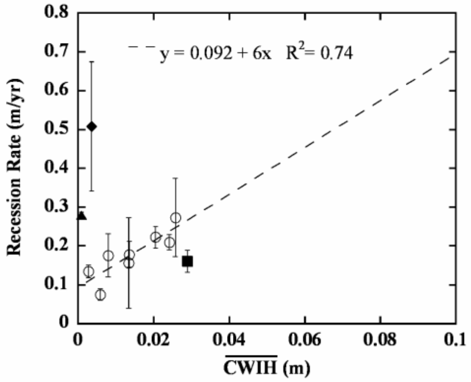
4. BLUFF STABILITY

Nearly 32 percent of the U.S. shoreline of the Great Lakes consists of erodible bluffs. The extent of the shoreline formed in erodible bluffs and dunes (and often complex response of this type of shoreline to wave erosion) makes slope processes an important part of the shore recession problem. Because much of the Great Lakes shoreline has bluffs of glacial till or lake sediment above the beach, one component of shore erosion is bluff instability. Bluff material properties (including strength, i.e., angle of internal friction and cohesion, and unit weight), slope geometry, stratigraphy, and groundwater level determine the static stability of a slope (Edil and Vallejo 1980). Natural time-varying weathering processes including precipitation, freeze/thaw action, sheet wash, seepage effects (collectively referred to as "face degradation" effects), and wave action can complicate bluff stability (Mickelson et al. 2004). Face degradation effects remove slope materials more or less continuously in relatively small quantities from the surface of the slope. Sheetwash is the unconfined flow of water over the slope surface after a rainfall. Sheetwash and rill erosion have been found to account for up to 34% of the material removed from a profile in Bender Park in Milwaukee County, Wisconsin (Sterrett 1980). Saturated surface soil that is frozen can, upon melting, be so weak that it flows down the slope. Freeze/thaw has been found to be a dominant cause of weakening of the soil and its subsequent removal on some coastal slopes (Vallejo and Edil 1981). No known past research that combines the effects of weathering processes on bluff recession rates exists. Even though the face degradation effects influence the timing and extent of any given bluff failure, erosion by waves is likely the main determinant of the long-term recession rate of bluffs because it prevents the bluff slopes from ever attaining equilibrium. Wave action at the toe of the slope serves to weaken and remove exposed bluff material, thereby undercutting the toe of the overall slope and reducing the stability -- and ultimately causing failure. These processes are schematically shown in Figure 7.

The long-term bluff response to wave erosion is complicated by the changing slope geometry. Over time, the slopes evolve in response to the factors listed above. The pattern and rate of slope change depends upon bluff height, stratigraphy, soil type, and vegetative cover (Edil and Vallejo 1980, Mickelson *et al.* 2004). Low (10 m or less) bluffs respond rapidly and more predictably to lake level, wave climate and precipitation patterns than high bluffs. The predominant slope processes of low bluffs, such as those at the Manitowoc County, Wisconsin, are shallow slumps, translational slides and face degradation (Brown *et al.* 2005).



a) Cohesive Bluffs



b) Noncohesive Bluffs

Figure 5. Bluff recession vs average cumulative wave impact height at west of the Bayfield Peninsula. Only open symbols are used for regression. Closed symbols are sites with unique characteristics (Swenson et al. 2006).

Generally, low bluffs that experience erosion at the base have no trees and very little vegetation. Due to the short "cycle" time of the slope failures that occur on these slopes, it appears that there is not enough time for trees to take root and grow. In contrast, high (30–45 m) bluffs, such as those at the Ozaukee or Milwaukee Counties, Wisconsin, change slowly because of the long "cycle" time to erode the large mass of material at the base after failure. An episodic failure mode is usually exhibited by the high bluffs (Mickelson *et al.* 2004). Figure 8 shows a typical sequence through which these high bluffs pass. Large, deep-seated slumps occur locally at a rapid rate, depositing the material at the base of bluff. The material acts like a buttress for a number of years until the waves erode the failed sediment. The waves then resume their direct attack on the intact bluff face and another large, deep-seated failure occurs eventually. The episodic nature of this process complicates recession rate computations based on aerial photos taken at any two dates unlike the case for the near-continuous process observed in low bluffs.

The common methods of analysis of bluff stability for the Great Lakes coastal bluffs involve limit equilibrium methods such as Bishop's method for rotational slides and infinite slope stability method for translational slides based on the effective stress method (Edil and Vallejo 1980, Hampton *et al*. 2004). These methods are typically applied to the current slope profile based on conservative but realistic soil strength parameters and stratigraphy obtained from field investigations and laboratory tests.

Potential high groundwater levels that are likely to occur over several decades are estimated. This approach, which was prevalent 30 years ago, is designated as deterministic method since only a single value of each parameter is used in the analysis. Subsequently, probabilistic methods of slope stability analysis evolved to take into account the variability typically observed over a reach of the shoreline in various slope stability parameters (e.g., strength, stratigraphy, groundwater levels). In an investigation both deterministic and probabilistic methods were evaluated with respect to their predictive capability in terms of field data collected over a span of 20 years (Edil *et al.* 2003).

Four analysis methods were used for comparison of the data collected along the western Lake Michigan shoreline. The methods were selected to compare the abilities of deterministic and probabilistic techniques to predict both rotational and translational failures. The methods included deterministic Bishop (BISHOP-D) and probabilistic Bishop method based on Monte Carlo simulation (BISHOP-MC) (Edil and Schultz 1983) for rotational slides and deterministic infinite slope method (INSLOPE-D) and probabilistic infinite slope method based on a First Order Second Moment (FOSM) extrapolation (INSLOPE-FOSM) for translational slides.

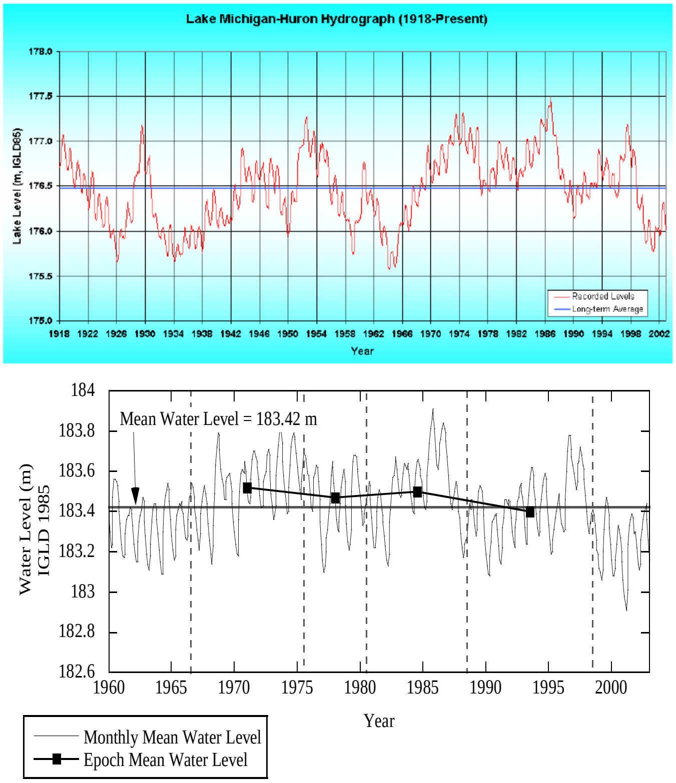


Figure 6. (a) Historical water levels for Lake Michigan showing the recent extended period of above average levels in the past three decades (Meadows et al. 2006) and (b).Monthly mean and long-term water levels in Lake Superior. Interval of dashed lines denotes each epoch (Swenson et al. 2006).

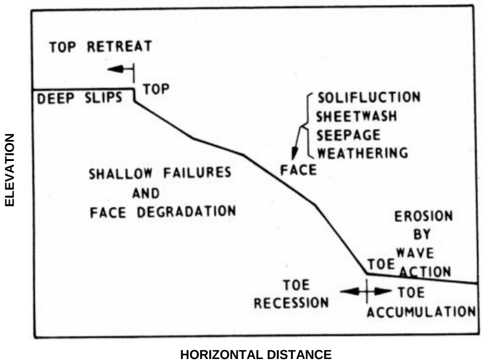


Figure 7. Processes in the Great Lakes bluffs and their locations on the bluff.

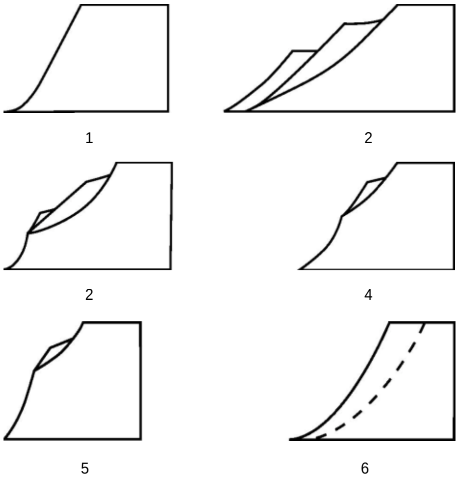


Figure 8. Phases of episodic changes for a high cohesive coastal bluff: (1) Steep unstable bluff; (2) large, deep-seated slump takes place causing up to 50 feet of bluff recession; (3) wave erosion of toe begins; (4) wave erosion continues lower bluff steepens; (5) wave erosion continues, lower steep segment of bluff grows higher; (6) failure occurs again. Cycle may take more than 50 years to be completed (Mickelson et al. 2004).

The two data sets collected along the Lake Michigan shoreline, respectively in mid 1970's and 1990s, were used as 'initial' and 'post-failure" descriptions. The four analysis techniques were applied to the slope data collected in 1970s and the results were compared to the post-failure descriptions collected in 1990s to evaluate the predictive capability of each technique. Each analysis method is evaluated on the percent of sites with correct predictions. The initial comparisons were made using the theoretical failure criterion for each method. For the deterministic methods, i.e., BISHOP-D and INSLOPE-D, safety factor, FS ≤ 1 was used to designate instability. For the probabilistic methods, i.e., BISHOP-MC and INSLOPE-FOSM, a method of presentation is to use a reliability index, β. This index can be created using the arithmetic mean of the recorded (BISHOP-MC) FS, E[F], and the standard deviation of the recorded (BISHOP-MC) factors of safety, σ[F].

$$\beta = (E[F] - 1.0)/\sigma[F]$$

A value of $\beta = 0$ corresponds to a 50% probability of failure. Higher values of β represent lower probabilities of failure and lower values of β higher probabilities of failure. A larger positive value corresponds typically to a more stable slope and less risk of failure. The reliability index can also be related to a probability of failure, provided the factors of safety have a normal distribution (Christian, 1996). For the probabilistic methods, β ≤ 0 was used to designate instability. Subsequently, a calibration of the analysis output was undertaken based on ground truth to allow a better predictive capability for each of the individual methods. These calibration values were determined using the observations recorded along the Lake Michigan Shoreline after a period of 20 years and are empirical. The calibrated failure criteria based on the field observations of failures improved the predictive capabilities.

Combining the results of different analysis methods applied to a single slope using the proposed calibrations improves the predictive capability significantly, i.e., to 90%. This was done for the data presented here by plotting the BISHOP-D FS values against the BISHOP-MC β values as shown in Figure 9 and looking into the zone of stable values; then comparing this to the INSLOPE-D and INSLOPE-FOSM analyses. This approach, which is based on stability analyses but calibrated based on empirical field data, is considered to be more effective than purely empirical stability correlations based on slope height and inclination. Slope stability analyses can provide reliable predictions with careful interpretation of the results. While this approach can be adopted for other sites and analysis practices, the actual calibrations should be considered site-specific. The acceptable range of reliability indices for natural slopes is not well defined due to the lack of experience with the technique. Literature suggests that, for designed slopes, a reliability index of 4.0 is stable, 4.0 to 2.5 is marginally stable, and a value less than 2.5 requires immediate remediation (Wolff, 1996). For the natural coastal slopes considered here, a much lower value of reliability index delineates actual failures. Similarly, such slopes also exhibit relatively low factors of safety in their natural condition (slightly above 1.0) for stability than typically considered in design, e.g., 1.3 or 1.5.

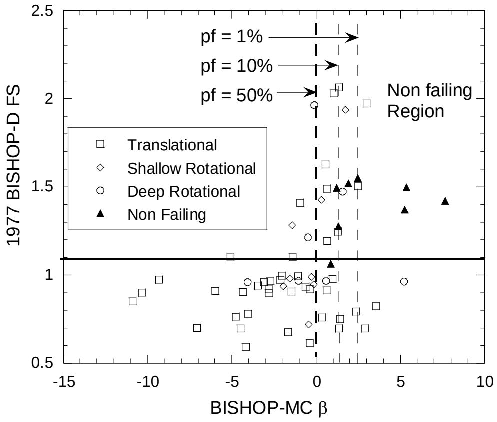


Figure 9. Comparison between Bishop-D FS and Bishop-MC β results (Edil et al. 2003). Pf: probability of failure.

Clearly, the nature of bluff failure influences the rate at which bluffs respond to changes in lake level or other external factors. Shore recession, in turn, affects the planning, design, and maintenance of transportation facilities and development in coastal areas in a significant way. A complex interrelationship of numerous factors affects the variability of coastal bluff recession rates along the Great Lakes. These factors include rate of toe erosion (as described above as a function of wave climate, water level, water level trend, shoreline orientation, fetch, and nearshore lithology and morphology), bluff stability (as a function of bluff lithology and morphology, rainfall, groundwater levels, seepage, freeze and thaw, and coastal-ice as described above), and shoreline structures. The variability of these factors from place to place probably explains the spatial variability of bluff recession rates. Several examples of variability can be sited. For instance, the bluffs in southwestern Lake Superior fail predominantly in translational slides (Anderson 2003) whereas the bluffs along western Lake Michigan show predominantly rotational failures especially if the bluffs are high, but translational slides are also encountered especially in low bluffs (Brown *et al*. 2005). Till properties also vary significantly, not only in terms of strength parameters, but also in terms of susceptibility to frost weakening and creep (continuous deformation at constant stress, which may lead to failure). Figure 10a shows the frost weakening behavior of two tills from Lake Superior (Hanson Creek and Douglas tills) and one till from Lake Michigan (Ozaukee till) at similar water contents. The Lake Superior tills had a strength reduction of about 60% whereas the Michigan till experienced 47% reduction due to 1 cycle of freeze-thaw. Figure 10b shows the creep rates (i.e., time rate of strain versus time) of the same tills at a constant vertical stress of 25 kPa in an unconfined test. Again, the Lake Superior tills have a higher creep tendency than the Lake Michigan till; as a matter of fact Hanson Creek till goes to creep rupture. Based on field experience and analysis, it was determined that a slope inclination of 22° provides an essentially stable slope against deep-seated rotational slides along the western Lake Michigan shoreline whereas much flatter angles (14° or less although not fully established presently) are required for a stable slope along the southwestern Lake Superior shoreline.

5. PRACTICAL APPROACHES TO MITIGATING COASTAL RECESSION

The most significant characteristic of coastal bluffs on the Great Lakes is the fact that they are actively evolving natural slopes that continually retreat at varying rates with constant or evolving geometry. This characteristic sets these slopes apart from other natural slopes in terms of stabilization approaches. There are basically two approaches to minimize impact on humans of actively retreating coastal slopes. Structural approaches are typically developed on a site-specific basis. Non-structural approaches typically involve planning and management decisions on a broader scale. The solution strategies for actively eroding coastal slopes are summarized in Table 1. Advice is available to riparian property owners and interested professionals on the coastal environment and how to protect coastal investments (Keillor, 1998 and 2003).

5.1 Structural (Stabilization) Approach

The structural approach, with some additional considerations, is similar to other natural slope stabilization efforts. A proper stabilization program should include (a) protection against wave action in all cases, (b) slope stabilization against deep slips if needed (important in the delayed instability often observed in high bluffs formed in stiff clay soils), and (c) stabilization against face degradation and shallow slips (including control of surface water) (Table 1 and Figure 11). Shore protection is a major component and may be more costly than slope stabilization. Problems associated with the execution of these solutions are of two types: (a) many attempts are not engineered and fail to anticipate the problems that will arise, and (b) engineered solutions often neglect to consider all aspects of the problem, thus have deleterious effects on another part of the system.

Numerous erosion control structures have been built to protect cohesive bluffs in the Great Lakes, particularly where urban development is greatest. These structures fit into two broad categories: shore-normal structures (e.g. groins, harbor jetties) built to trap sand from the littoral drift (i.e., longshore transport of sediments), and shore parallel structures (e.g. seawalls, bulkheads, revetments) built to create a physical barrier between attacking waves and cohesive shore deposits. Offshore breakwaters built to trap sand and prevent wave attack fit into both categories. In more recent years, awareness of the impact of such structures on neighboring coastal reaches and nearshore ecology has increased (Meadow *et al.* 2006) and typically structures that stop all longshore transport of sand are discouraged. Rock (riprap) revetments and offshore breakwaters (including submerged breakwaters) that allow some longshore transport are common forms currently favored. Additionally, recent awareness of the importance of lake-bed downcutting has suggested armoring or paving lakebed by use of densely packed cobble-size (15 to 45 cm in diameter) stones. So far, it has been used only on an experimental basis in the Great Lakes.

Several variables determine the long-term effectiveness of shore protection structures:

1. The structure must have enough mass to withstand the forces exerted on the structure by waves impinging on the lakeward side of the structure and by the forces exerted by downslope movement of cohesive bluff material behind the structure,
2. The structure must have sufficient height to prevent wave overtopping and consequent erosion of cohesive bluff material behind the structure, and
3. If the first two conditions are met, then issues such as adequate foundation design to support the structure and installation of weep holes to relieve hydraulic pressures become important.

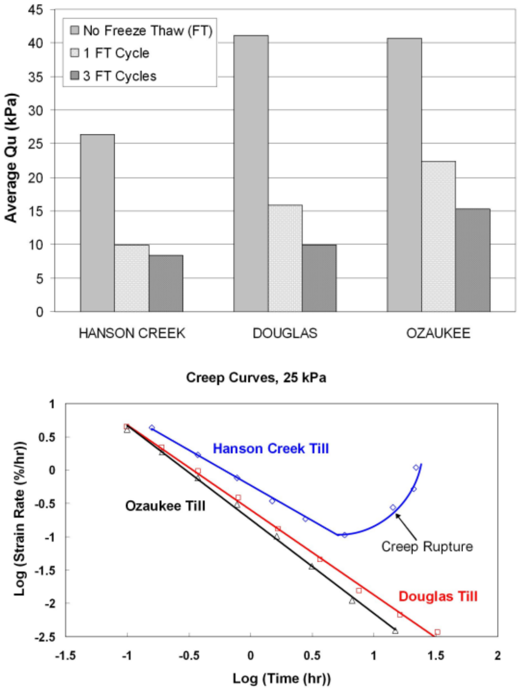


Figure 10. (a) Comparison of strength loss (unconfined compressive strength Qu) as a result of freeze-thaw (FT) cycles and (b) creep rate versus time response at 25 kPa of two tills from Lake Superior and one till from Lake Michigan.

A variety of approaches are available to stabilize the bluff once the bluff toe is protected. Prevention of mass movement requires an anticipation of the type of movement, location of potential failure surface, size of potential failing block, and anticipation of the likely triggering mechanism(s). Bluff stabilization approaches typically include:

1. modification of slope geometry by reduction of the slope angle through cutting back the top of the slope, or buttressing it against sliding by filling at the toe to reduce driving stress,
2. controlling surface water running onto the slope,
3. re-vegetating the slope to protect slope face, and
4. lowering the groundwater table, thereby reducing pore pressure and increasing resistance to sliding

Table 1. Strategies for Mitigating Bluff Failure and Recession

PROCESS	SOLUTION/MITIGATION	
	STRUCTURAL (STABILIZATION): Design	NONSTRUCTURAL (MANAGEMENT): Prediction
TOE EROSION	SHORE PROTECTION (Revetments, breakwaters groins, seawalls, beach nourishment, etc.)	SHORE RECESSION RATE (Long-term and cyclic)
DEEP ROTATIONAL SLIDES	SLOPE STABILIZATION (Re-grading, buttressing, dewatering, etc.	STABLE SLOPE ANGLE AGAINST SEEP SLIDES
FACE DEGRADATION AND SHALLOW SLIDES AND FLOWS	SURFACE PROTECTION (Vegetation, surface water management, berms)	ULTIMATE ANGLE OF STABILITY AGAINST SHALLOW SLIDES AND FLOWS

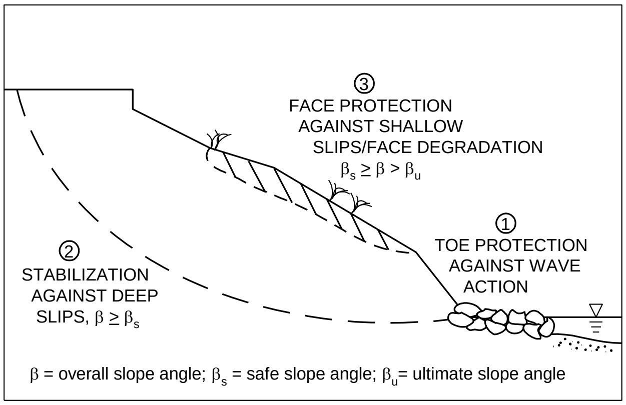


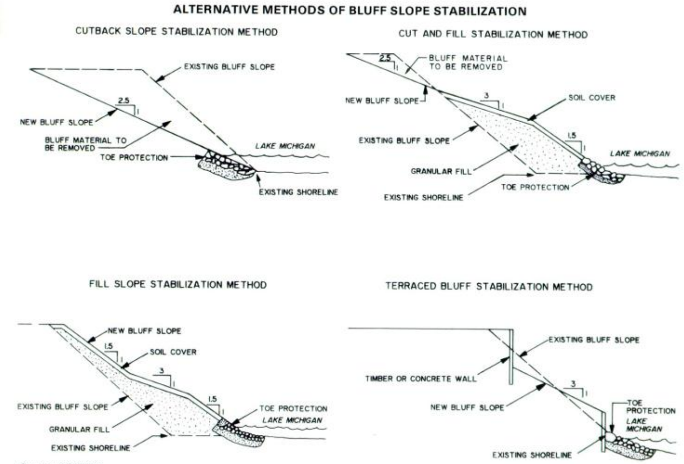
Figure 11. Steps in stabilization of coastal bluffs

Use of structural means such as retaining walls, drilled shafts, etc. to increase resistance to sliding, has been limited, though the use of stabilizing berms or buttresses (sometimes internally reinforced) is on the rise.

An integrated approach, as shown in Figure 12, assures the effectiveness of shore protection over a sufficiently long period of time with proper maintenance. This site-specific approach to protection, if not undertaken over a reach of shoreline (i.e., a segment with similar wave climate, geomorphology, and geologic setting), will likely result in outflanking of the protected segment by continued recession of the neighboring unprotected shoreline and result in eventual failure.

5.2 Management Approach

The nonstructural planning and management approach is particularly suitable for undeveloped land where mitigation of hazards to transportation, housing, and commercial facilities can be planned and managed over an extensive part of the shoreline (the size of a county or at least several kilometers are usually considered). This approach is usually aimed at minimizing future structural damage while allowing erosion to take place, thus avoiding problems with structures described in the previous section. In this case, the need for understanding bluff processes is critical because predictions of future recession over a long period of time with changing water level and climate conditions are necessary (Table 1). This approach necessitates an understanding of bluff processes and development of qualitative (and preferably quantitative) models of bluff evolution. The main problem of prediction of slope evolution is related to understanding the response times to environmental changes and the time necessary for bluffs to pass through an evolutionary sequence. The main tool used in the nonstructural or management approach is the establishment of a setback requirement for new buildings or infrastructure. This requires knowledge of coastal recession over a long time, at least 30 to 50 years, and the determination of stable slope angles. Typically, historical aerial photographs are used to establish the recession rates and geological and geotechnical analyses are used to determine the stable slope angles. Research conducted primarily during the last few decades has identified the operating processes and their possible magnitudes (Edil, 1982). A nonstructural setback distance can be estimated as shown in Figure 13 (SEWRPC, 1989). In this case, the setback distance consists of two components: erosion risk distance is the distance from the existing bluff edge that could be affected by recession of the bluff over some appropriate time (50 years?) plus the setback necessary to regrade the bluff to a stable slope angle. The minimum facility setback distance is an additional safety zone.



Source: SEWRPC.

Figure 12. Alternative Methods of Bluff Stabilization Common in the Great Lakes (SEWRPC 1989)

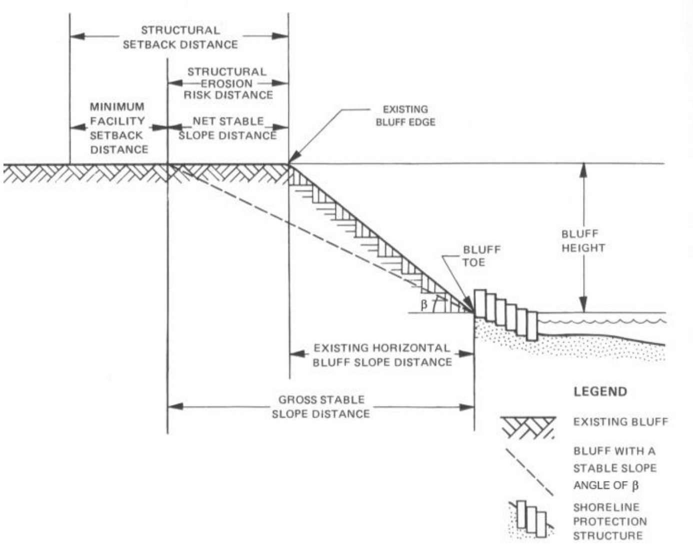


Figure 13. Determination of Setback Distance in Management Approach (SEWRPC 1989)

6. ENVIRONMENTAL AND ECOLOGICAL IMPACTS OF SHORE PROTECTION STRUCTURES

Although sparsely developed areas along the Great Lakes shorelines remain unprotected by structures, numerous attempts have been made over the past 150 years to stop erosion in more developed areas. The coastal structures have had a severe impact on the beach/nearshore system. Shore-normal structures, such as groins and harbor structures, trap sand to create a beach. This commonly creates or aggravates erosion along the downdrift shore. Eroding bluffs and erosional embayments are typical features downdrift of shore-normal structures in the Great Lakes. For groins, this effect may extend hundreds of meters. For long harbor jetties, the effect may extend for kilometers.

Most shore-parallel structures do not trap sand (breakwaters are the exception). However, they may adversely affect coastal processes. Downward deflection of wave energy along vertically faced structures scours the lake bed unless a scour apron is installed along the base of the structure. If the structure is built at the back of a beach too narrow to dissipate wave energy, turbulence along the face of the structure may erode the beach. Spray generated by waves hitting vertically faced structures may saturate the bluff face and erode loose material. Vertically faced structures also reflect wave energy offshore and/or against an adjacent shore. Using armor-stone construction reduces problems of wave scour, wave spray, and wave reflection, but the irregular surface of the structure restricts access to the lake.

Recreational use of the lake is adversely affected by structures. As just noted, the irregular surface of armor-stone (or concrete-rubble) structures restricts access to the lake. However, with proper design, structures can be designed to minimize adverse impacts, limit erosion, and provide access to the lake.

Armoring a cohesive bluff shore cuts off an important source of sand for the littoral system. Loss of sand from the beach and nearshore also results in greater turbidity, as the sand-starved shore and nearshore are exposed to erosion by frequent, small-wave events. This adversely affects water quality. Loss of sand from the nearshore also alters the nearshore biologic habitat. Many organisms that inhabit the nearshore are adapted to a mobile sand substrate and the bar and trough system that forms where sand is present. Loss of this sand and replacement by a cobble and boulder covered wave cut platform has a negative effect on these organisms and encourages growth of nuisance species like zebra mussels. The full extent and nature of these impacts are still not fully understood (Meadow *et al.* 2006).

7. SUMMARY

Wave erosion and associated bluff instability present a continuous problem in the coastal slopes. There are semi-empirical approaches that delineate the effect of the fundamental operating factors on shore erosion and bluff instability. These approaches, which are site or region-specific by their very nature, are summarized and can be adopted in other locations by careful considerations based on local conditions. It is anticipated that historical recession rates may change with global climate change as the water levels are likely to deviate from the modern patterns. Therefore, such impacts need to be considered in planning and management of coastal development. Coastal structures are still a viable approach; however, their design and justification require greater care since there is a higher level of perception of their deleterious effects on neighboring properties and their environmental and ecological impacts in the near shore.

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