Bluff Response in Glacial Till: South Shore of Lake Erie

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Bluff response to wave erosion was monitored from 1986 to 1998 at three sites along a 1.5 kilometre stretch of shoreline on the south shore of Lake Erie. This shoreline consists of bluffs ranging from five to 17 metres in height, developed in over-consolidated till. In 1986, during an eight-month field season, the study sites were monitored at one to two week intervals, and from 1987 to 1998 once a year. Beach width and erosion height at the bluff toe were measured, and photographs of the bluff profile were taken. In 1986, record high lake-levels and associated narrow beaches resulted in severe toe erosion, reaching up to two metres on the bluff face. This initiated various types of bluff failure resulting in near-vertical profiles at all sites. From 1987 to 1996, lake-levels dropped about a meter, beaches widened, and toe erosion reduced. During this period, the presence of a wide and thick beach at Site 2 halted toe erosion and the low bluff (five metres) stabilized. At Sites 1 and 3, the presence of a moderately wide beach allowed some toe erosion to occur and the bluffs (eight metres and 17 metres respectively) maintained vertical to near-vertical profiles. Severe bluff toe erosion occurred again at all sites during the high lake-levels of 1997-98, in which the bluff response mechanism of 1986 was repeated. Between the two high lake-level periods, the bluff response mechanism and subsequent geometry of the bluff profile was found to be related to spatial variations of beach width, toe erosion rates and bluff height.

Keywords: Bluff recession, toe erosion, coastal erosion, Great Lakes.

Bluff response and the resulting geometry of the bluff face is a function of wave erosion at the base and on the near shore profile, and the geological nature of the materials. The bluff response to wave erosion at the toe is manifested by a variety of landslides that occur with different time duration. Because of continuous lake-level fluctuations and corresponding pulses of accelerated toe erosion during high lake-levels, bluff face geometry remains in a state of dynamic equilibrium. Although in recent years some attention has been given to the bluff base and near shore erosion (e.g. McGreal, 1979; Carter and Guy, 1988; Amin, 1991; Davidson-Arnott and Langham, 1995; and Amin and Davidson-Arnott, 1995), few studies have been done on bluff recession processes, and in particular on how bluffs evolve over time (Hutchinson, 1973; Quigley and Gelinas, 1976; Quigley et al., 1977; Valejo and Degroot, 1988). There may be no study that investigates the slope evolution process on low to medium height bluffs of glacial till in the lower Great Lakes.

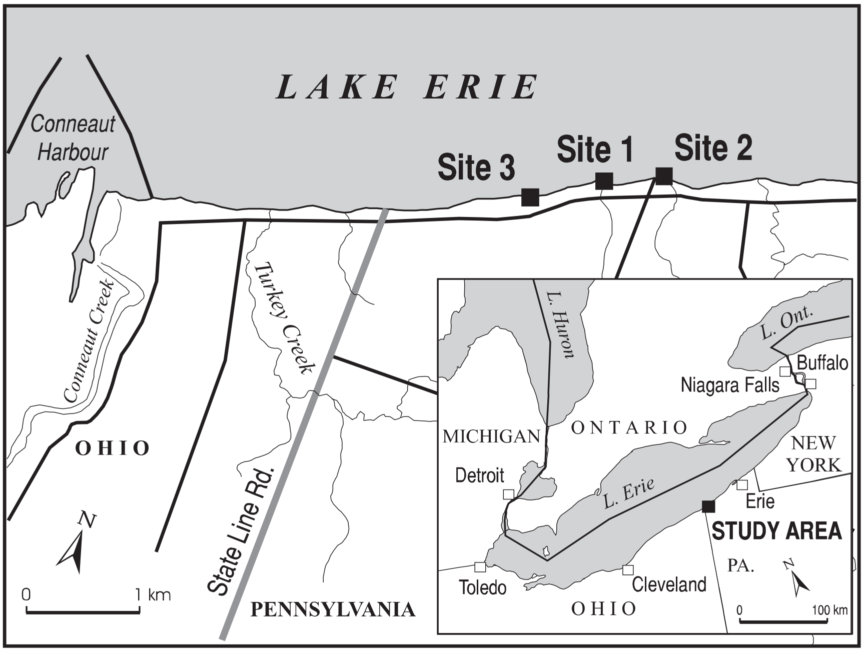

Figure 1: Location of study area.

A considerable portion of the shoreline in the lower Great Lakes is composed of weak Quaternary glacial deposits. Because of narrow beaches, these bluffs are subject to severe erosion that often prompts various attempts at shore protection, usually at great economic cost. With better knowledge of the bluff form evolutionary processes, in both the short and long term, a better approach to these problems might be adopted.

The purpose of this paper is to model the bluff evolution process of low to medium height bluffs composed of glacial till, from a section of shoreline near the Ohio-Pennsylvania border along Lake Erie (Figure 1). During this time period, the lake-level fluctuated about one metre (Figure 2). The highest lake-level of 175 metres (Based on International Great Lakes Datum, IGLD – 1985) was recorded in 1986. Since then it decreased to about 174 metres (close to the long-term average) in 1989-90, and again increased progressively close to 175 metres in summer of 1997. These observations made through a complete cycle of lake-level fluctuation provide a unique opportunity to document the bluff response process to almost one cycle of lake-level fluctuation.

Study Area

Bluffs in the study area are typically about 12 metres high, but vary from five to 17 metres at the selected sites. The bluffs are lower where the land has been dissected by tributaries flowing into the lake. For example, the bluffs at Sites 1 and 2 are five metres and eight metres high respectively, whereas the bluff at Site 3 away from any tributary is 15 metres high. Bluff recession rates within the study area averaged 0.5 - 1.0 metres per year over the period 1938-1975 (Knuth and Crowe 1975). Crest recession at the three sites (Sites 1-3) measured in this study during the period 1986-1996 ranged from 0.3 - 0.67 metres per year.

The general stratigraphy along Lake Erie's south shore consists of four major lithologic units (D'Appolonia/Haley and Aldrich, 1978). These, from top to bottom, include: a) poorly cemented lacustrine sand representing strand deposits; b) massive lacustrine clay, silt, and sand; c) glacial till; and d) shale bedrock. Within the study area, the bluffs are made primarily of till material overlain by a thin deposit of lacustrine silt. Two distinct units of till material can be recognized in the study area - an upper unit of stiff to very stiff, yellow brown to gray, clayey silt to silty clay with trace amounts of sand and gravel, and a lower unit of very stiff to hard, highly fissured, gray silty clay with occasional cobbles and small boulders.

The lower till is denser than the upper till, and has prominent vertical relief joints. Greatly increased penetration resistances were recorded in the lower till during borehole sampling (30 to 100 blows per foot versus four to 30 blows per foot for upper till) by D'Appolonia/Haley and Aldrich (1978). The upper till in contrast does not contain relief joints. In most bluff outcrops, the upward fading of the vertical relief joints can be diagnostic of the transition between the lower and the upper till. The presence of vertical relief joints from bluff toe to crest at Sites 1 and 2 indicates that these bluffs are composed of lower till only. The high bluff at Site 3 is composed of both lower and upper till, overlain by a shallow

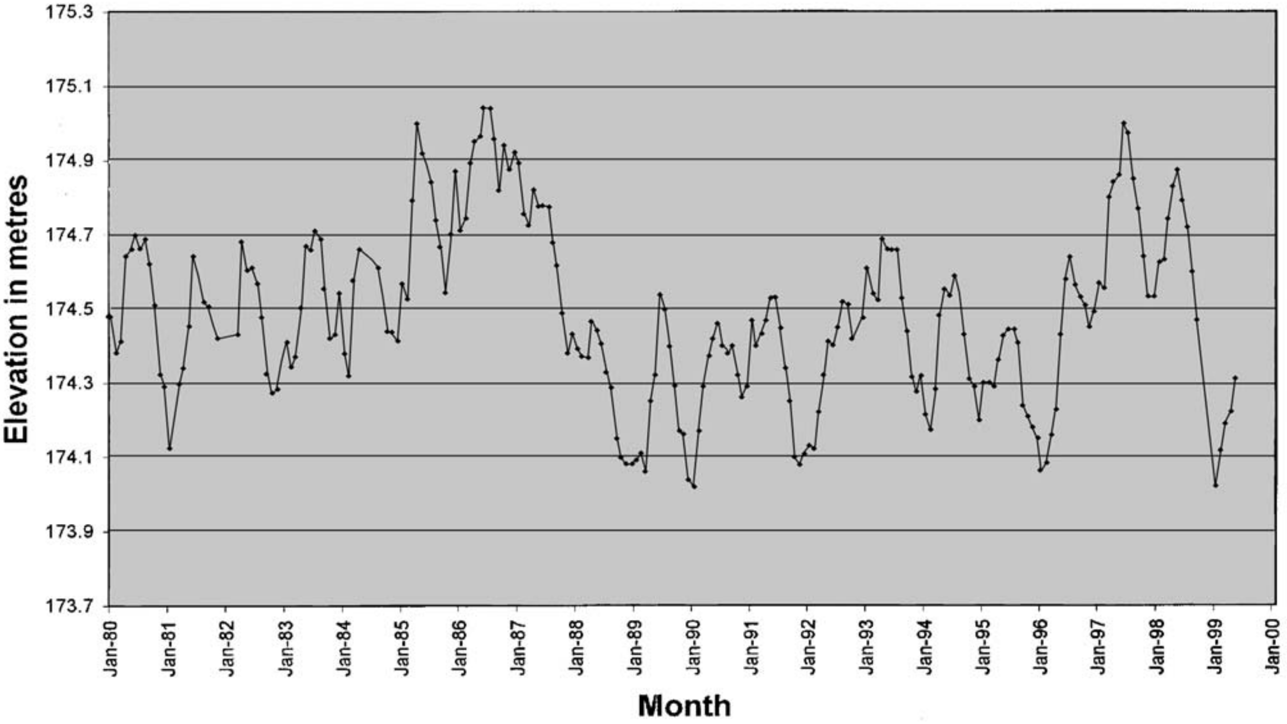

Figure 2: Mean monthly lake-levels recorded at Erie, Pennsylvania (United States Department of Commerce).

layer (about one metre thick) of lacustrine silt. At this site the lower till extends about 10 metres upward from the toe of the bluff. Shale bedrock (Chagrin Shale) is not exposed along the study area shoreline. During this study, scuba diving in May, 1996 (lake-level 174.5 metres) revealed the presence of bedrock at two metres depth of water about 200 metres offshore at Site 1. This reduces the rate of near-shore erosion, and can be related to lower rates of crest recession at the study sites.

Low bluffs, such as at Sites 1 and 2, are almost vertical during high rates of toe erosion, whereas the high bluffs (Site 3) have a sigmoidal shape, with a convex bulge at the lower part and a slightly concave shape toward the crest. Bluff profiles, however, are in a continual state of change, reflecting near shore processes and subsequent bluff responses. The upper till consists of 76 percent clay and silt and 24 percent sand and gravel. For the lower till, these percentages are approximately 74 and 26 respectively. Extensive testing of Atterberg limits by Amin (1991, 74-81) showed that the characteristics of the lower unit at all three sites were similar and fell within a narrow range. The liquid limit ranged from 21.2 to 21.5, the plastic limit from 11.6 to 18.0, the shrinkage limit from 6.0 to 7.2, and the plasticity index from 7.5 to 9.6. These values corresponded very closely to lab data reported by D'Appolonia-Haley and Aldrich (1978). Based on these properties, the lower till material was classified as silty clay of low plasticity (CL). The liquidity index values for all four sites were determined to be less than zero, confirming the highly stiff and brittle nature of the till material. The average compressive strength of the till material was found to be 16 MPa (2320 psi), while the shear strength, under undrained conditions, was assumed to be one half of the compressive strength, i.e., eight MPa (1160 psi). The water content of the material at the bluff base typically ranged from eight to 12 percent. The liquid limit of the upper till varied from 22.1 to 26.6 percent, the plastic limit from 14.5 to 20.2 percent, the water content from 9.1 to 19.2 percent, and the unconfined compressive strength from 63 to 87 TSM (D'Appolonia-Haley and Aldrich, 1978, Table 4.4).

The bluffs are fronted by narrow beaches, two to eight metres wide from the berm crest to the bluff toe during low wave conditions, with an average slope of five degrees. During storms and at higher lake-levels, beaches become inundated in most places. These beaches consist primarily of medium to coarse sand with varying amounts of gravel and cobbles. The near shore profile has an average slope of about one degree out to 600 metres offshore. Except for scattered boulders, there is little sediment present on the near shore profile. The near shore profile is cut on glacial till for about 200 metres from the shoreline, and on shale bedrock beyond that distance.

Lake Erie is subject to seasonal and long-term water level fluctuations that reflect variations in precipitation and evaporation over the basin (Figure 2). During the period of 1985-86 it experienced record long-term high lake-levels, some one metre higher than the long-term average of 173.9 metres (IGLD-1985). During this study (1986 to 1998) the lake-level fluctuated within one meter, but was always above the long-term average. Within this period the lake dropped very close to the average level during 1989-90, and rose close to the all time high (175 metres) during the summer of 1997.

Methods

The current study stems from an earlier study of bluff toe erosion (Amin, 1991; Amin and Davidson-Arnott, 1995) in the same study area. This study takes a longitudinal view of bluff response from 1986 to 1998 of the entire profile for the three sites shown in Figure 1. In 1986 during an eight-month field season, the study sites were visited almost every week. From 1987-1998, the study sites were visited annually, except in 1991 and 1993.

Beach width was measured along three profiles, at 10 metre spacings at each site. The beach width in this study was considered the linear distance from the berm crest to the base of the bluff, denoted as backshore by Komar (1976, 12). The average of three such measurements at each site was taken as being representative of the beach width. In 1986, beach width was monitored weekly from April to December at Site 1, and from July to December at Sites 2 and 3. To allow for comparison with single visit data collected in other years, in this study an average beach width was taken from the 1986 data for each site. Since field data were collected only once a year, during April to June in three of the years and August to November in six of the years, from 1987 to 1998, the data may not have captured seasonal variations in beach width. To estimate the magnitude/extent of this variation, field data from 1986 were examined. The 1986 data show that the beach, in general, was wider in April, July to September, and in November, and generally narrower during May to June, in October and in December (Amin, 1991). Variations in beach width ranged from 0.5 to 2.0 metres from site to site, which amounts to less than 25 percent of the widest beach at each respective site.

In 1986, the magnitude of toe erosion could be ascertained for each site since the data were based on weekly monitoring of peg-lines that lasted for six to eight months from site to site (Amin, 1991; Amin and Davidson-Arnott, 1995). The weekly measurement ranged from no erosion to as high as 10 centimetres of erosion of *in situ* bluff material at the toe. The total erosion at Site 1 for the eight month period (May 19 - December 20) at the lowermost peg was about 80 centimetres. Depending on the severity of a storm (or storms) the wave erosion extended upward on the bluff face. In a severe storm, erosion was recorded at pegs located 1.75 metres from the beach bluff intersection, whereas during moderate to slight erosion events, wave erosion reached up to 1.0 and 0.5 metres respectively. For subsequent years (1987-1998), with a single visit per year, it was not possible to measure toe erosion. However, based on the above information, an indirect estimate of the extent of toe erosion could be achieved by recording the height of wave erosion mark on the bluff face. In absence of any fixed datum, the height of erosion on the bluff face was measured from the beach-bluff intersection during field visits from 1987-1998. Although the elevation of the beach-bluff intersection can potentially vary both spatially and temporally, it can still be used as an indirect measure of the extent of erosion at the bluff base. During the 1986 field season, the total variation in beach thickness, as measured at the beach-bluff intersection from April to December, was about 0.5 metres at Site 1. The elevation was higher from June to September and lower in April to May and from September to December. The variation in beach thickness was less pronounced at Sites 2 and 3.

Bluff crest recession at the study sites was also monitored by taking shore normal linear measurements from a fixed point of reference on the bluff crest. Extensive photographs were taken of the entire bluff from preferred angles and fixed locations on the beach to monitor progressive changes in the bluff profile.

Field observations and results

In 1986 with the lake-level at the all-time recorded high, it was found that the short-term bluff response due to toe erosion varied with bluff morphology, joint pattern, and shape of the erosion zone within the toe area. Bluff response was quicker (weeks) where sharp notches (0.3 metres deep and less that 0.5 metres high) had developed (Site 2) than where erosion had led to the formation of a concave zone (Sites 1 and 3) about two metres high (Amin, 1991). At low to medium bluffs (Site 2 and 1 respectively), nearly parallel retreat of the bluff took place, whereas at high bluffs (Site 3), steepening of the bluff occurred with no significant recession of the bluff crest during the study year. Manifestations of bluff response to toe erosion were in the form of slope movements including slumps (rotational slides), slab failures (translational slides or plane failures), earth falls, earth flows, and mud flows. Earth falls and slab slides were the predominant modes of failure immediately above the toe area, where the till was more jointed, whereas earth flows and localized slumps occurred more frequently near the crest area (Shakoor and Amin, 1994).

The long-term responses of the bluff are shown for the three sites in Figure 3. Temporal variation of beach width and bluff toe erosion height for the study sites are given in Figure 4. At Site 1, bluff toe erosion for subsequent years was not as severe as it was in 1986. Wave erosion marks hardly reached more than one meter on the bluff face from the beach-bluff intersection (Figure 4), whereas in 1986 the concave erosion zone at this site was about two meters high with significant overhangs of the upper part of the bluff (Figure 5). Although the beach at Site 1 had increased in width since 1986 (about three metres in 1986 to more than eight metres in 1989), especially during the low lake-levels of 1989-90 (174.1 to 174.3 metres, IGLD-1985), this was

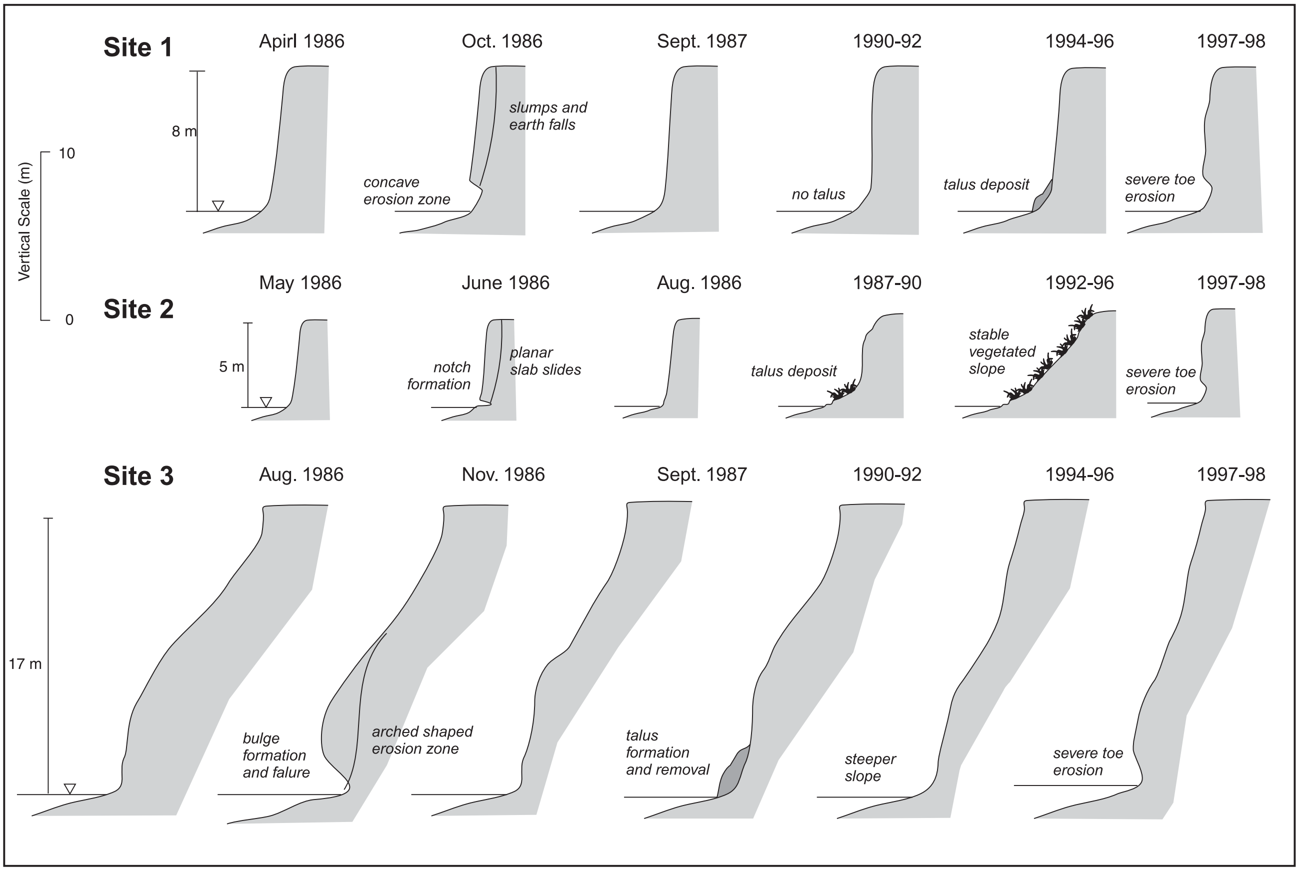

Figure 3: Schematic diagram showing bluff response over time. The bluff crest recession (1986-96) rates for sites 1-3 are 0.30 m, 0.57 m, and 0.67 metres per year respectively.

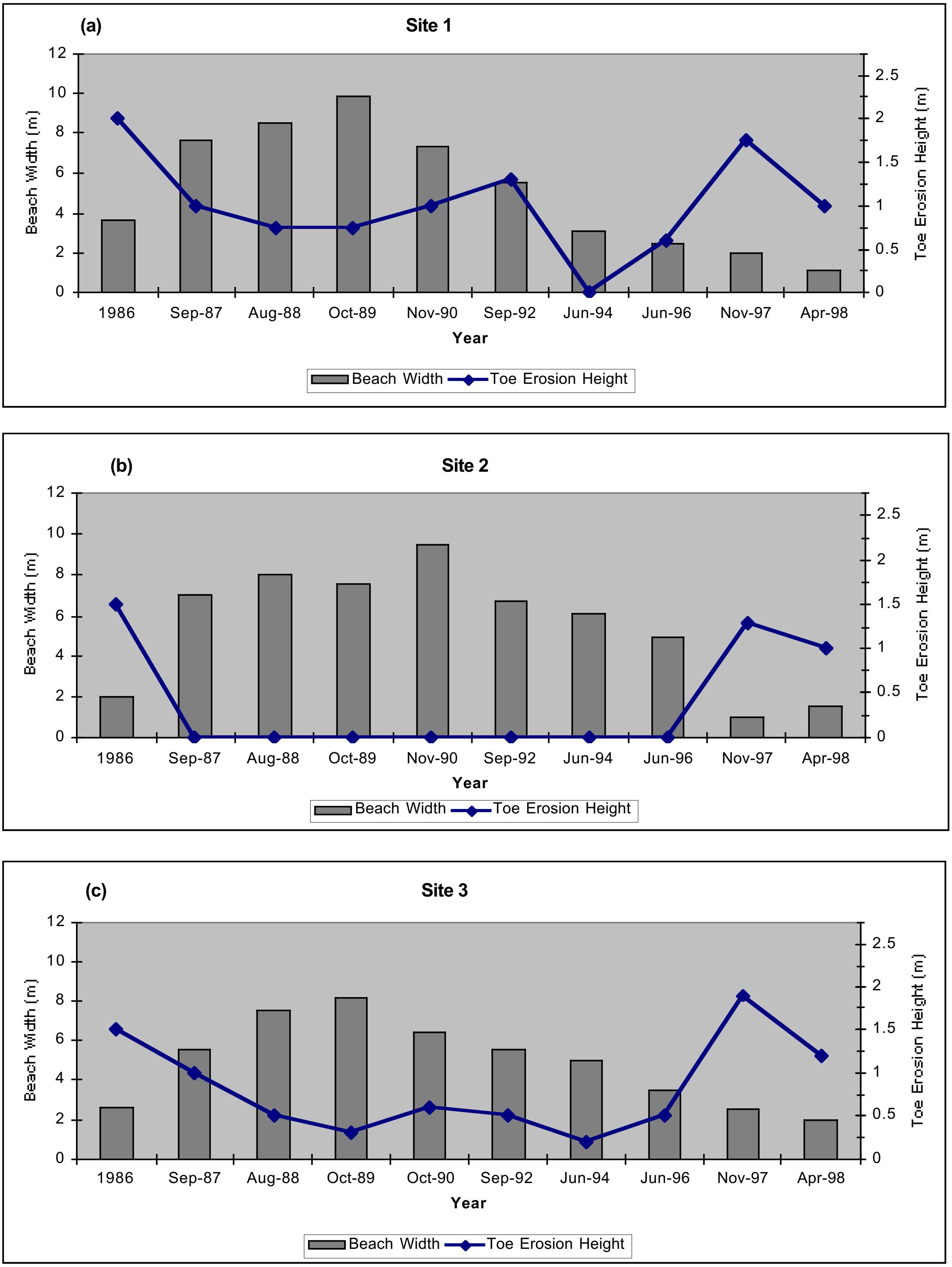

Figure 4: Temporal variations of beach width and bluff toe erosion height at (a) Site 1, (b) Site 2, and (c) Site 3.

not enough to stop toe erosion. As a result, the bluff was almost vertical, with no sign of stability (Figure 6). Talus cones were observed at the bluff base during five visits from 1987 to 1996, and these provided only temporary protection from wave action. In 1997, pronounced bluff toe and beach erosion were observed once again at Site 1 after an episode of high lake-levels (ranging from 174.5 to 174.9 metres, IGLD-1985) and a very narrow beach (less than two metres). This initiated formation of a concave erosion zone at the bluff base similar to what was observed in the 1986 bluff geometry.

In 1986, the low bluff at Site 2 went through a multiple cycle of toe erosion and bluff failure. The relatively narrow beach (less than two metres from April to October) at this site allowed swash and waves to reach the toe more frequently than at other sites, thereby promoting rapid development of notches. Notch development was followed by earth falls that frequently affected the entire bluff up to the crest line (Figure 7). With this process the beach widened significantly (from two to six metres) by the end of the field season in 1986. The beach remained consistently wider (ranging from six to 10 metres, Figure 4) and thicker (thickness was not measured, but observed) and there was little evidence of toe erosion from 1987 to 1996. As expected, reduced or insignificant erosion at the toe of the bluff helped the bluff profile gradually evolve into a more stable slope and finally attain the desired angle of repose (Figure 8). Gradual colonization of the slope with grasses and woody shrubs further reduced subaerial erosion, and provided a quasi-equilibrium state of slope stability. This equilibrium was interrupted by further severe beach and toe erosion in the 1997-98 season with marked high lake-levels. Severe toe erosion removed all previously slumped material that had helped attain the angle of repose; the resulting erosion made the profile again almost vertical. The beach narrowed to the width observed in 1986 (about two metres) with wave action eroding the *in situ* toe material. The 1997-98 toe erosion process looked identical to the 1986 process (Amin and Davidson-Arnott, 1995).

The bluff at Site 3 is relatively high (17 metres) and was a sigmoidal shape in 1986 (Figure 9). The resulting erosion form at the toe is described as an arch shaped zone, about 2.00 metres high and 0.75 metres deep at the base. This caused a pronounced bulging of the lower till. The response of the lower part of the bluff to toe erosion was the failure of the bulge in the form of earth falls. Over two to six weeks, these earth falls were washed away. The bluff response at Site 3 was not immediate; a lag time of about four to six months was recorded between the formation

Figure 5: Formation of a concave erosion zone due to wave erosion, and the resulting overhang at Site 1.

Figure 6: Failure of the overhangs and subsequent removal of talus material by wave activity maintained a near vertical profile at Site 1.

Figure 7: Notch development and subsequent plane failure at Site 2.

of the erosion zone at the toe and failure of the convex bulge. The upper part of the bluff remained relatively unaffected. Because of the bluff height, sub-aerial processes on the bluff face (dominated by rain-wash and piping) caused the bluff crest to retreat independently, which ultimately produced the sigmoidal shape of the bluff profile. However, failure of the bulges resulted in an overall steepening of the bluff face.

The beach at Site 3 also widened over the study period compared to the width observed in 1986 (about 2.5 metres in 1986 and 3.5 to 8 metres from 1987 to 1996). However, the beach was not wide enough to prevent toe erosion completely. Toe erosion was slight to moderate, reaching on average 0.5 metres high on the bluff face, which is one-fourth the height of the 1986 erosion mark. Within two to three years post-1986, continued slumping of the lower bulge made the overall slope steeper. At the same time, continued erosion at the toe, although very small, removed the slumped material and prevented the bluff profile reaching stability. The slope was not as vertical as at Site 1, but it became progressively steeper throughout the study period.

In 1997, the lake rose to 175 metres, very close to the 1986 level. This initiated beach and bluff toe erosion at all sites. By the end of the year the beach-bluff zone had a profile similar to that of 1986 with erosion marks at the toe region and consequent slumps and slides leaving materials on the beach. This was followed by a new cycle of severe toe erosion and bluff failure.

Discussion and Summary

The evolution of bluff profiles over the study period from 1986-98 at the three study sites provided three bluff response models (Figure 3). At Site 2, the continuous presence of a relatively wider and thicker beach from the end of 1986 to 1996 prevented toe erosion almost completely. This allowed the vertical bluffs (found in 1986) to progressively attain an angle of repose due to the accumulation of talus material at the toe. This helped the bluff face to reach stabilization, at least temporarily, similar to the Type-1 slope model proposed by Quigley and Gelinas (1976), and Valejo and Degroot's (1988) Model C, for bluffs with wide protective beaches and no toe erosion.

At Sites 1 and 3, continued erosion of the bluff toe maintained a near vertical bluff profile throughout the study period. However, occasional slumps and materials produced by other sub-aerial processes provided brief protection to the toe in the form of talus deposits at both sites. In spite of limited toe

Figure 8: Stable slope at Site 2 due to colonization with grasses and shrubs, thereby reducing sub-aerial erosion.

Figure 9: Toe erosion at Site 3 in 1986 resulted in the formation of an arch shaped erosion zone at the base and an associated bulging of the bluff face above the toe area.

protection, the profiles manifested at Sites 1 and 3 are indicative of the Type-2 slope with continuous toe erosion identified by Quigley and Gelinas (1976), and the bluff response Model B of Valejo and Degroot (1988) that results due to moderate toe erosion. The slight differences in bluff response between Sites 1 and 3 are due to variations in height and bluff morphology. With a moderately low bluff (eight metres) and with uniform composition (lower till), the profile at Site 1 was almost vertical throughout the study period. The bluff at Site 3 was considerably higher (17 metres, and composed of both lower and upper till), and of sigmoidal shape initially. Sub-aerial processes dominated the bluff face, resulting in a profile with a steepened (but not vertical) bluff face.

The bluff profile changes observed at the study sites were a result the rate of of toe erosion, which is a direct function of beach width, thickness, and lake-level. Although the lake-level fluctuated uniformly over time for all three sites in this study, the erosion phenomenon observed was not uniform. Even a small spatial (along shore) variation in beach width, beach thickness and wave energy distribution was found to be crucial in determining toe erosion and bluff response processes in the short term. However, exceptionally high lake-levels, such as those in 1986 and 1997, inundated all beaches and resulted in a more uniform response.

In this study, short-term (months to a year) bluff profile responses were also found to be related to bluff height and composition. Low bluffs at Sites 1 and 2 with uniform bluff composition (lower till only) experienced parallel retreat with toe erosion, which means that the crest receded almost immediately (one to four months) with toe erosion. The high bluffs at Site 3 composed of both the lower and the upper till, however, became steeper with toe erosion without immediate retreat of the bluff crest. This observation could also be due to the fact that low bluffs are dominated by wave erosion processes, whereas high bluffs are subject to both wave erosion and sub-aerial processes.

Acknowledgements

I would like to thank Professor Robin Davidson-Arnott for his assistance in field work and his constructive suggestions on the draft. The paper has also benefited from valuable suggestions from the editor, two anonymous reviewers and Patricia Chalk. I thank Marie Puddister for her cartographic help and Robert Abbott and Saad Amin for their assistance with diagrams. The work was supported in part by a Bloomsburg University research grant.

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