Frequency of Effective Wave Activity and the Recession of Coastal Bluffs: Calvert Cliffs, Maryland

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ABSTRACT

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The Calvert Cliffs, Chesapeake Bay, Maryland, USA, erode by direct wave undercutting or by freeze/thaw erosion accompanied by wave removal of slope debris. Directly undercut slopes recede more rapidly, with long-term rates exceeding 1.0 m/yr; freeze/thaw slopes recede at rates approaching 0.5 m/yr. The frequency of wave height and water level at the shoreline is estimated for eleven sites based on a 37-year wind record, estimates of storm surge, offshore wave geometry, nearshore wave transformation, and breaking wave type. Locations experiencing the largest slope recession are not uniformly those with the largest cumulative wave energy; the resistance to erosion of the slope toe must also be accounted for. An index of relative wave strength is defined as the ratio of wave pressure T and the cohesive strength S of the slope material. For the Calvert Cliffs, a minimum relative wave strength for initiating erosion of intact material is $0.05 < T/S < 0.1$. A cumulative duration of ≥ 50 hours per year for $T/S \geq 0.1$ distinguishes undercut and nonundercut slopes and recession rates greater or lesser than 0.5 m/yr. The relative wave strength index may be used to identify sites at risk of increased erosion. At one site with a small historical erosion rate, the loss of a protective beach and associated decrease in toe elevation caused a positive shift in the frequency of large T/S. Direct wave undercutting and increased slope recession may be anticipated at this site, as indicated by the development of an undercut notch during the course of the study.

ADDITIONAL INDEX WORDS: *Coastal erosion, wave climate, sea cliffs.*

INTRODUCTION

Coastal slope recession is typically measured over historical periods from maps and photographs. Future recession rates may be estimated by extrapolating historical rates if it can be assumed that there will be no change in the environmental conditions controlling slope erosion. If there is a change in one of these factors, such as water level or storminess, a simple extrapolation of historical recession rates will be inaccurate to the extent that corresponding changes in erosion processes and rates are not accounted for. A general basis for forecasting slope recession is needed that can account for the suite of erosion processes operating under different conditions. Development of such a model is hindered by the complex nature of the physical mechanisms involved and by the variation in time and space of the factors that control erosion.

The controls immediately relevant to the undercutting of coastal slopes—the magnitude and frequency of waves and water levels at the slope toe and the erosion resistance of the slope material—each depend on numerous other factors for which predictive models do not exist and whose future occur-

rence can only be forecast probabilistically. Slope erosion may also occur by mechanisms other than direct wave attack, and these may be controlled by still more factors, such as material strength, or temperature and moisture supply. Although the complexity of the problem limits the nature and detail of questions that may be successfully addressed, the clear engineering and management importance of the problem makes any advances of immediate importance.

Here, we consider the recession of eroding bluffs along the western shore of the Chesapeake Bay, Maryland, USA. The sites examined include a range of slope recession rates, wave exposure, slope toe elevation, and material properties. We describe the active erosion mechanisms and develop estimates of the wave and water level climate at the shore and the erosion resistance of the slope material. We then evaluate whether these estimates are indicative of the erosion processes and rates by comparison with historical slope recession rates measured on maps dating to the mid-nineteenth century.

An ability to identify the domain of the dominant toe erosion processes and their controls provides a minimum basis for evaluating future recession rates under conditions of environmental change. An index representing the influence of both cumulative wave activity and material resistance is needed to identify locations susceptible to accelerated erosion in response to changes in the controlling variables. We are

interested in examining whether the cumulative uncertainty—both in the physical mechanisms involved and the frequency of erosion events—is too large to develop a useful slope recession index. The particular questions we use to explore this question are:

(1) Are there threshold wave and water level conditions that initiate direct undercutting of the slope toe?
(2) Can the erosive ability of the waves and the material resistance of the slope toe be summarized in a way that
   • allows direct comparison of the erosion potential among sites with differing wave activity, toe elevation, and material strength,
   • distinguishes between actively undercut and nonundercut slopes,
   • correlates with slope recession rates, and
   • identifies locations at risk of accelerated erosion.
(3) Is there a particular storm, or combination of waves and storm surge, that is most effective at producing slope recession?

The last question focuses on the tradeoff between magnitude and frequency in determining the erosive effectiveness of waves of different magnitude. This is a classic question in geomorphology that is by no means unique to coastal erosion. In their classic paper, WOLMAN and MILLER (1960) provide their most complete development for the case of sediment transport in rivers and demonstrate that floods of moderate size tend to move the most sediment and, presumably, set the dimensions and pattern of river channels. They also extend this argument to other cases (notably the erosion of cohesive river banks in humid temperate regions, the form and alignment of desert dunes, and the slope of beach profiles) and note that few cases exist to demonstrate the concept in erosional environments. In the fluvial sediment transport case, their demonstration of the effectiveness of moderate events requires a specified relation between the magnitude of the driving force (water discharge) and the resulting process (sediment transport). Although a comparable rate law (*e.g.* between wave pressure and erosion rate) is not available for the retreat of coastal bluffs, a comparison of cumulative wave activity and historical erosion rates provides a basis for qualitatively addressing the magnitude and frequency question in an erosive coastal environment.

EFFECTIVE WAVE ACTIVITY AND SLOPE RECESSION

Although the various forces causing coastal slope recession may be listed, their number, complexity, interdependence, and variability in space and time make it difficult to find simple correlations between driving forces and slope response. Typically, the immediately relevant variables, wave height and water level at the shoreline and erosion resistance of the slope toe, are unknown. Wave conditions may be represented by measured or hindcast offshore waves, or simply by wind speed, although offshore wave parameters do not account for wave transformations in the nearshore. The range and complexity of erosion mechanisms are such that a wide variety of material properties may influence resistance to

wave erosion. An index of erosion resistance may be based on a measure of material strength, such as compressive or shear strength, although no strength measure directly replicates the material properties mobilized to resist wave attack (KAMPHUIS, 1987; SUNAMURA, 1992).

GELINAS and QUIGLEY (1973) and KAMPHUIS (1987) established simple power relations between the long-term average offshore wave power and the historical recession rates of tall bluffs on the north shore of Lake Erie (Canada). QUIGLEY *et al.* (1977) noted the important influence of lake level on the rate and type of slope failure, and demonstrated the cyclical nature of slope recession in tall bluffs subject to large failures, wherein periods of active undercutting are interrupted by periods during which slope debris protects the toe from wave activity. Empirical relations between slope recession and an average measure of offshore wave energy do not account for the local variability in erosion resistance or the transformation of waves as they traverse the nearshore, so site specific predictions from such relations will have considerable uncertainty.

CARTER and GUY (1988) measured local toe erosion with erosion pins in five low bluffs along the south shore of Lake Erie (USA). They identified minimum thresholds of water level and storm surge associated with active toe erosion, although these thresholds were nonunique because nearly all events with no measurable erosion (74% of the total) also exceeded one or both thresholds. They emphasized the importance of preparation of toe material by weathering (freeze/thaw, wet/dry, joint enlargement) which transforms strong cohesive materials into easily eroded, noncohesive material.

DAVIDSON-ARNOTT and OLLERHEAD (1995) measured vertical erosion of the inner nearshore in front of bluffs in glacial till on Lake Ontario (Canada). They found that the rate of nearshore lowering (to which bluff recession is directly related for long-term equilibrium profiles) was positively related to the magnitude and duration of offshore waves measured approximately 10 km from the site. The spatial variability in erosion was quite large, which they suggest is a result of variations in till strength and the proportion of coarse sediment cover, both of which were difficult to measure in the field, particularly under the appropriate wave conditions.

McGREAL (1979) conducted a statistical analysis of factors controlling the short-term erosion rate of bluffs in glacial deposits on the east coast of Northern Ireland. For this low energy environment with high slope toe elevations, he identified threshold values of spring high tide and wind speed necessary to raise the water level to the slope toe and cause direct wave erosion. Spatial variation in erosion rates was correlated most strongly with shoreline orientation, with material strength playing a lesser role, except for short time periods.

SUNAMURA (1982) demonstrated that the recession of rock cliffs on the east shore of Japan could be modeled as a function of rock compressive strength and the magnitude and frequency of wave height. Although local wave heights were only approximately estimated from long-term records of visual observations of waves 50 to 100 km from the study sites, he was able to demonstrate a correlation between cliff recession distance and the duration of wave strength relative to the

rock compressive strength. A critical wave height for initiating erosion was estimated by fitting a theoretical relation between recession distance and relative wave strength, rather than direct observation. Sunamura concluded that recession rate increases with the duration of waves larger than the critical height and that recession was due entirely to the larger, rarer waves, although the study periods were of short duration (two and six years).

HALE and GREENWOOD (1980) adopted a different approach to the magnitude and frequency of effective wave events. They used wind records to generate a synthetic wave climatology for Kouchibouguac Bay, New Brunswick (Canada), a low energy, storm-wave dominated environment. Recurrence intervals for different storm events were calculated and used with direct observations of different types of coastal processes to estimate their return period. Rip channel excavation and bar migration in the inner nearshore were estimated to have a return period of less than one month. Modification of bars in the outer nearshore and barrier washover had a return period of approximately one year, whereas breaching of barrier islands had a return period of four to twelve years. Although these estimates demonstrate the relative frequency of different events, Hale and Greenwood were not able to assign absolute values of work done (e.g. as a volume of sediment transport) in the different events, so the relative effectiveness of the different storms could not be assessed.

The approach taken here combines some aspects of the previous studies. We use long-term wind records to develop a synthetic wave and water level climatology for our sites. Frequency distributions are developed for offshore waves, which are then transformed over the nearshore bathymetry to account for varying fetch, bathymetry and shoreline orientation. Together with an estimate of storm surge, the result is a frequency distribution of wave height and water level at the shoreline. Wave strength at the shoreline is expressed as a wave pressure and depends strongly on whether the waves break before reaching the slope toe, directly on the slope, or do not break at all. Erosion resistance is estimated using an undrained vane strength. The final result for each site is a frequency distribution of local wave pressure scaled by material strength. Slope recession rates are taken from measurements of shoreline position on mid-nineteenth century maps and recent vertical aerial photographs (KERHIN et al., 1993).

STUDY AREA

The open shoreline of Calvert County, Maryland extends 45 km along the western side of the Chesapeake Bay (Figure 1). Sixty-five percent of this shoreline consists of steep slopes 10 to 35 meters high. Most of these slopes, well known as the fossiliferous Calvert Cliffs, are actively eroding. Slope recession rates measured over a 140 year period vary widely along the cliffs, from near zero to greater than two meters per year (KERHIN et al., 1993; DOWNS, 1993).

The Calvert Cliffs face toward the east, northeast, and southeast (Figure 1). The middle Chesapeake Bay has a gentle arc shape, giving major fetch directions from the northeast
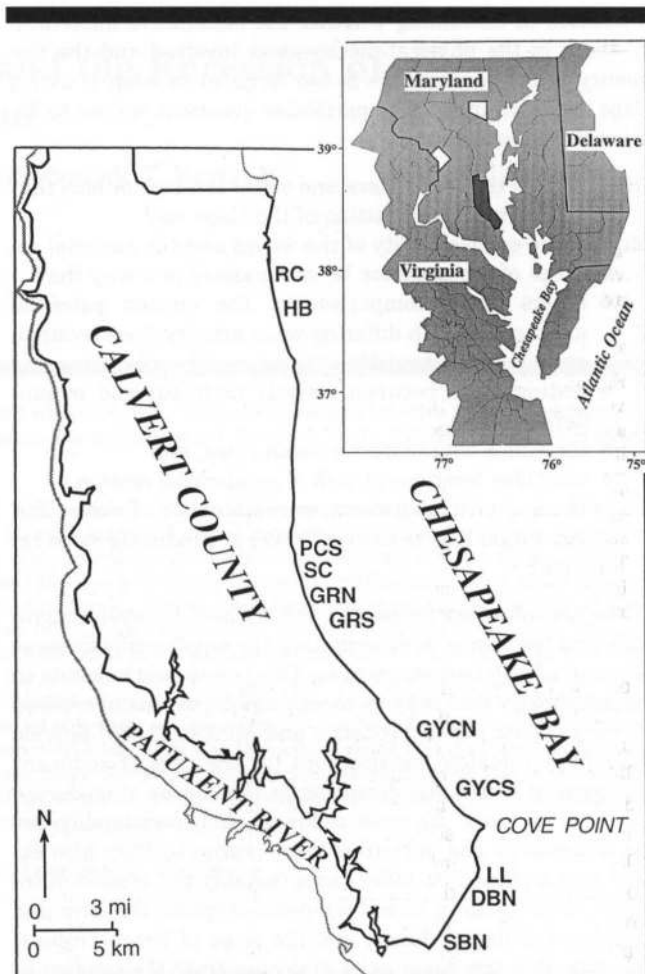

Figure 1. Calvert County, Maryland. Initials represent study sites for which historical erosion rates are compared with the frequency of relative wave strength. Names and properties of the study sites given in Table 1.

and southeast along the main channel of the bay. The fetch directions used here are north to northeast (0°–60°), east (60°–120°), and south to southeast (120°–180°). Fetch lengths vary along the shoreline from 10 to 20 km for east winds, 70 to 105 km for north-northeast winds, and 135 to 175 km for south–southeast winds.

The central axis of the Chesapeake Bay is formed by a channel of 15 m average depth and is the remnant of the Susquehanna River channel during the last glacial maximum. Post-glacial sea-level rise produced gradual recession of the valley walls, creating wide, shallow shelves between the channel and the present shore along both sides of the bay. The slope of the western shelf ranges from 0.3 degrees along the northern and central portions of Calvert County to 0.6 degrees near the Patuxent River at the county's southern boundary (U.S. NOAA, 1984, Hydrographic Chart 12263).

The Calvert Cliffs are composed primarily of Miocene shallow marine deposits which are non-lithified, interbedded fossiliferous sands, gravelly sands, silts, and clays. Thin, laterally discontinuous patches of indurated, gravelly sands, com-

Table 1. *Nearshore and lower slope properties.*

Site	Nearshore Type	Near-shore Slope	Slope Toe Elevation[1] (m)	Histori-cal Erosion Rate[2] (m/yr)	Lower Slope Strength[3] (kPa)	Lower Slope Angle (°)	Lower Slope Material[6]	Dominant Erosion Mechanism
Randle Cliffs (RC)	Multiple bars	0.0111	−0.09	0.3	125 (103, 0.9 m)[4]	78–85	clayey silt	Freeze/Thaw
Holiday Beach (HB)	Multiple bars	0.0163	0.80	0.35	125	52–64	clayey silt	Freeze/Thaw
Scientists Cliffs (SC)	Multiple bars	0.0125	1.00	0.1	60	48–63	sandy clay	Freeze/Thaw
Governor Run North (GRN)	Multiple bars	0.0215	1.00	0.1	105 (30, 1.0 m)[4]	48–55	sandy clay/sand	Freeze/Thaw
Gray's Ck. South (GYCS)	Planar	0.0115	0.45	0.4	77	50–70	silty clay	Freeze/Thaw
Laramie Lane (LL)	Planar	0.0100	0.60	0.4	98 (26, 1.0 m)[4]	65–75	clayey silt	Freeze/Thaw
Seahorse Beach North (SBN)	Two Bars	0.0222	0.35	0.2	77	65–75	clayey fine sand	Freeze/Thaw
Parker's Ck. South (PCS)	Multiple bars	0.0085	0.00	0.8	48	75–80	sandy clay	Wave Undercut
Governor Run South (GRS)	Multiple bars	0.0155	1; 0.3[5]	0.1	30	70–80	sandy clay/sand	Wave Undercut
Gray's Ck. North (GYCN)	Planar	0.0115	0.35	1	5	60–70	sandy shells	Wave Undercut
Driftwood Beach North (DBN)	Two Bars	0.0210	0.30	0.6	26	70–80	clayey fine sand	Wave Undercut

[1]Elevation relative to 1929 National Geodetic Vertical Datum
[2]From historical maps and orthogonal aerial photographs, 140 yr. period, Kerhin et al. (1993)
[3]Vane shear strength; some sites have a change in strength with elevation
[4]Where strength changes with elevation, value in parentheses gives strength of upper unit and elevation of boundary between units
[5]Higher elevation assumed for beach in place, lower elevation is current
[6]Size classification system of Shephard (1954)

monly known as ironstone, are the strongest material present in the slopes. Twenty-two stratigraphic units have been distinguished within the cliffs (SHATTUCK, 1904; KIDWELL, 1982); the number of geotechnically distinct units is approximately the same, although not always following the same boundaries as the sedimentologically defined units (MILLER, 1995). The sedimentary strata are undeformed and nearly horizontally bedded, with a regional dip of less than one degree to the southeast. The sequence of materials exposed at water level varies gradually and predictably along the shoreline (VOGT and ESHELMAN, 1987). Nine different units are found within the tidal zone for the sites discussed here. The geotechnical properties of these units tend to be laterally uniform over the distances 500 m or less in which they are exposed to wave action (MILLER, 1995).

The lower portion of the tall bluffs in Calvert County are typically composed of moist, fine-grained materials with measurable cohesive strength (Table 1). Stress release joints are typically found parallel to the slope in the fine-grained strata. Tall bluffs are typically absent where coarser, fossiliferous units with little cohesive strength intersect the tidal zone, presumably a result of rapid undercutting and erosion in advance of the general shoreline retreat since the Chesapeake Bay reformed following the last glacial maximum. The exceptions are heavily cemented, carbonate-rich strata and one location (GYCS) that is currently eroding rapidly, but was presumably protected in the past by the Cove Point sand cape (Figure 1), which has been documented to be slowly migrating south (DOWNS, 1993).

SUMMARY OF SLOPE TOE EROSION MECHANISMS

Material in the lower slope is eroded by either direct wave removal of intact material or by weathering and gravitational transport down the slope face. In the first case, undercutting by wave action directly produces recession of the slope toe.

In the second case, wave removal of debris accumulated at the slope toe maintains the slope angle and ongoing slope erosion processes. Although both suites of processes can occur on the same slope, we observe that one or the other typically dominates. Clearly, slope processes dominate where the combination of wave climate and material resistance is insufficient to cause wave erosion of intact material. Where wave undercutting occurs, the slopes tend to fall as undercut blocks, so that notch cutting and blockfall determine the recession rate, rather than surficial slope erosion processes.

Four of the 11 sites we investigated are subject to direct wave undercutting of intact material. Typically, wave action produces a notch within the wave zone by quarrying cm-scale blocks of cohesive material. The overlying material is then undercut and falls in a slab-like failure that we term spalling (Figure 2a). Typically, the failure occurs along steep, slope-parallel stress-release joints that are often damp. If not immediately broken up by subsequent wave action, fallen slabs can lean intact against the slope until a later storm breaks them into smaller, transportable pieces.

The lower slopes of the remaining seven sites erode primarily by freeze/thaw disintegration of material near the slope surface, which causes grain- to cm-scale particles to fall to the slope toe or creep as a viscous slurry (Figure 2b). Wave-cut notches in intact material are generally absent on these slopes, although large wave events sometimes produce small notches that are removed by subsequent freeze/thaw recession of the lower slope. Active mass wasting of a melting slurry is readily evident on sunny winter days following a sub-freezing night. Most commonly, thawing occurs on the day immediately following a sub-freezing night, although during an 8-day sub-freezing period in January 1994, ice formed to a depth of 10 cm within the slope. The ice formed in slope-parallel sheets of 0.5 to 1.0 cm thickness separating 1 to 2 cm thick soil sheets. Upon thawing, the entire frozen layer slumped to the beach.
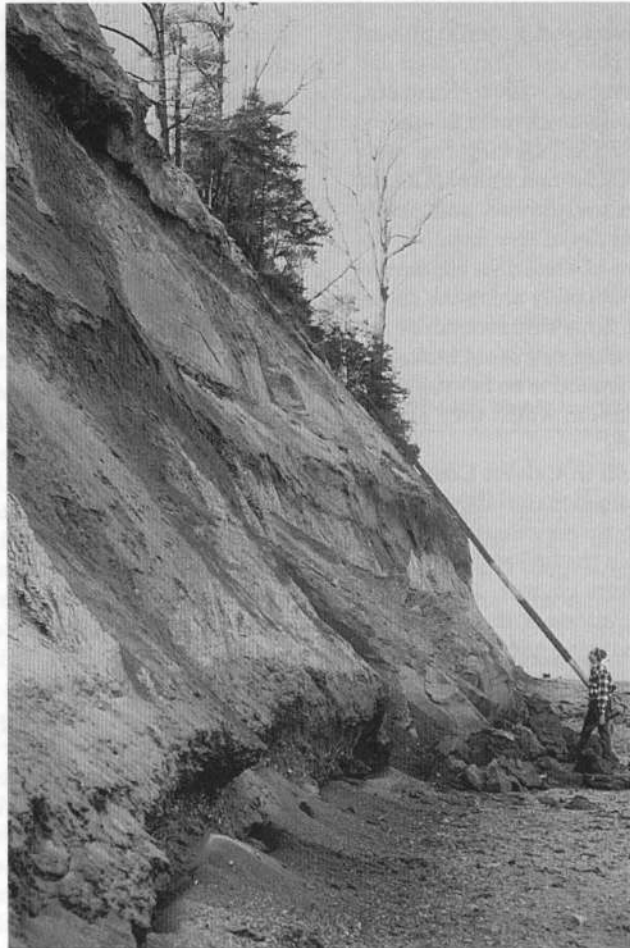
Figure 2. (a) Slope directly undercut by waves. Once undercut, blocks of intact material up to 0.5 m thick and 2 m long separate along stress-release joints and fall to the beach, to be removed by subsequent wave activity. (b) In foreground, abundant slope-toe debris produced by freeze/thaw disintegration and subsequent mass wasting. Colluvial debris has been partially removed by wave activity. In background, slope toe covered by block falls resulting from undercutting and steepening of the lower slope by wave erosion of intact slope material.

Erosion pins were placed in drilled holes along the lower portion of four slopes (three at SC and one at GYCS, Figure 1) and monitored over one or two winters in 1992/93 and 1993/94 (SCHWEITZER, 1993; MILLER, 1995). The 1992/93 winter had 42 subfreezing nights (38 freeze/thaw cycles), which was slightly milder than the mean of 46 subfreezing nights (41 freeze/thaw cycles) based on 12 years of record at the Patuxent Naval Air Station, located across the mouth of the Patuxent River from the southern end of the study area (Figure 1). The 1993/94 winter was somewhat colder, with 57 subfreezing nights (41 freeze/thaw cycles). During the 1992/93 winter, mean erosion rates for the lower slope at SC were 5 to 7 cm/yr and at GYCS were 31 cm/yr. During the colder 1993/94 winter, erosion rates of 7 to 10 cm/yr were observed at SC; the pins at GYCS were completely eroded early in the second winter. These freeze/thaw erosion rates are similar to the local long-term slope recession rates of 5–10 cm per year at SC and 40 cm/yr at GYCS.

In the absence of evidence of direct wave undercutting of intact material, the observed freeze/thaw erosion rates and their similarity to the long-term slope recession rates suggest that the recession rate of these slopes is set by the rate of freeze/thaw erosion. The freeze/thaw dominated slopes tend to have a larger silt and clay content, which not only increases the moisture retention of the slope, but also tends to provide a larger cohesive strength and resistance to direct wave erosion. On these slopes, wave action is still required to remove the accumulated debris from the slope toe, or a protective, insulating debris layer will develop on the slope face. The rate of slope recession, however, appears to be set by the rate of freeze/thaw mass wasting.

Slope angles of the lower portions of the bluffs vary between 45° and 90°, with no distinction between the two suites of erosional processes except that the directly undercut slopes have a narrower range of angles, between 60° and 80°. The different erosion mechanisms are associated with different historical erosion rates: all slopes observed to be directly undercut by waves have larger historical recession rates than those not directly undercut, although it is important to note that the most rapidly retreating freeze/thaw dominated slopes retreat at rates comparable to the more slowly retreating wave undercut slopes (Table 1).

NEARSHORE WAVE AND WATER LEVEL CLIMATE

Shoreline orientation, slope toe elevation, storm surge, and wave climate all vary among the study sites along the Calvert County shoreline. Multiple shore-parallel bars are found within 1,000 m of much of the Calvert County coastline. Waves traversing the nearshore are commonly observed to break and reform more than once. All of these factors cause both the magnitude and frequency of waves and water level to vary along the shore. Because one of our objectives is to compare the wave climate at different locations, we develop a site-by-site summary of wave and water level conditions which includes the effect of nearshore wave transformation. The result is an estimate of the frequency distributions of wave height and water level at the shoreline for all winds in the dominant fetch directions. Because the interaction among

Table 2. *Frequency of storm surge and offshore waves.*

Wind Speed Interval (m/s)	NNE Waves Fetch = 70 to 105 km		E Waves Fetch = 10.5 to 20 km		SSE Waves Fetch = 135 to 175 km	
	Frequency (days/yr.)	Storm Surge Elevation (m)	Frequency (days/yr.)	Storm Surge Elevation (m)	Frequency (days/yr.)	Storm Surge Elevation (m)
<2.7	24.6	n.a.	17.9	n.a.	31.5	n.a.
2.8–6.7	19.8	0.4	10.4	0.4	25.7	0.4
6.8–8.9	10.5	0.5	3.8	0.45	13	0.5
9.0–11.6	2.6	0.6	0.7	0.5	2.6	0.6
11.7–17.4	0.8	1.0	0.2	0.9	0.2	1.0
>17.5	0.07	n.a.	0.03	n.a.	0.12	1.3

waves, water level, and shoreline retreat is likely to be nonlinear, this summary of local shoreline wave climate should give a more realistic representation of wave/shoreline interactions than long-term mean values of offshore wave energy.

A frequency distribution of winds from the dominant fetch directions was developed using a 37-year record (1945–1982) of hourly wind speeds at the Patuxent Naval Air Station. Frequencies of five wind speed intervals were cumulated for the three dominant fetch directions (Table 2).

For each wind class, storm surge was estimated using empirical relations developed for the Chesapeake Bay by BOON et al. (1978) for extra-tropical storms and by CHEN (1978) for tropical storms. Storm surge from the BOON et al. (1978) curves agreed well with observed water levels at two sites (RC and SC) during three storms with sustained NNE winds. Mean water levels were estimated visually and marked on shoreline structures to be later surveyed in relative to an established datum. Storm surge water levels (and all other elevations used this work) are relative to the 1929 National Geodetic Vertical Datum. Tropical storm Danielle (25 September 1992), with sustained NE winds of 11–13.5 m/sec, produced a storm surge water level of 0.95 m at RC and 0.92 m at SC. Estimated water levels at both sites were 1.00 m from the model of BOON et al. (1978), as well as from the wave set-up formulation in the Shore Protection Manual (U.S. ARMY, 1984) using local hourly observations of wind speed, wind direction, and duration. Two different storms (1 January 1993 and 3 March 1993) with sustained NE winds of 9–11 m/sec produced a storm surge of 0.50 m at SC, compared with 0.60 m estimated from the model of BOON et al. (1978) and 0.55 m calculated from hourly wind observations. No events suitable for evaluating the local accuracy of Chen's model occurred during the study period (although Danielle was a tropical storm, its wind field was locally similar to that of an extra-tropical storm). The storm surge assigned to each wind class is given in Table 2 as an increase in water surface relative to mean stillwater.

Offshore significant wave heights were taken from the 15 meter shallow-water wave charts in the Shore Protection Manual (U.S. ARMY, 1984). Because the transformation of a wave as it traverses the nearshore depends on its offshore wave height, a distribution of wave heights was assigned to each wave class. A Rayleigh distribution of wave heights was

used because it is found to provide a good representation of wave heights (LONGUET-HIGGINS, 1952) and may be calculated from the significant wave height.

To account for the influence of multiple wave breaking, as well as variable shoreline orientation and wind direction, wave transformation through the nearshore was calculated using RCPWAVE, a linear short-wave model for wave propagation over arbitrary bathymetry (EBERSOLE et al., 1986; CIALONE et al., 1992). The model includes refractive and bottom-induced diffractive effects and calculates wave reformation after breaking. The bathymetric grid used for modeling the nearshore of each site was established using shore-transverse bathymetric profiles approximately every 300 m. The profiles were measured using shore-based total station readings from a reflector mounted on a boat traveling between surveyed buoys. Simultaneous fathometer readings were used to fill in the bathymetry between surveyed points. A bathymetric grid with offshore spacing of less than 7 m and alongshore spacing of 28 to 30 m was developed for each site using a numerical contouring algorithm (SHEA, 1994). The waves used in the shoreline wave climatology were those calculated for the most shoreward grid points, which were located between 5 and 10 m of the slope toe.

Wave modeling was done for each of the three wind directions and four of the six wind intervals (Table 2). Winds smaller than 2.7 m/sec were assumed to not produce waves and storm surge sufficient to erode slope material. Nearshore wave conditions for the 6.8–8.9 m/sec interval were interpolated from values calculated for the other four wind speed intervals. In each case, the wave modeling was done using the storm surge water level associated with that wind condition (Table 2).

WAVE STATE AT THE SLOPE TOE

The wave force exerted on the slope toe depends on not just the wave dimensions, but also on whether the wave breaks before reaching the slope, breaks directly on the slope face, or does not break at all (SUNAMURA, 1992). Waves breaking directly on the slope face exert the largest forces on the slope material; waves that break before reaching the slope toe exert a smaller force, and waves that do not break at all exert the least force (KIRKGOZ, 1994). To estimate the frequency distribution of wave force at each site, it is necessary to develop separate expressions for wave pressure for each type of wave, as well as a basis for estimating the wave type. The general wave breaking criterion used here is H/d = 0.78, where H is wave height and d is water depth, which is appropriate for the nearshore slopes in the study area and consistent with the formulation in RCPWAVE.

Wave observations at the study sites suggest that waves that break more than one wavelength offshore tend to reach the slope toe as a translational turbulent bore. In contrast, waves that begin breaking within approximately one-half wavelength of the slope tend to not strike the slope face as fully developed breaking waves. Using the wave breaking criterion of H/d = 0.78, these observations suggest that a workable set of rules for classifying the wave type at the slope toe is, for broken waves,
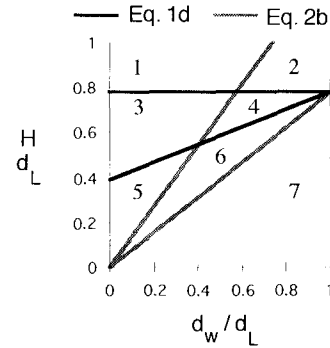

Figure 3. Schematic illustrating alternative wave breaking criteria, represented by Eqs. (1d) and (2b). Using Eq. (1d), regions 3 and 4 of the graph represent waves that break at an offshore distance between one wavelength and the location of $0.5(d_L + d_w)$; larger waves (regions 1 and 2) break further offshore and smaller waves (regions 5, 6, 7) would not break before reaching the slope face. Using Eq. (2b), regions 2, 4, and 6 represent waves with $0.85 < H/d_w < 1.35$, which should produce maximum slope face pressures following the results of KIRKGOZ (1995). Both larger waves (regions 1, 3, 5) and smaller waves (region 7) would produce smaller slope face pressures.

$$\frac{H}{d_L} > 0.78 \tag{1a}$$

for breaking waves,

$$\frac{H}{d_L} < 0.78 \quad \text{and} \quad \frac{H}{0.5(d_L + d_w)} > 0.78 \tag{1b}$$

and for unbroken waves,

$$\frac{H}{0.5(d_L + d_w)} < 0.78 \tag{1c}$$

where d_L and d_w are the water depth one wavelength offshore and at the slope toe, respectively, and the boundary between breaking and unbroken waves is taken to occur at the average of d_L and d_w. Eqs. (1a) through (1c) may be combined to define the domain for breaking waves as

$$0.39\left(1 + \frac{d_w}{d_L}\right) < \frac{H}{d_L} < 0.78. \tag{1d}$$

Waves with larger H/d_L are treated as broken and waves with smaller H/d_L as unbroken (Figure 3).

In laboratory studies, KIRKGOZ (1991) found that the largest wave impact pressures occur over a range of d_w about a depth d_{wm} that produces perfect breaking against a wall and maximum wave impact pressures. Kirkgöz found d_{wm} to depend on the offshore wave steepness. For the range of offshore wave steepness in this study, an empirical relation of KIRKGOZ (1995) suggests that d_{wm}/d_b falls between 0.75 to 0.80. For $H/d_b = 0.78$, therefore, d_{wm} is equal to H within a few percent. For design purposes, KIRKGOZ (1995) recommended that impact pressures close to the maximum may be expected for a depth range of $0.74d_{wm} < d_w < 1.18d_{wm}$ for vertical walls and that the range of d_w producing large impact pressures decreases slightly with wall inclination from the

vertical. Substituting H for d_{wm}, the result is that maximum wave impact pressures may be expected for

$$0.85 < \frac{H}{d_w} < 1.35 \qquad (2a)$$

which may be rearranged in the form of Eq. 1d as

$$0.85\frac{d_w}{d_L} < \frac{H}{d_L} < 1.35\frac{d_w}{d_L}. \qquad (2b)$$

This relation is compared to the first wave criteria in Figure 3.

In the following, we use Eq. (2a) to define the domain of breaking waves, provided that $H/d_L < 0.78$ (regions 4 and 6 of Figure 3). Broken waves are taken to be those with $H/d_w > 1.35$ or $H/d_L > 0.78$ (regions 1, 2, 3 and 5 of Figure 3) and nonbreaking waves as those with $H/d_w < 0.85$ (region 7 of Figure 3). Estimates of wave type were also made using alternative criteria (breaking waves occurring in region 4 and in regions 3 and 4 of Figure 3), but are not reported on here. These breaking criteria gave results that are different in detail, but qualitatively similar to the results we present. The criterion we use was chosen for its simplicity and stronger empirical basis.

To make use of the extensive existing work on wave forces on structures and to provide a consistent comparison with erosion resistance expressed as a strength, we calculate wave force as a pressure. Although pressure is not the only component of wave action producing erosion, we assume that other factors act in proportion to the pressure. Because material is eroded at all scales down to the grain scale and material, once eroded, is irretrievably lost to the slope, we assume that the rate at which waves can pluck and quarry material from the slope face will be determined by the larger values of wave pressure, even if localized and of short duration.

The maximum pressure of a wave breaking on steep walls has been found to be proportional to the wave height in a range of experimental studies (*e.g.* KIRKGOZ, 1991, and earlier experiments listed in SUNAMURA, 1992). In the absence of a theoretical solution, Sunamura suggests the following simple relation for the maximum pressure exerted by waves breaking directly on the slope face

$$P_{me} = 35\gamma H_b \qquad (3)$$

where γ is the unit weight of water and H_b is breaker height. This expression corresponds approximately to the wave pressure exceeded 10% of the time for wall angles between vertical (90°) and 55° in the extensive laboratory experiments of KIRKGOZ (1991). Eq. (3) is used here to calculate the pressure due to breaking waves.

The pressure exerted by waves that break before reaching the slope is calculated as

$$P_{mo} = 1.6\gamma d_w \qquad (4)$$

an empirical result given by HOM-MA and HORIKAWA (1964). For most cases in our study, P_{mo} given by Eq. (4) is within a factor of two of an approximate relation developed by the U.S. Army Corps of Engineers (U.S. ARMY, 1984, p. 7–193). In the rare cases for which the slope toe elevation was above the stillwater level, the broken wave pressure is reduced by assuming a linear loss of surge height between the stillwater line and the assumed point of highest wave run-up (CAMFIELD, 1991).

Nonbreaking wave pressure was calculated as the hydrostatic pressure at the stillwater level. Using the approximation that 78% of the wave height is above the stillwater level (U.S. ARMY, 1984, p. 7–192), this gives

$$P_s = 0.78\gamma H_b. \qquad (5)$$

Comparison of Eqs. (3) and (5) shows that nonbreaking wave pressures are negligibly small in environments where wave breaking can be anticipated.

Alternative measures of wave pressure were considered, particularly for breaking waves, which exert the largest pressures on the slope toe. Breaking wave pressures were calculated using the MINIKIN (1963) formulation which gives values that are comparable to Eq. (3) for smaller wavelengths, but become smaller by as much as an order of magnitude for larger wavelengths. Eq. (3) was chosen for its simplicity and its stronger empirical basis. The alternative breaking wave pressures gave cumulative wave pressures that were different in detail, but similar on a relative basis to those reported below. The general conclusions we draw are the same for either method.

ESTIMATING RELATIVE WAVE STRENGTH

A range of material properties give rise to resistance of erosion by waves, so it is unlikely that any single measurable property can accurately represent wave erosion resistance for all cases. Here, we use the in-situ undrained shear strength, as measured by a hand-held rotary shear vane. For material close to the slope surface, this strength corresponds closely to the apparent cohesive strength. Although it is obviously not a direct replication of the material resistance mobilized during a wave impact, we adopt this measure primarily because it permits repeatable and expedient in-situ measurement and because the observed values correspond well to the relative erodibility of the materials at our sites (*e.g.* stiff, massive silty clay with high cohesive strength is evidently more difficult for waves to erode than loose shelly sand with little cohesive strength). Susceptibility to wave erosion clearly varies among our study sites and some measure of material erodibility, even if approximate, is necessary to compare wave activity, material resistance, and the resulting erosion among the different sites.

In situ strength of the stratigraphic units exposed at tide level was measured using a hand-held Torvane rotary shear vane. Tests were made where each unit occurred in the tidal zone. Strength varied between units by a factor of 25 or more, from 5 kPa to greater than 125 kPa, which was the limit of the device (Table 1). The variability of strength within a unit was much smaller. In all cases, the standard deviation of strength observations within individual stratigraphic units was less than 25% of the mean value given in Table 1. In some cases, a boundary between units of different strength occurs within the range of possible water levels, in which case the value of strength is changed when the stillwater level rises above the material contact (Table 1).

To compare relative wave activity at different sites, a sim-

ple and consistent basis is needed for representing the wave pressure relative to the material strength. We use the ratio T/S, where T is the instantaneous wave pressure and S is the cohesive strength of the slope material. In the following, we evaluate the magnitude and frequency of effective wave attack in terms of the frequency distributions of T/S for each site.

MAGNITUDE AND FREQUENCY OF EFFECTIVE WAVE EROSION

The calculated wave pressures for each wind condition and each site were combined with the frequencies for each of the 13 wind categories to give a frequency distribution of T and T/S for each site. The influence of storm surge on the wave pressure frequency is included in two ways: the water level determines *whether* the waves break on the slope toe (if not, T = 0) and the water depth through which the waves pass, which influences wave height, wave type, and the wave pressure exerted on the slope face. For waves reaching the slope face, we do not distinguish between waves breaking at different elevations, except when the material strength varies with elevation within the wave zone.

The frequency of relative wave strength is shown in Figure 4 for each of the 13 sites. The values plotted are running averages over a range of T/S of a factor of 4, to partially account for the fact that offshore wave height and period were input as grouped values rather than continuous distributions. The frequency distribution for most sites is bimodal, a result of the filtering effect on wave height of nearshore bars and the differing frequencies of winds from different directions. Figure 4a represents sites without direct undercutting of the toe. In these cases, toe recession proceeds primarily by freeze/thaw and wave action is limited primarily to removal of toe debris. Figure 4b represents the four sites with directly undercut slopes.

Comparison of parts a and b of Figure 4 shows that the directly undercut slopes tend to have a greater frequency of large relative wave strength, although the distinction between the two types is by no means distinct. Nonundercut slopes include cases with large, but rare relative wave strength (*e.g.* LL and SBN). This suggests that larger waves, although more destructive, do not produce direct undercutting if they are of insufficient duration. Nonundercut slopes also include cases with very frequent, but small wave strengths (*e.g.* RC and SBN). This suggests that there is a threshold value of relative wave strength, on the order of 0.05 < T/S < 0.1, that will not produce direct undercutting.

If a particular range of T/S were responsible for most of the direct undercutting (analogous to the river discharge producing the most sediment load in the Wolman-Miller magnitude/frequency example), it should be evident on Figure 4 as a frequency common to the directly undercut slopes, but not the nonundercut slopes. Comparison of the maximum T/S frequencies for nonundercut slopes with the minimum frequency for directly undercut slopes (Figure 4c) shows that the frequency of moderate wave strengths, on the order of 0.1 < T/S < 0.5, is greater for all directly undercut slopes, suggesting that it is the moderate storm that is most responsible for
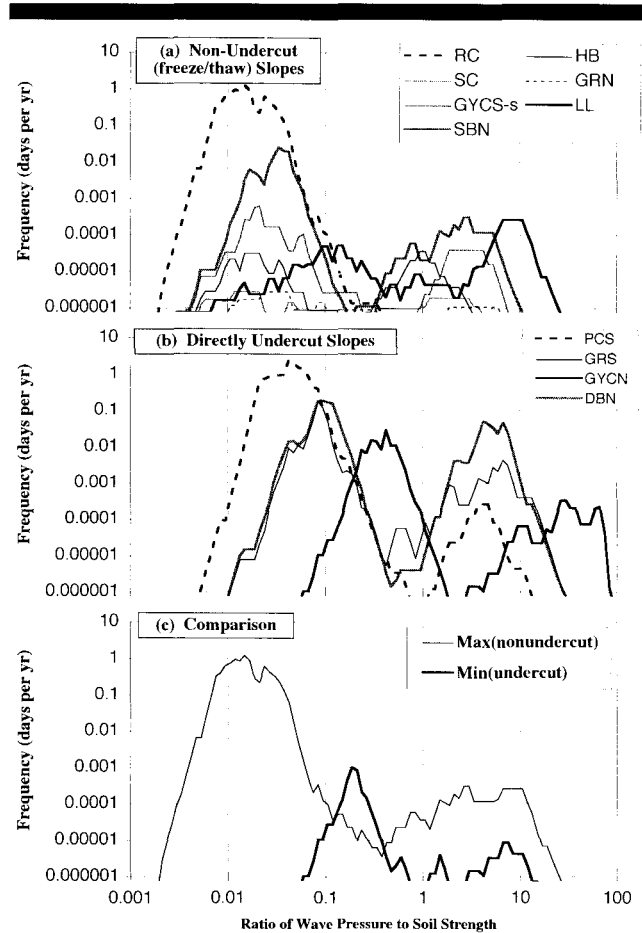

Figure 4. Frequency distribution of relative wave strength, expressed as ratio of wave pressure T to cohesive soil strength S. (a) Nonundercut slopes, (b) directly undercut slopes, (c) comparison of minimum frequency for undercut slopes and maximum frequency for nonundercut slopes. One criterion for effective wave activity is a range of relative wave strength experienced only by undercut slopes; the frequency of T/S for all undercut slopes exceeds T/S for all nonundercut slopes only in the range 0.15 < T/S < 0.5.

directly undercutting slopes. Although this particular result may be indicative, we do not expect that it must hold for all locations. For example, an actively undercut site may have a high frequency of very large waves, but few waves of moderate strength, by virtue of its location along the bay and its local shoreline configuration. Nonetheless, the general heuristic argument of WOLMAN and MILLER (1960) may be used to suggest that neither the largest or smallest waves are responsible for most of the toe erosion. Extremely large but very rare waves would be too infrequent to produce a significant proportion of the slope recession. Frequent, small waves would not be sufficiently strong to erode intact material and would also be associated, in general, with little wave setup and lower water levels.

Direct comparison with the magnitude/frequency argument made for rivers is not possible because a comparable rate law (*e.g.* mass of sediment eroded per unit shoreline width as a function of wave magnitude) is not available. However, a fur-
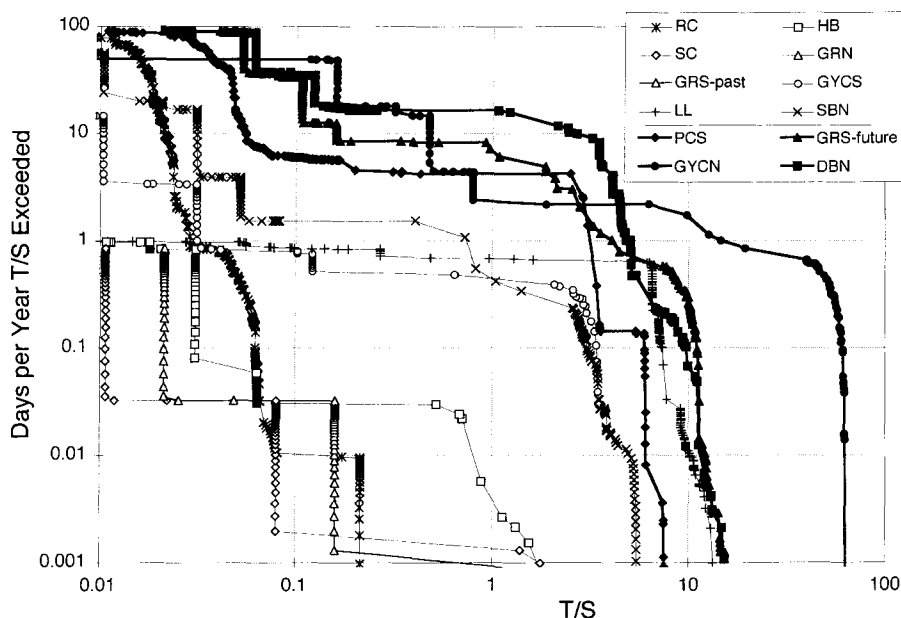
Figure 5. Cumulative frequency distribution of T/S. Undercut slopes shown with filled symbols and heavy lines; nonundercut slopes shown with open symbols and light lines. Cumulative frequency of T/S for undercut slopes exceeds that for nonundercut slopes over the approximate range 0.05 < T/S < 2 for durations on the order of two days per year.

ther distinction between the two cases suggests that any particular range of wave magnitude or T/S is not likely to be readily or consistently associated with the most slope recession. The frequency distribution of discharge in rivers is smooth, continuous, and can generally be approximated by a lognormal distribution. When combined with a power relation between discharge and sediment load, a discharge of moderate size will be associated with the transport of the largest amount of sediment and, therefore, will be the most effective at performing work (WOLMAN and MILLER, 1960). In contrast, the frequency distribution of relative wave strength is not lognormal (Figure 4), or necessarily even continuous, when the tides, storm surge, and wave height associated with individual locations and storms of different type, magnitude, and direction are combined into a single frequency distribution (particularly for storm-wave dominated coasts). As a result, it is not necessary that a particular range of wave strength will be consistently and unambiguously associated with the largest proportion of slope recession at different locations.

Nonetheless, because both magnitude and frequency of wave attack clearly play a role in determining whether a slope is directly undercut, a reasonable approach is to consider not the frequency of relative wave strength (the details of which will vary from site to site), but the cumulative frequency of wave strength exceeding some threshold. Figure 5 shows the cumulative exceedance frequency of T/S for all 11 sites. A cumulative exceedance greater than about two days per year for T/S in the range of 0.05 to 2 clearly distinguishes between undercut and nonundercut sites. The frequency distributions for undercut and nonundercut slopes overlap for

T/S greater than about 4, further suggesting that the extreme values of T/S do not determine whether a slope will be undercut.

The relation between these frequency distributions and the historical erosion rate are shown in Figure 6, where the frequency distributions for individual sites are arranged according to historical erosion rate. All undercut slopes recede at larger rates than the nonundercut slopes, although the largest recession rate for nonundercut slopes (0.4 m/yr) is not substantially different from the smallest recession rate (0.6 m/yr) for an undercut slope. A special case is Governor Run South (GRS). This site has a small historical erosion rate and is presumed to have been protected by a beach over most or all of the historical erosion rate period. The beach eroded during the course of the study, presumably as a result of decreased alongshore sand supply due to trapping by an updrift groin field. As a result, the toe elevation of the site decreased by 0.7 m, which causes the frequency of T/S to increase. With a larger toe elevation, the cumulative T/S frequency for GRS is comparable to that of GRN (Figure 6). At the lower elevation, the cumulative T/S frequency for GRS is comparable to that of the directly undercut slopes (e.g. PCS and DBN). This suggests that the site will now erode by direct undercutting and that slope recession will proceed at a rate much greater than the historical value of 0.1 m/yr. This is supported by field observations of an incipient undercut notch at the site.

The relation between the historical erosion rate and cumulative T/S is shown more directly in Figure 7, which plots the historical erosion rate as a function of the cumulative duration over which T/S exceeds different values of a thresh-
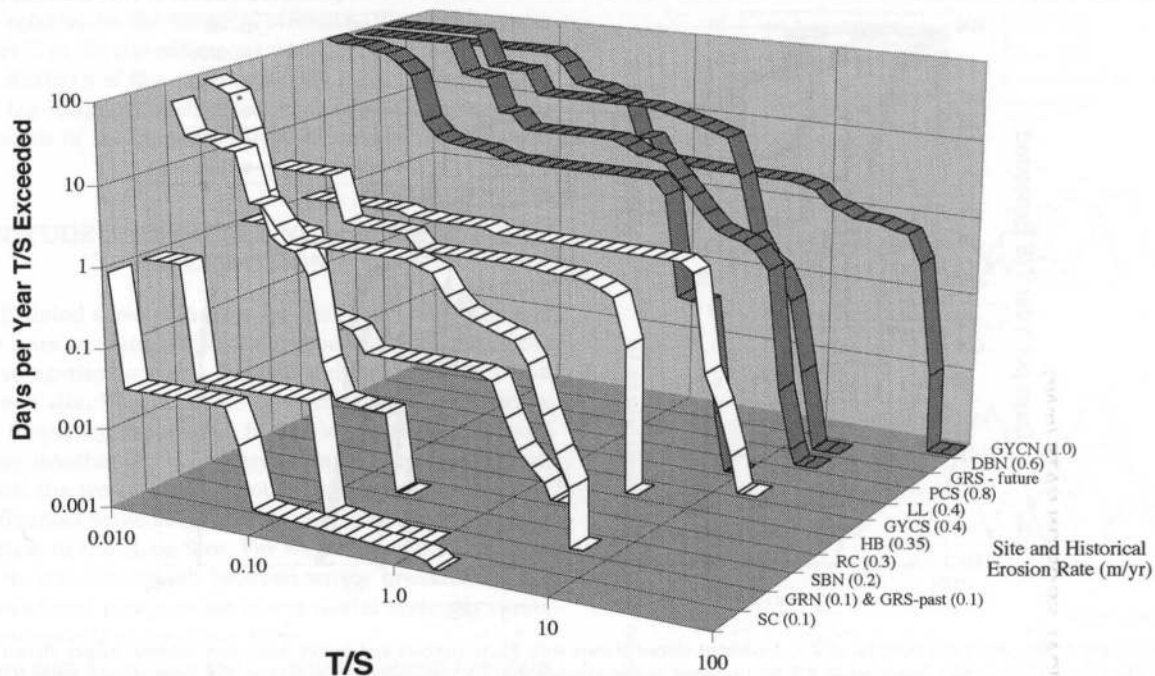
Figure 6. Cumulative frequency distribution of T/S. Individual sites are separated by historical erosion rate. Undercut slopes shown with gray strips; nonundercut slopes shown with white strips. Site initials and historical recession rate (m/yr) shown as labels on right. Actively undercut slopes recede at larger rates than those that recede through slope erosion and wave removal of toe debris. Cumulative frequency of T/S distinguishes between undercut and nonundercut slopes and between moderate and high rates of slope recession.

old N (N = 0.1, 0.2, 0.5, 1.0, 2.0). There is a clear separation between nonundercut and undercut slopes. The historical erosion rates for directly undercut slopes are uniformly larger than for the nonundercut slopes, with a threshold of approximately 0.5 m/year. A duration of T/S > N of about 50 hours also separates the two cases for 0.1 < N < 2.0. Although an approximately linear relation between historical erosion rate and T/S exceedance is evident on some of the plots, we do not expect that any simple or unique relation exists because of the many other factors, such as grain size, soil moisture supply, antecedent moisture, and solar exposure which directly effect the toe material erodibility and the rate of freeze/thaw. Nonetheless, a clear threshold exists between undercut and nonundercut slopes. The relation would actually appear stronger if two additional sites that were investigated were included. These had negligible T/S and no measurable historical erosion and so cannot be plotted on Figure 7.

Comparison of Figures 4 and 7 shows that the threshold between nonundercut slopes with a slower recession rate and directly undercut slopes with a more rapid recession rate is not represented by a unique value of relative wave strength. Rather, the strongest distinction is defined in terms of a cumulative duration of approximately 50 hours for relative wave strength larger than a threshold strength of the order of T/S ≈ 0.1.

CONCLUSIONS

Recession of the Calvert Cliffs can be driven by direct wave undercutting of intact slope material, or by wave removal of eroded debris from the slope toe. Many of the slopes we examined were sufficiently strong to withstand direct wave undercutting under the current wave climate, but, nonetheless, retreat at rates nearly as large as the slopes that are directly undercut. The dominant process producing this erosion is freeze/thaw disintegration of the slope material, together with gravitational slumping or, less commonly, direct wave removal of loosened material from the lower slope. Accurate forecasting of slope recession rates must account for erosion dominated by slope processes, as well as direct undercutting by waves.

The locations experiencing the largest slope recession along the Calvert Cliffs are not uniformly those sites with the largest cumulative wave energy. Rather, they are the slopes with the largest wave energy relative to the erosion resistance of the slope material. We define a relative wave strength as the ratio of wave pressure T to the cohesive strength S of the material. We estimate the frequency distribution of relative wave strength based on a 37-year wind record, estimates of storm surge, offshore wave geometry, and nearshore wave transformation.

The frequency distribution of relative wave strength is irregular, possibly even discontinuous for the particular combinations of tides, storm surge and wave height associated with individual locations and with storms of different type, magnitude, and direction. Two sites, one with a larger frequency of moderate wave strength and the other with a smaller frequency of very high wave strength, may have com-

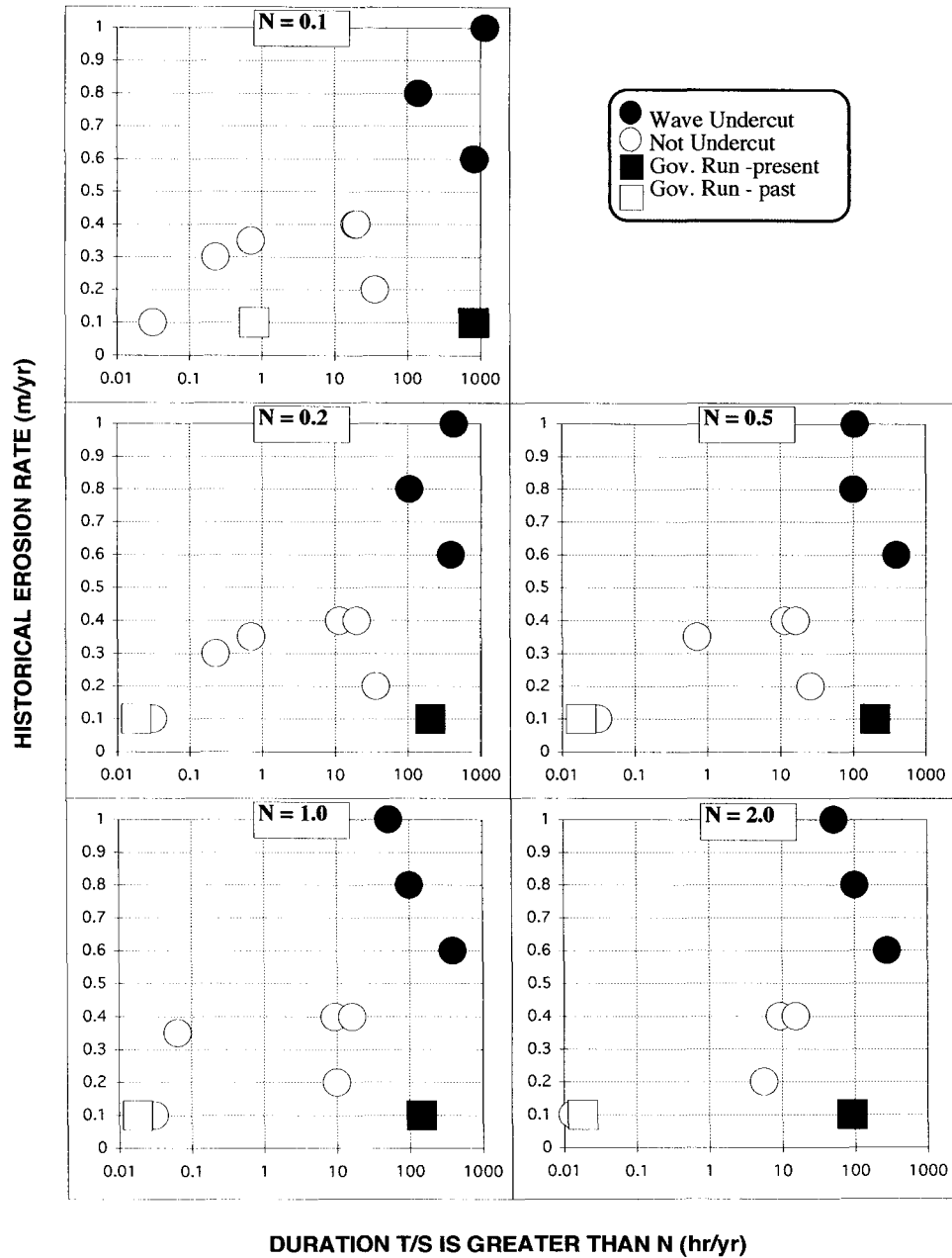**DURATION T/S IS GREATER THAN N (hr/yr)**

Figure 7. Historical recession rates vs. the cumulative duration of T/S exceeding 0.1, 0.2, 0.5, 1.0, 2.0. An historical erosion rate of 0.5 m/yr and a cumulative duration of the order of 50 hours per year separates undercut and nonundercut slopes. Governor Run has a small historical recession rate; recent beach erosion has lowered the slope toe and increased the cumulative exceedance of T/S, suggesting that the slope will be undercut and recede at a greater rate in the future.

parable undercutting rates, but little or no overlap in their T/S frequency distributions.

A minimum relative wave strength for initiating erosion of intact material may be defined for our sites as 0.05 < T/S < 0.1. The potential for slope toe undercutting for larger values of relative wave strength is not related to any particular value of relative wave strength, but to the cumulative exceedance of T/S above a threshold. A cumulative duration of ap-

proximately 50 hours per year for relative wave strength larger than T/S ≈ 0.1 distinguishes between undercut and nonundercut slopes. Because the recession rates for all undercut slopes we observed were larger than those of nonundercut slopes, this cumulative exceedance also distinguishes between slope recession rates greater or lesser than 0.5 m/yr.

Any factor, such as a decrease in slope toe elevation or increase in water level, that increases the duration of T/S is

likely to increase the probability or rate of direct undercutting by waves and, therefore, the overall recession rate of the slope. We document one such case for a slope with a small historical erosion rate. A protective beach at the site was eroded during the study and the exposed toe elevation decreased by 0.7 m as the result of sand trapping by an updrift groin field developed gradually over the past 40 years. Historically, the primary erosion mechanism at the site was freeze/thaw disintegration, accompanied by gravitational slumping and wave removal of the debris. With the decrease in toe elevation, the duration of large values of T/S has increased into the range associated with direct wave undercutting of other slopes we studied. Since the loss of the beach, an incipient undercut notch has developed, which suggests that erosion at the site will now be dominated by wave undercutting and increased recession.

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