The Influence of the Shore Slopes Ratio on the Nature of a Transgressing Shore

Roger N. Dubois

Department of Geography
University of Maryland Baltimore County
Baltimore, MD 21228, U.S.A.

ABSTRACT


In this study a cross-shore profile extends from the foredune crest to the shoreface toe and is characterized by the shore slopes ratio (SR). SR is obtained by dividing the slope tangent of a cross-shore profile by the slope tangent of a shoreface base segment that is abandoned during times of transgression. SR predicts the type of response that an equilibrium shore profile will take as it transgresses in the face of a relative sea-level rise. When SR is greater than unity, the landward trend of the abandoned shoreface base slope intercepts the shoreline below sea level, and a net loss of sediments occurs from a cross-shore profile during times of transgression. Sediments lost from profiles are deposited in landward and seaward compartments normal to the shoreline and at the shoreline termini. When SR is at unity, the trend of the abandoned shoreface base slope intercepts the shoreline at the crest of the foredune, and there is no net sediment loss or gain at a shore profile during transgression; the volume of sediment eroded from a beach is equal to that deposited on a shore bottom. This volumetric sediment balance is recognized as Bruun's rule. Finally, when SR is less than unity, the trend of the abandoned shoreface base slope intercepts the shoreline above the foredune and during times of transgressions a net gain of sediment derived from terrestrial sources is required to preserve the cross-shore profile symmetry. Of the three shore conditions, field evidence reveals that SR is frequently greater than unity. Thus, care must be taken before applying Bruun's rule at a field site; field data must first show that SR is at unity.

ADDITIONAL INDEX WORDS: Barrier island, beach erosion, Bruun's rule, nearshore, ramp, sea-level rise, sediment budget, shoreface, shorerrise.

INTRODUCTION

This paper continues to examine the transgressive barrier model as presented by DUBOIS (1995). The transgressive barrier model consists of a set of equations used to predict long-term rates of beach erosion and of volumetric changes for various shore compartments in response to a relative sea-level rise. For an Atlantic shoreline segment of Long Island, New York, being subjected to a relative sea-level rise of 2.7 mm/yr (Hicks and Hickman, 1988), the model predicted an average beach erosional rate of 0.67 m/yr which was within the observed range of 0.3 to 0.9 m/yr (Leatherman and Allen, 1985). In addition, the model predicted 1.3 million m$^3$ of sediments should be eroded from a transgressing beach and shoreface, and of this total amount about 800,000 m$^3$ should be deposited in shore normal compartments while the remaining 500,000 m$^3$/yr should be displaced by longshore currents and discharged at shoreline termini. The net drift is from east to west, and at the western end of Fire Island, the observed rate has been estimated between 230,000 to 460,000 m$^3$/yr (Panuzio, 1969) which is within the predicted gross littoral discharge.

Additional insights on the nature of a transgressing barrier shoreline can be gleaned from the model and from data acquired from the Long Island study (DUBOIS, 1995). The purpose of this paper is to show that the shore slopes ratio (SR) reveals whether a net sediment gain or loss will occur for an equilibrium cross-shore profile during transgression, and to suggest that a unity SR value is the criterion that must be met before Bruun's rule can be applied to shoreline studies. The following is a discussion of the transgressive barrier model and the shore slopes ratio.

TRANSGRESSIVE BARRIER MODEL

The model assumes that (a) the shoreface profile is an equilibrium energy profile; progressive waves generate a shoreward net bottom stress that drives sands landward until an increasing shoreface slope has reached equilibrium (Inman and Bagnold, 1963; Inman and Dolan, 1989), (b) the seaward limit of an equilibrium profile is at the juncture of the shoreface toe and the ramp (Everts, 1987), and (c) the shape and dimensions of a cross-sectional beach and shoreface profile remain reasonably constant as the full profile transgresses in the face of a relative sea-level rise.

As sea level rises (S), the depth of initial shoreface forcing (D$_1$) is elevated (S') by an amount equal to S and displaced horizontally landward from position X$_1$ to X$_2$ (Figure 1). With D$_2$ now at X$_2$, the shoreface profile becomes steeper and the rate of wave-energy dissipation increases along the bottom (Bruun, 1988) causing waves to erode the profile until a new equilibrium state is established (Figure 1). Sediments eroded
from the shoreface are deposited in shore normal compartments and at the termini of a shoreline (Dubois, 1995). Given that the coordinates of a shoreface profile follow a power function (Bruun, 1954; Dean, 1977)

$$D = AX^m,$$

where D is the water depth, X is the horizontal seaward distance from shore, m is the shape parameter, and A is a scale parameter reflecting the texture of sediments at the shoreline (Dean, 1977), the equation for predicting the rate of beach erosion ($\Delta X$) as a function of a relative sea-level rise (Dubois, 1990) becomes

$$\Delta X = (D/A)^m - [(D - S)/A]^m. \quad (2)$$

As a shoreface transgresses (Figure 1), it abandons a small segment at its base, and as time passes the sum of the abandoned segments form a ramp (Everts, 1987; Dubois, 1995). The beach erosion rate in (2) is dependent on the slope angle ($\phi$) at the shoreface base (Figure 1) and on $S$, tangent $\phi$ is given as

$$\tan \phi = S'/\Delta X_1, \quad (3)$$

where $\Delta X_1$ is the horizontal displacement of $D_1$ and is equal to $\Delta X$. Thus, $\Delta X$ can also be expressed as

$$\Delta X = \Delta X_1 = S'/\tan \phi. \quad (4)$$

For a transgressing beach and shoreface, the volumetric rate of sediment change ($V_i$) is given as

$$V_i = (S'X_i) - (Y\Delta X_i), \quad (5)$$

where $X_i$ is the sum of $X$ and the horizontal beach width ($W$) from the dune crest to the shoreline and $Y$ is the sum of $D_1$ and the dune crest elevation ($E$) (Figure 1) (Dubois, 1995). A negative value in (5) reflects a net loss of sediments from a shore profile; a positive value reflects the opposite state, which in turn would require a terrestrial source of sediment supply to feed the shore system if positive values persisted for a significant length of shoreline.

If the $V_i$ equals zero, then

$$Y\Delta X_i = S'X_i. \quad (6)$$

Equation (6) is Bruun's rule (Bruun, 1962; Schwartz, 1967) and is valid only when

$$Y/X_i = S'/\Delta X_i \quad (7)$$

or

$$(Y/X_i)(S'/\Delta X_i) = 1. \quad (8)$$

The left side of (8) is here termed the shore slopes ratio (SR). When SR is greater or less than unity, a net loss or gain of sediments takes place, respectively, as a shore profile transgresses (Figure 2A and 2C); at unity, there is no net change of sediment volume in a cross-shore profile (Figure 2B).

The relationship between $V_i$ (5) and SR was investigated for a 105 km segment of the Atlantic barrier shore of Long Island, New York.

STUDY AREA AND METHODOLOGY

The following is a brief description of the study area and of the methodology; more details are given in Dubois (1995). The study area extends 134 km from Fire Island Inlet to Montauk Point (Figure 3). The Atlantic shoreline of Long Island, New York, has been transgressing for at least the past 5,000 yrs (Sanders and Kumar, 1975; Williams, 1976; Rampino and Sanders, 1980) and is being subjected to a relative rise of sea level at a rate of about 2.7 mm/yr (Hicks and Hickman, 1988). For the past 150 years, the shoreline has been eroding at an average rate of 0.3 to 0.9 m/yr (Leatherman and Allen, 1985). The net littoral drift is from east to west and ranges from about 230,000 to 460,000 m$^{3}$/yr of sediments at western end of Fire Island. The primary source of sediment for the drift comes from the transgressing beach and shoreface zones (Dubois, 1995).

With values of depths and corresponding offshore distances having been obtained from the Long Island East and West topographic-bathymetric maps (1:100,000) published by the United States Geological Survey (USGS) and by the National Ocean Service, the constants in (1) were empirically solved by regression analysis for 43 lines spaced at 2.5 km apart for a barrier shore segment of Long Island (Figure 3). The first line begins 9 km east from the western end of Fire Island. Because a bar or terrace extends about 300 m offshore to
where the curved shoreface merges with the linear ramp. With $A$, $m$, and $D_i$ values (Dubois, 1995) and for an $S$ of 2.7 mm/yr (Hicks and Hickman, 1988), equation (2) was solved for each of the 43 lines. $Y$ and $X_i$ were measured from USGS topographic maps and the aforementioned maps for each line. With values of $\Delta X$, $Y$, and $S$ in hand, equation (5) and SR were solved for each line.

**RESULTS AND DISCUSSION**

Each profile line was geometrically similar to the cross-shore geometry of panel A in Figure 2. For each line, therefore, the shore slope tangent ($Y/X_i$) was greater than the abandoned shoreface base slope tangent ($S'/\Delta X_i$), and in turn the shore slopes ratio (SR) was greater than unity (Table 1).
During times of transgression, shore profiles with SR values greater than unity exhibit a net volumetric loss of sediment ($V_t$) from a shore zone (Table 1), and as SR increases so does $V_t$ (Figure 4). Roy et al. (1995) reported a similar response; for barrier islands as ramp slopes decrease in comparison to shore slopes, the volume of sediments eroded from a shoreface increases.

Because SR was greater than unity, Bruun’s rule was not applicable at the study site. Bruun’s rule is valid only if the trend of the abandoned shoreface base slope intercepts the landward limit of a beach (Figure 2B) which along barrier shorelines is at the foredune crest. As seen from numerous cross-shore profiles (Bruun, 1954; Everts, 1978; Inman et al., 1993; Cowell et al., 1995), the trend of the abandoned

Figure 3. Location of study area. Numbers along the shoreline are profile numbers.

Figure 4. The relation between the shore slopes ratio and the predicted volumetric rate of change for a transgressing beach-shoreface zone. Note that when $V_t$ is zero, SR is near unity with a value of 1.09.
shoreface base slope intercepts the shoreline well below sea level (Figure 2A), thereby implying that Bruun’s rule has limited application. It has been suggested that Bruun’s rule may be valid only in the beach-nearshore zone (DUBOIS, 1992). This hypothesis was tested at the study site.

Envision A-A’ in Figure 2B as extending from the foredune crest to the seaward edge of the nearshore where contact is made with the shoreface, i.e. the shoreface seaward of the nearshore (INMAN et al., 1993). Assume that as sea level rises, only the beach and nearshore transgress; the shoreface is not eroded, but is simply abandoned. Under this condition, ΔX is equal to S/Tan β where β is the angle of the upper shoreface in contact with the nearshore. At each of the 43 lines, Tan β was obtained by measuring the horizontal distance between the contour at the nearshore-shoreface junc-

ture and the next seaward contour. In most cases, this involved measuring the distance between a 4 and 6 m isobath. The vertical distance of Tan β was the difference between the two employed isobaths. The width of the beach-nearshore zone (X), the sum of E and the water depth at the nearshore-shoreface juncture. Substituting the appropriate the beach-nearshore parameters into equations (8) and (5), the shore slopes ratio and the volumetric rate of change were calculated and are symbolized as SR, and V, respectively.

For a restrictive assumption where only the beach-nearshore zone transgresses in response to a 2.7 mm/yr relative rise in sea level, the results showed that the average predicted ΔX was relatively small at 0.1 m/yr and under-predicted the average observed rate of beach erosion: SR, and V, averaged close to unity and near zero, respectively (Table 2). As SR, values increased from less than to greater than one, V, changed from a net depositional setting to a net erosional one (Figure 5). For nearly 70 percent of the lines, SR, was smaller than unity, thereby reflecting a beach-nearshore zone with a transgressive pattern similar to panel C in Figure 2.

With the average SR, value being nearly equal to unity, Bruun’s rule was applicable to this model of a transgressive beach-nearshore zone. The results were similar to a Lake Michigan study which found by empirical means that in response to rising lake levels from the spring to summer of 1971, the volume of sediment eroded from a beach was nearly equal to that deposited in the nearshore; no sediments were eroded from the shore bottom lakeward from the first longshore bar (DUBOIS, 1976, 1977). With rising lake levels and with low wave energy models, the foreshore crest transgressed into the backshore at an average tangent value of 0.0429 (DUBOIS, 1975) while the first longshore bar crest transgressed at an average tangent value of 0.0457 (DUBOIS, 1975); thus, the end points of the shore profiles transgressed along a common slope (Figure 2B). The beach-nearshore profile transgresses in response to rising water levels and to altering regimes of swells and storm waves. Following storm waves that erode sediments from a beach and deposit them in the nearshore, not all nearshore sediments are returned to the beach by swells. A sediment layer equal in thickness to the rise in water level remains on the nearshore bottom (DUBOIS, 1982). It appears, therefore, that if SR, is at or close to unity, Bruun’s rule can be applied to the beach-nearshore zone for a relatively short time frame, on the order of a year or so, when the shoreface may not extensively transgress. For time frames spanning a decade or more when a shoreface has transgressed (MOODY, 1964), Bruun’s rule may not apply to the beach-nearshore zone because in all likelihood SR will be significantly greater than unity. Other concerns have been noted regarding the applicability of Bruun’s rule to the beach-nearshore zone (DUBOIS, 1995).

**SUMMARY**

The shore slopes ratio (SR) characterizes the cross-shore profile symmetry. When SR is greater or less than unity, a net volumetric loss or gain of sediments occurs, respectively,
at a cross-shore profile during transgression. The landward trend of the abandoned shoreface base slope intercepts the shoreline below sea level when SR is greater than unity, whereas the trend is above the foredune crest when SR is less than unity. When SR is at unity, the trend of the abandoned shoreface base slope intercepts near the foredune crest, and the sediment volume eroded from a beach is equal to that deposited on the shore bottom; this scenario describes Bruun’s rule. Thus, a unity SR value is the criterion that must be met before Bruun’s rule can be applied. Bruun’s rule may be implemented in the beach-nearshore zone for a relatively short time frame. However, because field evidence reveals that SR values are often greater than unity, the usefulness of Bruun’s rule is questioned when applied to a transgressing shoreface or to any part of a shore profile for relatively long time frames.

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LITERATURE CITED


