Marine Geology 284 (2011) 217–229

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

Equilibrium responses of cliffed coasts to changes in the rate of sea level rise

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ARTICLE INFO

Article history:
Received 17 September 2010
Received in revised form 21 January 2011
Accepted 31 January 2011
Available online 9 February 2011

Communicated by J.T. Wells

Keywords:
cliffed coasts
rocky coasts
coastal erosion
sea-level rise
Bruun rule
dynamic equilibrium

ABSTRACT

Basic formulae have long been used to predict the effects of sea-level rise on coastal recession; for instance, the geometric 'Bruun rule' (and its modifications) has often been applied to sandy coasts, both low-lying and steep. However, the behavior of rocky coasts, whether strongly or poorly lithified, should be significantly different than that of sandy coasts given that rocky coast evolution depends upon the irreversible breakdown of rock, whereas sandy and depositional systems are controlled by the transport (and related transport gradients) of mobile sediment. Here, we investigate the basis of a modeled relationship which suggests (with a number of caveats) that the equilibrium soft-rock cliff recession rate can be estimated by the square root of the relative change in sea-level rise rate. Although this relationship was derived using the numerical model SCAPE (Soft Cliff And Platform Erosion), which simulates a broad soft-rock cliffed coastal system driven by stochastic environmental forces, here we show that a simplified modeling approach also reproduces the relationship. We then extend this approach to develop a general theoretical framework within which it is possible to consider the potential responses of the different types of cliffed coasts to changes in the rate of sea level rise. Although a wide variety of processes affect different coastal settings, this framework demonstrates how the strength and the nature of feedbacks within cliffed system control their response to sea-level rise. This suggests that cliffed environments controlled by different processes can still respond in similar ways to changes in the rate of sea-level rise. Most rocky coasts would be expected to respond as a damped, or 'negative feedback' system between the extremes of a 'no feedback' system that is unresponsive to sea-level rise rate and an 'instant response' system characterized by a linear response similar to the Bruun rule. This framework suggests that a potential 'inverse feedback' case could also exist, in which increased rates of sea-level rise reduce the rate of coastal recession. In almost all cases, it is apparent that cliffed coast response to sea-level rise depends not only upon the total elevation change of sea level, but on the rate of the sea-level rise. These theoretical investigations and the classifications presented provide a framework to understand the behavior of systems affected by a wide array of processes, and provide expectations that can be tested using more complex models of cliffed coast evolution in a variety of environments, whether sandy or rocky, hard or soft.

1. Introduction

How coastlines respond to sea-level rise remains one of the cornerstone challenges confronting coastal geomorphologists and engineers (Dubois, 2002). It has long been conceptualized that, as a result of the dynamic processes occurring at the coast, rising sea levels cause significantly more coastline change than passive inundation alone. However, we have relatively limited physical understanding of exactly how coastal regions respond to changes in sea level, and there remains significant uncertainty regarding any predictions of the response of coasts to the sea-level accelerations predicted for the upcoming century and beyond (e.g. Meehl et al., 2007; Rahmstorf, 2007). This lack of predictive ability arises in part from the complexity of the coastal environment, but also because predicted rates of sea-level rise over the next century are unprecedented during historic times, making it difficult to extrapolate historic measurements into the future. Coastal managers rely on predictions of future shoreline position to assess hazards and risk, predictions which may be based on experience, statistics (e.g. Hall et al., 2002; Hapke and Plant, 2010), or process understanding (e.g. Trenhaile, 2010). At present, our lack of knowledge of the relationships between the rates of sea-level rise and coastal recession leaves significant uncertainty in all future predictions.

The most commonly applied relationships between sea-level rise and shoreline recession follow the concepts of equilibrium profile geometry and sediment conservation, as introduced by Bruun (1962) and most often applied to low-lying coasts. 'Bruun rule' relationships are based upon mass conservation principles and might apply on cliffed coasts composed of cohesive but unconsolidated sediments (e.g. sand-gravel cliffs or bluffs). However, different relationships

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0025-3227/$ – see front matter © 2011 Published by Elsevier B.V.
doi:10.1016/j.margeo.2011.01.007

should be expected to represent the evolution of cliffed shores, in particular rocky and consolidated coasts whose evolution is controlled by break down of *in situ* material through erosion and weathering. Naylor et al. (2010) emphasize the need for general theoretical sea-level-rise relationships for rocky coasts, using the general definition of rocky coasts being predominantly erosional landforms.

Here, we investigate the potential equilibrium responses of cliffed coasts to an increased rate of sea-level rise. First, we focus on a recently proposed relationship between sea-level rise rate and erosion rate by Walkden and Dickson (2008), appropriate for soft rock coast evolution. The second part of the paper investigates cliffed coasts more broadly, using the characteristic erosional responses to changes in sea-level rise rate to compare and contrast the evolution of sandy, consolidated, soft rock, and hard rock coasts.

1.1. Geometric sea-level rise relationships

The evolution of a coast comprised of unlithified, non-cohesive, or 'sandy' sediment is controlled by gradients in sediment transport, both along- and across-shore. Observations suggest that, over long timescales, the cross-shore shoreface, extending to the depth where waves no longer affect sediment transport, attains an equilibrium shape (Dean, 1991). Assuming that no sandy sediment is lost or gained from the active profile in the cross-shore direction and that the shoreface maintains an equilibrium shape, the conservation of mass leads to a relationship where the landward rate of movement of the shoreline, ε (distance/time), is a linear function of the sea-level rise itself (S, distance/time):

$$\varepsilon = \frac{S}{\alpha_e}, \qquad (1)$$

as proposed by Bruun (1962) (Fig. 1a). Here we take α_e to represent the effective slope controlling sea-level rise response.

Which geometric boundaries accurately represent the effective slope, α_e, has been an issue of significant debate. Although some applications (Bruun, 1962; Zhang et al., 2004) suggest that the effective slope should be the shoreface slope, α_{sf} (Fig. 1), or, for low-sloped coasts, some other modification accounting for barrier geometry (Dean and Maurmeyer, 1983), recent analytic research provides a rigorous demonstration that long-term equilibrium requires that the coastal recession rate follow the regional upland slope, α_r (Wolinsky, 2009; Wolinsky and Murray, 2009) (Fig. 1b,c). Equilibrium sea-level response based upon mass conservation must follow the trajectory of regional slope—any other response is a transient.

1.2. Application of geometric relationships to cliffed coasts

The Bruun rule has also been adapted and applied to cliffed coasts (Fig. 1c). Numerical experiments by Roy et al. (1994) demonstrate that regional slope controls the long-term trajectory of sandy coastal

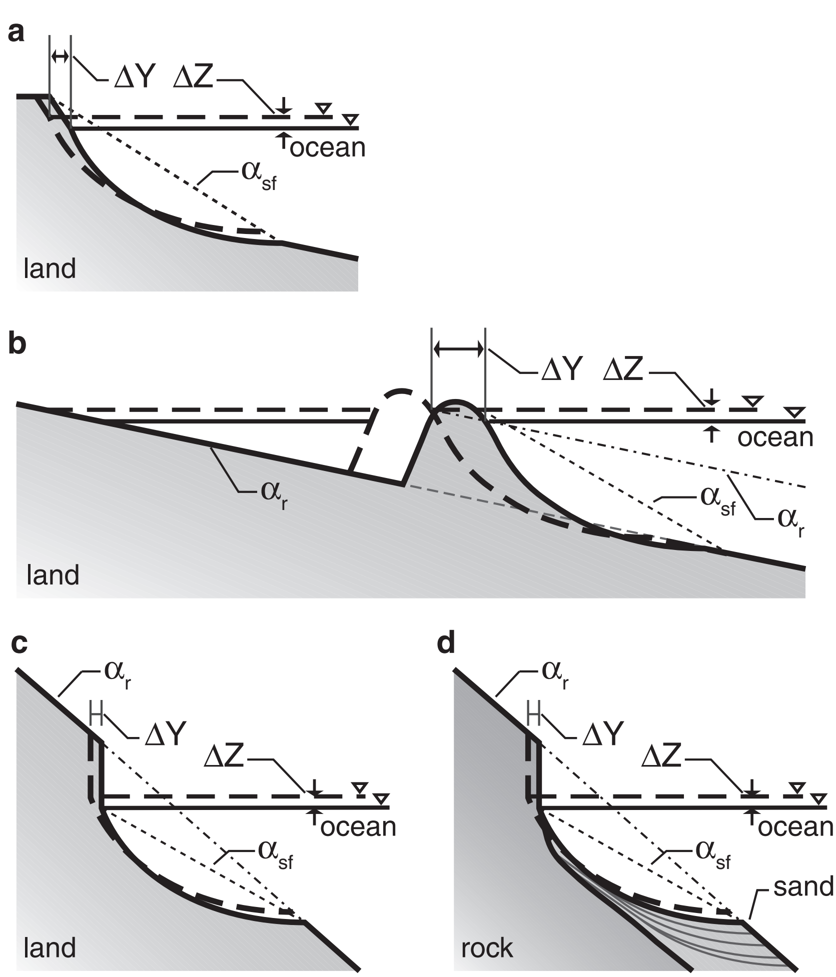

Fig. 1. Geometric relationships of coastal recession, representing (a) the original 'Bruun rule', (b) a modification for a barrier environment, and (c) application to a steep coast. This relationship may also apply to rocky coasts when the entire active profile, (d), is covered by mobile sediment.