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Effects of varied lithology on soft-cliff recession rates

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A B S T R A C T

Geomorphic modelling is a key method to understand the soft cliff recession process to predict future rates of retreat and responses to climate change. A range of process-based models have been used; however the influence of varied vertical lithology has yet to be quantified. This paper describes modifications to the 2D SCAPE (Soft Cliff and Platform Erosion) model, carried out to explore such interactions between vertical changes in cliff resistive strength and prevailing coastal conditions. As expected, weaker (/more resistant) layers lead to more (/less) rapid retreat. However, this effect is strongly influenced by the position of such layers relative to mean sea level, where the erosive potential is greatest. Moreover, model simulations reveal that layers of variable resistance give an asymmetric response in terms of both rates of retreat and the timeframe for the effect to be realised. For example, a reduction of material strength of 1/5 (in comparison to the remainder of the cliff) about mean sea level results in a rapid 130% increase in the rate of retreat in comparison to the introduction of a five times more resistant layer of the same characteristics. This variation in response can be attributed to the different magnitudes of feedback governing profile reshaping associated with the change in lithology. For example, the introduction of a weaker layer amplifies erosion through its greater erosive potential combined with steepening of the overlying section. The results have important implications for the management of coastal cliffs exhibiting variable stratigraphy, combined with the potential for future interactions with sea-level rise.

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1. Introduction

Soft rock cliffs are composed of lithologies that are poorly consolidated or poorly cemented, including glacial tills, clays, shales and soft sandstones (Pye and French, 1993; Damgaard and Dong, 2004; Hackney et al., 2013). As a result of their geological structure they are associated with high rates of shoreline retreat (in excess of 1 m/yr around the world; Sunamura, 1992; Dickson et al., 2007; Eurosion, 2004; Lee, 2008). This process is highly episodic and stochastic, related to the prevailing meteorological conditions combined with basal marine erosion at the cliff toe (Hobbs et al., 2002; Schwartz, 2005). A detailed understanding of this process and its subsequent impact on future recession rates is required to inform a range of coastal management activities including; a) technical and economic appraisal of coastal strategies (e.g. hold the line versus no active intervention); b) calculation of sediment budgets; and c) estimation of the life of existing and future cliff-top infrastructure such as buildings and shore parallel roads (Hall et al., 2002). Traditionally, prediction of future rates of cliff retreat has been undertaken through extrapolation of historical data into the future. However, this method is being increasingly recognised as unreliable considering the complexity of the cliff recession process and the impacts of climate change (which present a change in future conditions).

One method which can respond to the above issues is process-based numerical modelling, which enables interactions between various components of the cliff system to be explored (e.g. rock strength and cliff erosion rates) and environmental and climatic changes to be simulated, provided they can be described in numerical terms (Quinn et al., 2010). A number of soft cliff models have recently been developed, including those described by Meadowcroft et al. (1999), Walkden and Hall (2005), Valvo et al. (2006), Trenhaile (2009) and Castedo et al. (2013). These models all consider the dominant physical processes of the cliff system, within which the shoreface, cliff face and fronting beach are recognised (Walkden and Hall, 2005). However, modelling inherently involves simplification of the system being described, thus existing cliff models may be criticised for the generalised manner in which they treat cliff behaviour. A key issue is the treatment of variable cliff lithology (including resistive strength and composition) on geomorphic processes and shore retreat.

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Modelling by Valvo et al. (2006) investigated how longshore variations in lithology can influence coastal planshape and rates of cliff retreat across a hypothetical linear frontage. They concluded that subtle shoreline indentations can develop, reflecting the heterogeneous nature of material strength (in their case defined by the weathering rate of the underlying rock). However, over time the amplitude of these indentations was shown to reach a steady state (uniform rates of retreat across the heterogeneous frontage) owing to the development of protective fronting beaches. Similar conclusions were drawn by Walkden and Hall (2011) in a series of recession rate sensitivity tests applying the quasi-3D SCAPE model to the North Norfolk coast, UK. They found that the CERC (Coastal Engineering Research Center) coefficient (which is a scaling factor of the long-shore transport rate; Hanson and Kraus, 1989) becomes a more dominant control on rates of cliff erosion than the resistive strength of the cliff (described by the equation of Kamphuis, 1992 to consider both material strength and some other hydrodynamic constants, as further discussed in Section 2) owing to negative feedback via the protective fronting beach volume. A range of field data supports this finding. For example, Moore and Griggs (2002), Sallenger et al. (2005) and Hapke et al. (2009) all identified correlations between high rates of cliff erosion and decreased beach width and elevation along the California coastline, USA. Similarly, Lee (2008) identified a non-linear increase in average recession rates as the beach profile area above high water level decreases, considering beach and cliff profile data for the north Norfolk and Suffolk coast, UK.

These findings emphasise the important role of a protective beach. However, its effect can be limited depending on wave energy and the volume of the beach (Robinson, 1977; Ferreira et al., 2000). This was highlighted by the two-dimensional (2D) SCAPE model results of Walkden and Dickson (2008), who found that the equilibrium recession rate was insensitive to beach volumes below 30 m^3/m. Similarly, the field comparisons of the relationship between beach wedge area and cliff recession rates made by Lee (2008) identified a threshold beach volume of 20 m^3/m.

Considering the concept that there is a threshold volume below which the beach has negligible influence on rates of cliff toe retreat, Walkden and Hall (2011) identified two contrasting modes of coastal behaviour:

- Mode A, where retreat is ultimately rock strength limited and regulated through fluctuations in the rock profile such that changes in beach volume are relatively insignificant;
- Mode B, where recession is regulated by the beach volume and ultimately retreat is sediment transport limited.

The distinction between these two behavioural modes has important implications for coastal management. However, our understanding of Mode A coasts is poor (Trenhaile, 1987). Thus, Carpenter et al. (2012) examined shore profile evolution on a site of varied soft cliff lithology on the south west coast of the Isle of Wight (UK) using the 2D SCAPE model (Walkden and Hall, 2005). Across the frontage, beaches were identified as below the protective threshold volume by Stuiver et al. (2013). Subsequently, the study emphasised the control exerted by more resistant rock layers on the emergent vertical shore profile shape, with distinctive ledge features identifiable within bathymetric data corresponding to harder rock layers. It can be hypothesised that such layers experience reduced rates of erosion on the basis of the planshape evolution of the study frontage, which includes the formation of a series of persistent, discrete headlands. However, such morphology could not be replicated within the current version of the SCAPE model owing to the use of a single material strength value to characterise the cliff face.

The findings highlight the importance of understanding the impacts of varied lithology, particularly on Mode A coasts, which may arise naturally through a low input of beach grade material (BGM) to the coastal system (e.g. a high proportion of fine grained material which is lost in suspension as described by Komar, 1998) or induced by coastal engineering structures reducing downdrift beach volumes (Brown, 2008). Moreover, in addition to longshore variations in material strength, it is important to understand the possible effects of vertical heterogeneity. For example, as schematised by Trenhaile (2009), cliffs may include thin beds of more resistant layers, or steeply dipping or horizontally bedded alternations in material strength. This will affect the dominant erosional processes, and as sea level rises the strength of the material being most influenced by marine processes may change.

This paper describes modifications to SCAPE 2D that allow the influence of horizontal layers of different material strength to be considered. The model has been previously used to simulate shore recession at a number of soft-rock sites including the Naze, Essex, UK (Walkden and Hall, 2005) and north Norfolk, UK (Dickson et al., 2007). Here we modify SCAPE to explore generic soft-rock shore platform and cliff responses to the impact of a single layer of more resistant rock, a single layer of less resistant rock, and multiple layers of variable resistance.

2. Overview of the SCAPE model

SCAPE[1] 2D (Walkden and Hall, 2005) is a reduced complexity model designed to simulate the emergence and retreat of soft rock shore profiles in the mesoscale (10 to 100 years). The components of the coastal cliff system described by the model are outlined in Fig. 1. Within SCAPE these are represented by both process-based and behavioural modules representing hydrodynamic loads, shore platform, cliff and beach morphodynamics. Such a holistic representation is necessary to capture the interactions and feedback on the shore profile that regulates the behaviour of soft cliff coasts. The process descriptions are relatively abstract to allow simulation of long periods and exploration of model sensitivities (Walkden and Dickson, 2008). On this basis only the processes considered dominant in the mesoscale are represented and the long term recession rate of the cliff top is assumed to be primarily determined by that of the cliff toe and interactions with the shore platform. Erosion of the upper cliff is assumed only to be relevant for the talus material it deposits at the cliff toe.

Some of the governing principles of 2D SCAPE are described below. Further detail is given by Walkden and Hall (2005), Walkden and Dickson (2008) and Walkden and Hall (2011). The cliff is represented as a stack of horizontally aligned layers of uniform height (d_z). The face of the lower part of the cliff and platform is formed by the seaward surfaces of these layers as illustrated in Fig. 2. However, initially, no differentiation is made between the cliff face and the shore platform; this junction emerges from a plunging, vertical cliff through the interaction of the processes modelled including marine action near mean sea level (Walkden and Dickson, 2008).

The cliff and platform erosion rate is based on Eq. (1) (Kamphuis, 1987):

$$E = \frac{H_b^{13/4} T^{3/2} \tan\alpha}{M} \tag{1}$$

where E is the erosion rate, H_b is the breaking wave height, T is the wave period, α is the average slope across the surf zone, and M (units $m^{9/4}\,s^{3/2}$) represents the material strength and some hydrodynamic constants.

Eq. (1) is an empirical description which was developed to describe the relationship between waves and recession rates of glacial till bluffs considering the northern shore of Lake Erie, Great Lakes, Canada (Kamphuis, 1987). The expression was adopted to represent the relationship between incident waves, the potential for waves to erode material, and also bottom slope. The inclusion of tanα relates the shore platform slope to the capacity of the wave to remove material and therefore provides an approximate representation of breaker shape and impact pressure. Several modifications were also made within SCAPE to represent marine environments including the representation

[1] The SCAPE model is currently a private research tool. However, it is intended that a version of the code will be made available via a Freeware license in the near future.

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