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Equilibrium erosion of soft rock shores with a shallow or absent beach under increased sea level rise

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Abstract
A process-based numerical model was used to explore the response of soft rock shores with low volume beaches to variable rates of sea level rise. Equilibrium recession rates were simulated for ranges of wave height and period, tidal amplitude, rock strength, beach volume and rate of sea level rise. Equilibrium shore profiles were found to be steeper with higher rates of sea level rise. Beaches were represented as protective surfaces yet were found to cause no significant reduction in equilibrium recession rate when their volumes were below a critical threshold. Reduced equilibrium recession rates were found with beaches that extended sufficiently far below low tide level. The model results imply that, given several constraints, a very simple relationship exists between increased rates of sea level rise and the response of eroding composite soft rock/ low volume beach shores.

Keywords: Climate change; sea level rise; shore profile; shore platform; cliff erosion; soft rock; coastal erosion.

1 Introduction

Understanding and quantifying shore profile response to accelerated sea level rise is one of the most important issues facing coastal geomorphology (Dubois, 2002). If the impacts of climatic change on the coast are to be understood then we need to know how sensitive shores are to accelerated sea level rise and how this sensitivity varies with factors such as rock strength, tidal range, wave climate, beach cover, historic rate of sea level rise, etc.

Numerical modelling has an important role to play in addressing this issue, through the quantification, exploration and application of conceptual models. In particular, numerical models are a powerful means of dealing with the complex interactions of multiple parameters and in testing their response to scenarios of future change. Unfortunately model development, both conceptual and numerical, is hampered by the short periods over which relevant observational data are available (typically decades to one century). This lack of data makes validation of models that describe the response of eroding shores to a *changing* rate of sea level rise very difficult. Nevertheless, as Nicholls and Stive (2004) observed, analysis of future erosion trends requires more than extrapolation of past rates combined with an "expert eye". Moreover, it is apparent that such analyses generally cannot be deferred in the face of population growth and development on coasts affected by rising sea levels (Cowell et al., 2006).

Some progress has been made in understanding how sandy shores respond to steady sea level rise. Bruun (1962) proposed that under a rising sea level, the equilibrium profile of a beach (i.e. its average long term form) would be maintained whilst rising with the average water level (see Fig. 1). Such an increase in elevation requires the deposition of a volume of sediment (*B*), which is mined from the upper profile (*A*). Consequently the equilibrium profile translates landward (*R*) as it rises. This results in the following simple linear relationship between the rates of sea level rise and recession:

$$R_2 = R_1 S_2 / S_1 \tag{1}$$

where *S* represents rates of sea level rise and subscripts 1 and 2 indicate prior and posterior conditions.

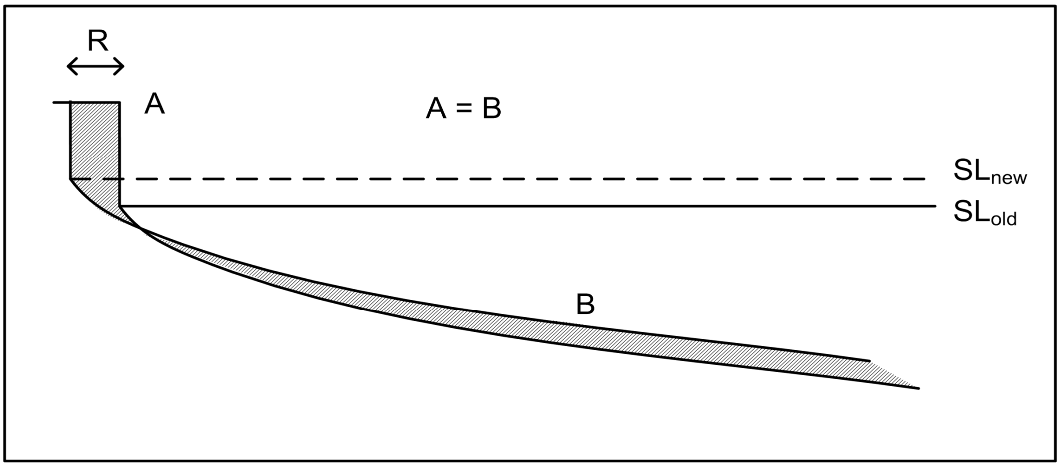

Fig. 1. Bruun's conceptual model of sandy shore response to sea level rise.

This simple conceptual model is not universally accepted, and does not account for longshore sediment transport which must play an important role in the response of sandy shores (see for example Dickson et al., 2007), but it does describe a mechanism through which sea level rise may drive beach erosion. One constraint on the range of applicability of the Bruun rule results from its assumption that the shore profile is entirely beach. Along many coastlines the beach is a surface deposit that can only stand limited erosion before the land underlying it is exposed and attacked. Here the shore profile is composed of both beach and rock. The rock element of such composite shores complicates morphodynamics as it can only erode (not accrete) and often contains fine sediments that are lost offshore. In addition, being purely erosive and relatively hard, rock may adopt a different equilibrium profile to that of a beach and take longer to achieve it.

The proportion of soft rock shorelines around the world is unknown. This is partly because in some locations shore platforms carved from rock tend to mimic the slope of the beach overlying them (Kamphuis, 1987), so that beaches of relatively low volumes can obscure large platform areas (perhaps the entire intertidal zone). Hence there is a tendency to classify as beaches coasts whose recession rate is partly, perhaps largely, determined by processes of rock erosion. Some large scale estimates have been made; for example the EUROSION project (2004) calculated that 11.7 % of Europe's coastline is soft rock, where 'soft rock' is defined as "…conglomerates and/or cliffs made of erodible rocks (e.g. chalk) and characterized by the presence of rock waste and sediments (sand or pebbles) on the strand".

In this paper we explore the behaviour of a model of the erosion of soft rock shores to conjecture about generic response to increased sea level rise. Section 2 outlines expected future rates of sea level rise and section 3 describes alternative methods for predicting the response of soft rock shores. The numerical model Soft Cliff And Platform Erosion (SCAPE) is described in some detail. A SCAPE model for the Naze coast was previously developed, calibrated and tested by Walkden and Hall (2005). This is used for the experiments presented in the current paper. In section 4 the parameters of the Naze model are perturbed to explore shore profile response to increased sea level rise and to variation in beach volume. In section 5 it is shown that despite the complexity of interactions described within the model, its results indicate the existence of a simple relationship between future and historic rates of sea level rise and rates of soft rock shore recession.

2 Future sea level rise

Tide gauge records indicate that global sea level has risen over the twentieth century at rates of 1.5 to 2 mm/yr (Miller and Douglas, 2004). By the end of the twentieth century this had risen to between 2.4 and 3.8 mm/yr (IPCC, 2007). When driven by scenarios of greenhouse gas emissions, climate models predict that sea level rise will increase due to global warming through thermal expansion of the oceans and the melting of land-based ice. For example the Intergovernmental Panel on Climate Change predicts that by 2090-2099 global sea levels will have risen by between 180 to 590 mm relative to levels in 1980-1999 (ibid). It is also apparent that increased sea level rise may continue for a long time. If CO_2 concentrations are stabilised within a few centuries, sea level rise due to thermal expansion will take centuries to millennia to reach equilibrium, whilst sea level rise due to ice melting will take several millennia (Church et al., 2001).

3 Modelling soft rock shore erosion

Until recently the complexity associated with the processes that erode soft rock shores had prevented the development of process-based models. As a result, predictions of the response of shorelines to sea level rise had relied on other methods such as analysis of historical trends (e.g. Leatherman, 1990), the Bruun rule and modifications of it (e.g. Dean, 1991). Bray and Hooke (1997) assessed several such methods and concluded that the modified Bruun rule was particularly suitable for predicting the response of eroding soft rock cliffed shores. The form of the Bruun model used by Bray and Hooke (1997) is given as Eq. (2).

$$R_2 = R_1 + \frac{(S_2 - S_1)L_*}{P(B + h_*)} \qquad (2)$$

where R_1 and R_2 are historic and future shore recession rates respectively, S_1 and S_2 are historic and future sea level rise, L_* is the length of the active (i.e. eroding) profile, B is the height of the retreating cliff, P is the proportion of sediment that is sufficiently coarse to remain in the equilibrium shore profile and h_* is closure depth. The use of such models has been debated at some length. Despite continued advocacy by some, other researchers contend that the Bruun rule is an overly simplistic representation of the response of shorelines to sea level rise and should be abandoned (Cooper and Pilkey, 2004). In any case it is apparent that coastal response to sea level rise is a complex morphodynamic issue, such that many feedbacks are to be expected beyond the simple profile translation envisaged by the Bruun rule (Stive, 2004).

Process-based mathematical modelling of rock-shore recession has been attempted by Trenhaile (2000) and Walkden and Hall (2005), but the scope and intention of the models differed. Trenhaile's (2000) model was targeted at investigating the sensitivity of shore platform morphology to variability in parameters such as tidal range, rock resistance and wave climate. It was later adapted to simulate the effects on present platform morphology of higher sea levels during the penultimate and last interglacial as well as the late Holocene (Trenhaile, 2001). By contrast, the SCAPE model described by Walkden and Hall (2005) was developed explicitly to simulate the sensitivity of shore profile response (including rates of cliff recession) over a timescale of decades to centuries. A comparison of SCAPE predictions with those made using the modified Bruun rule (Eq. 2) show that SCAPE predicts a more complex suite of responses and lower overall sensitivity of soft rock shores to sea level rise (Dickson et al., 2007). In addition to the relatively small (spatial) scale application described below, SCAPE has also been used to construct regional scale models of 50 km of the UK's North Norfolk coast (ibid). Confidence in the output of that model was based on comparison with alongshore variations in recession rate derived from historic maps recorded over 117 years.

3.1 SCAPE

SCAPE simulates the emergence of soft rock shore profiles. Walkden and Hall (2005) describe its development, structure and application, including calibration and testing at the Naze Peninsula, in Essex, UK. This study uses the Naze model essentially unchanged except, to minimise run times, only the central model section is used; i.e. a 2D slice was extracted from the quasi 3D Naze model. The components of the system described by the 2D model in this study are illustrated in Fig. 2. It can be seen that SCAPE has process-based and behavioural modules representing platform, cliff and beach, as well as hydrodynamic loads. Such holistic representation is necessary to capture interaction and feedback that regulates the behaviour of such coasts. The process descriptions are relatively abstract to minimise run times and so allow simulation of long periods and exploration of model sensitivities.

Every model timestep (one tidal period), data describing wave height, period and direction, tidal amplitude, and rate of sea level rise are read from input files and the system state (rock profile, beach width, beach depth, nearshore wave conditions) is recalculated. In the present study the drivers (wave climate, rate of sea level rise and tidal conditions) are identical to those used by Walkden and Hall (2005). The tidal characteristics are described in Table 1.

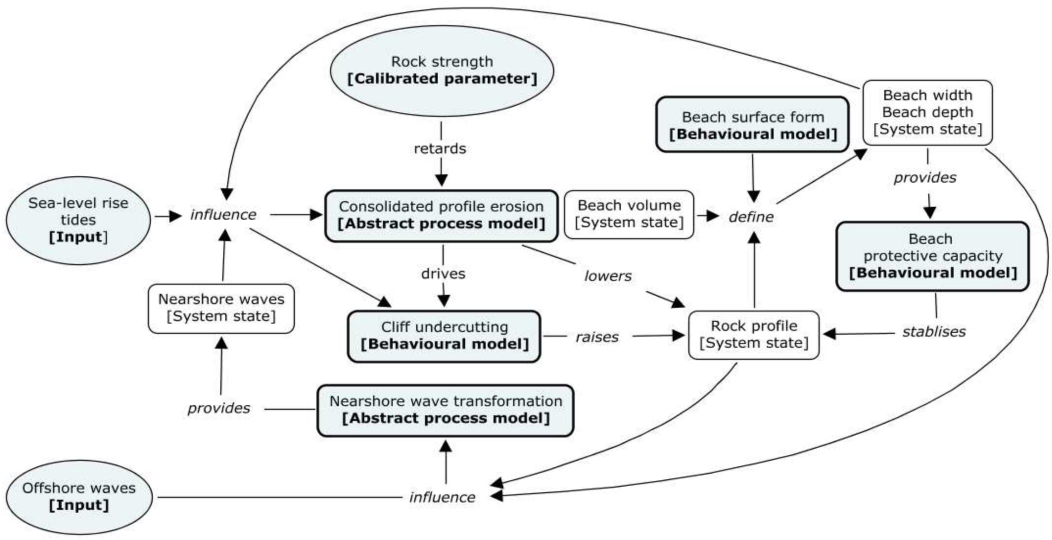

Fig. 2. Processes represented in SCAPE.

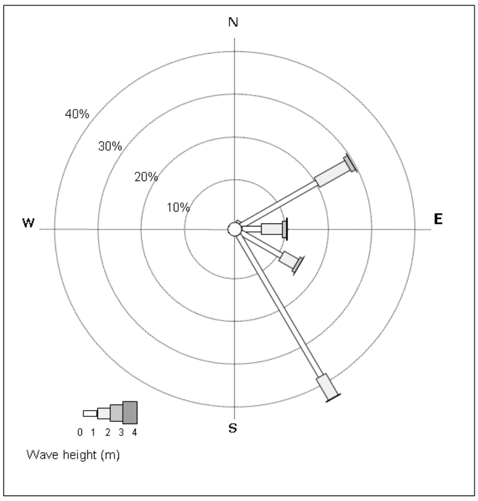

Fig. 3. Naze wave rose.

Tidal stage	Abbreviation	Level (m OD)
Mean high water spring	MHWS	2.04
Mean high water neap	MHWN	1.24
Mean low water neap	MLWN	1.06
Mean low water spring	MLWS	1.76

Table 1. Tide levels at the Naze relative to UK ordnance datum.

Wave conditions are mild to moderate. A wave rose produced from data hindcast from a 20 year period is shown in Fig. 3. Only 0.2% of conditions had a significant wave height greater than 3 m, and none were greater than 4 m. Relative sea levels have been rising at the Naze at ~2 mm/yr.

The wave conditions are assumed to be constant throughout a tidal timestep. Wave transformation due to shoaling and refraction is calculated using linear wave theory. A beach is represented as a surficial layer on the rock, as illustrated in Fig. 4. Q3D SCAPE beach volumes are determined from the erosion and composition of the rock and from losses through wave driven sediment transport. However, sediment transport is not represented in the 2D model used here, and so to prevent continual beach growth the rock is not treated as a sediment source. Instead the beach volume is varied stochastically about defined average values. The pattern of random variation was taken from a Q3D version of the model. The surface shape of the beach was assumed to follow a curve given by:

$$d = A_p x^{2/3} \tag{4}$$

where d is the depth of water and x is the offshore distance from the still water line (Bruun 1954, Dean 1991). The coefficient A_p is site specific, and for the Naze was found through surveys of the actual beach to be 0.16 and the berm level was estimated to be 2.2 m (see Walkden and Hall, 2005). The lower surface of the beach is defined by the shore platform shape. As the model runs, and the platform surface evolves, the beach surface is translated horizontally until the correct beach volume is encompassed. The beach profile rises with long-term sea level rise.

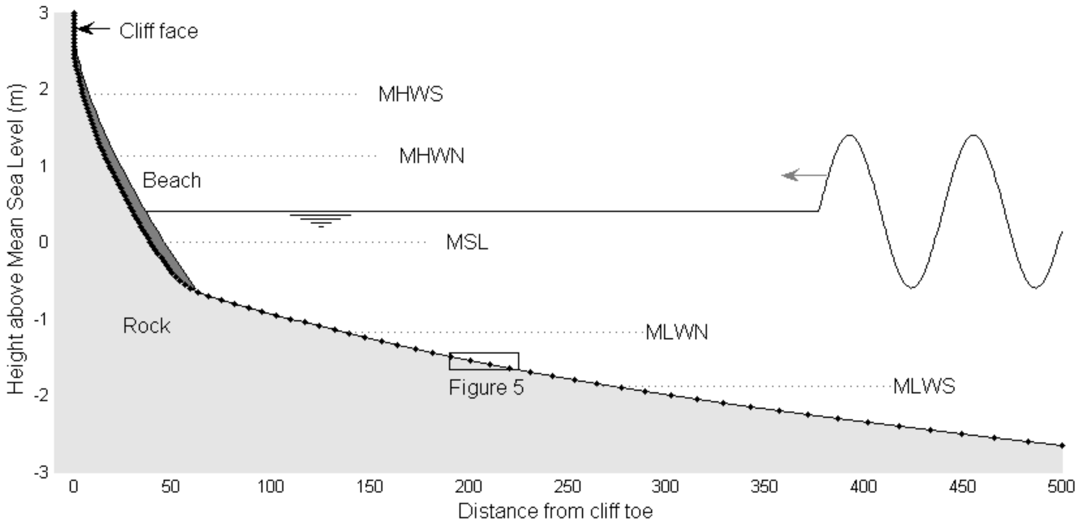

Fig. 4. Conceptualisation of shore profile.

Beaches generally protect the shore platforms that they cover. Based on observational data (Ferreira et al. 2000) a simple rule was adopted whereby beach depths greater than $0.23H_b$ were assumed to be fully protective. It was further assumed that this protective capability decreased linearly for shallower beaches.

The SCAPE rock profile is represented as a vertical stack of horizontally aligned elements of height *dz*, the seaward edge of which make up the exposed face of the shore platform and cliff (Fig. 5). No differentiation is initially made between the cliff face and shore profile, this boundary emerges through model iteration.

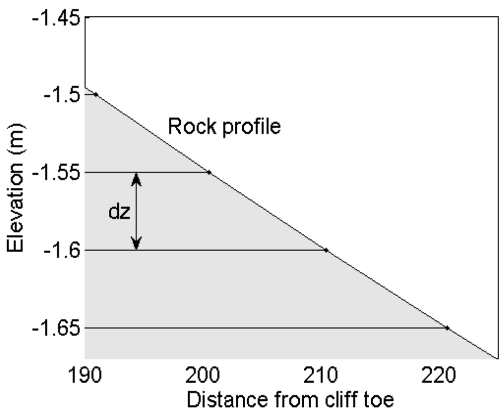

Fig. 5. Exposed surface of model rock elements

Fig. 6 illustrates the conceptual shore profile and the integration of erosive potential for a single tidal timestep. At every stage of the tidal oscillation the breaking wave field has the potential to erode the rock surface. This is represented by a function f_1. The seaward extent of f_1 is approximately equal to the water depth at which waves begin to break. To obtain the total erosive potential over a tidal cycle the instantaneous distribution of erosion must be integrated over the tidal period. As can be seen in Fig. 6 the integrated erosive potential tends to be concentrated at the tidal extremes, simply because this is where the water level spends the most time. Importantly, the actual erosion experienced by any exposed rock element also depends on (the tangent of) its slope. This means that gently sloping elements (generally lower in the profile) tend to erode less than the (typically higher) steeper elements.

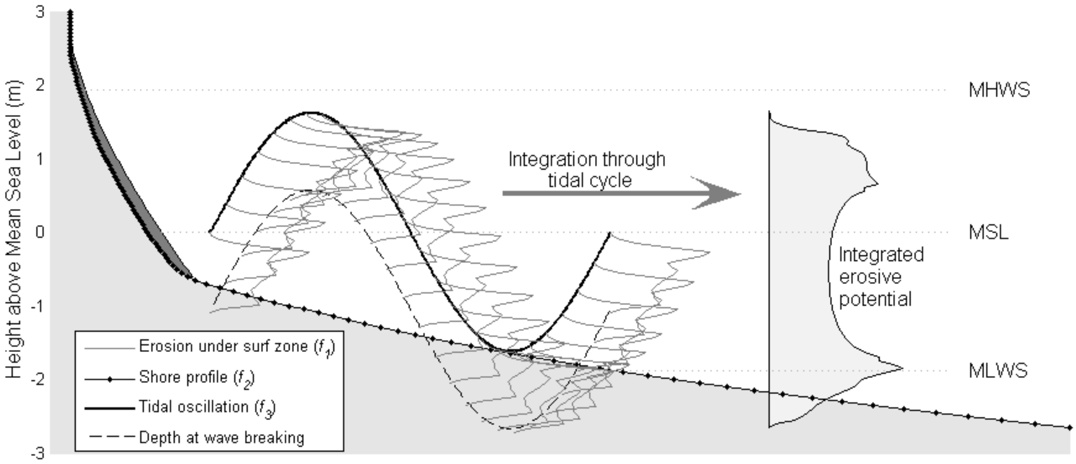

Fig. 6. Integration of the erosion pattern of a breaking wave field during a tidal timestep (tidal amplitude = 1.62 m, water depth at wave breaking = 1.04 m).

In more formal terms, every timestep erosion of each element (Δy) is calculated with the expression:

$$\frac{\Delta y}{\Delta t} = H_b^{13/4} T^{3/2} K^{-1} f_1(f_3(t) - z) \tan(f_2(z)) \tag{3}$$

Where horizontal and vertical dimensions are y and z respectively, t is time, H_b is the breaking wave height, T is the wave period and K is a calibration term representing rock strength and some hydrodynamic constants, (units $m^{9/4}s^{2/3}$, see Kamphuis, 1987 and Walkden and Hall, 2005). f_1 is a dimensionless distribution of soft rock erosion under a breaking wave field, which was referred to above and was derived by Walkden and Hall (2005) from physical model tests of Skafel (1995). f_2 is the tidal variation in water level, which is represented as a sinusoid about mean sea level (MSL). f_3 is the slope of each rock element and therefore changes throughout the simulation in response to the calculated erosion. Gradually the model iterates towards a profile form that is in dynamic equilibrium with the input conditions. Sea level rise is implemented as a shifting frame of reference for Eq. (3).

Skafel's tests explored the distribution of erosion of a realistic profile of intact till under pseudo-random breaking wave fields and included the abrasive effects of sand. The incorporation of Skafel's erosion distributions limits SCAPE to the representation of soft rock shores. Without extensive testing a definition of the rock types to which this model may be applied must remain vague, but Walkden and Hall (2005) suggest a range of soft mudstone to soft clay.

This coastal system, and therefore the dynamically stable emergent profile form, is regulated through feedback. This may be illustrated by considering the interaction of the cliff and shore platform. A sequence of events that cause high cliff toe retreat tends to widen the platform and raise the cliff toe. This reduces the erosive capability of subsequent waves at higher sections of the profile. This negative influence continues until ongoing processes narrow and lower the platform. Thus a period of unusually high cliff toe retreat is followed by a period of unusually low retreat, and the long term average is stabilised. Such behaviour also regulates smaller scale profile morphology.

Fig. 7 and 8 illustrate model iteration towards equilibrium. Fig. 7(a) shows the profiles that result from the first ten recession events acting on an initially vertical profile. The shore platform begins to form and the cliff toe becomes clearly demarked. The profiles are far from smooth because of spatial variation in erosion caused by differences in wave height and tidal range and by local feedback between slope and erosion. The effect of the concentration of erosion at around high and low tide can be seen in the development of two notches. The overhangs above these notches are assumed to collapse along a vertical plane (i.e. leaving a vertical cliff) every ten erosion events. Such overhangs and failures become smaller and less frequent as the profile evolves.

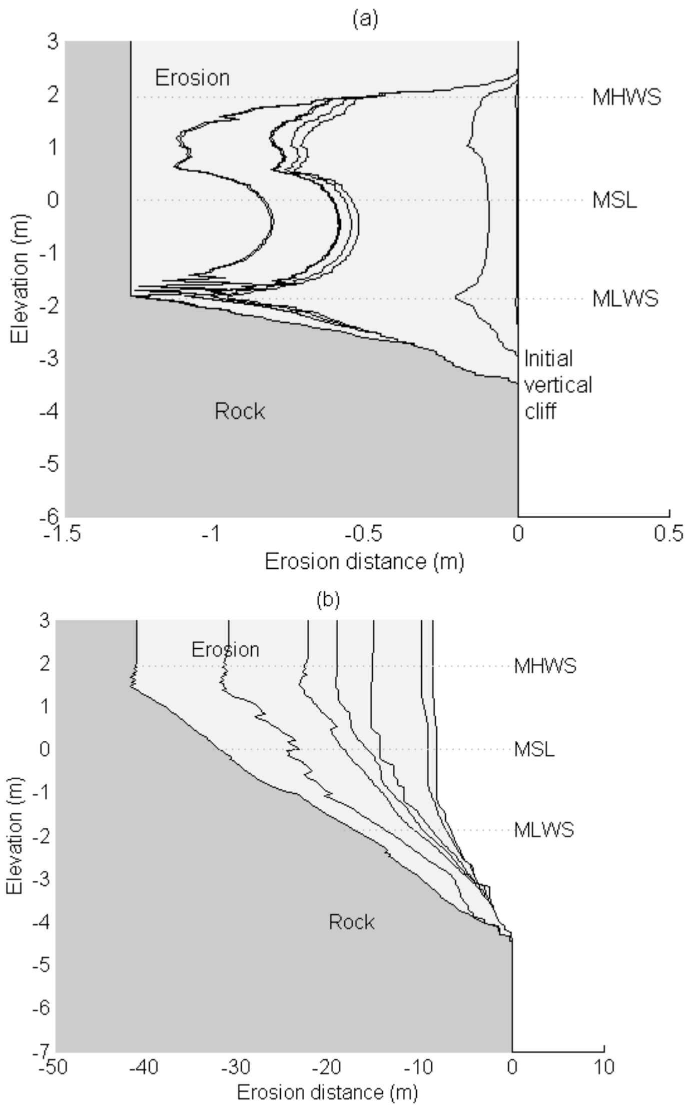

Fig. 7. Initial stages of simulated profile erosion: (a) first ten events from an initially vertical cliff, (b) seven profiles extracted at 100 tide intervals, representing the first simulation year.

Fig. 7(b) shows the evolution of the same profile between timesteps 100 and 700. It can be seen that a distinct shore platform emerges, and that its intersection with the cliff face translates upwards, reaching approximately 1.5 m above mean sea level. When the model is used to represent longer periods, as in Fig. 8, the profiles become smoother and more stable and the influence of sea level rise on profile shape becomes evident. Eventually the profile achieves dynamic equilibrium and no longer changes (on average) relative to the (rising) sea level. In this state the starting conditions have no effect on the profile state and the average equilibrium retreat rate (ε) becomes constant.

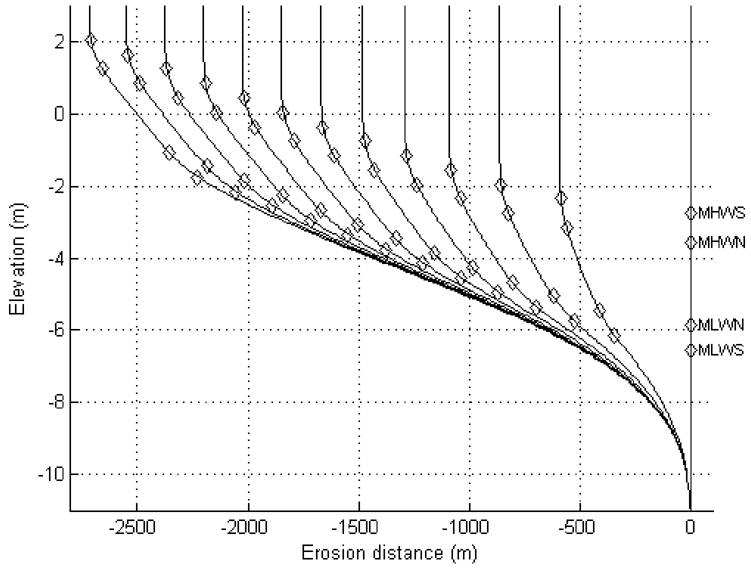

Fig. 8. Mature simulated profiles, representing 2400 years of development in 200 year stages.

Walkden and Hall (2005) used SCAPE to reproduce the profile form of a study site, the Naze peninsula, on the Essex coast in southern England. A quasi 3D (Q3D) model was assembled with a series of SCAPE profiles that interacted through longshore exchange of beach material. More details of the model and input data are given below. Dickson et al. (2007) later constructed regional scale SCAPE models of 50 km of the coast of North Norfolk (UK). Confidence in these models was based on comparison of their output with alongshore variations in recession rate, derived from historic maps recorded over 117 years.

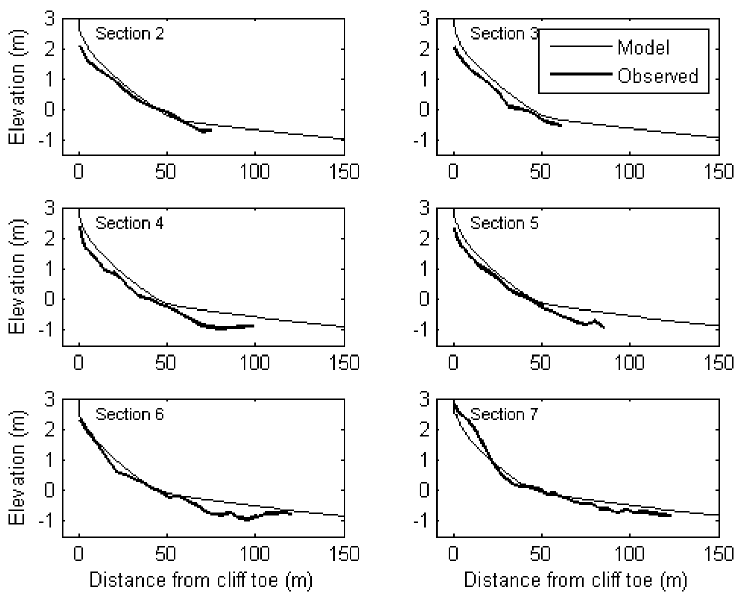

Fig. 9. Comparison between observed and modelled shore profiles at the Naze.

4 Model response to increased sea level rise

As outlined above, the work presented in this paper uses the SCAPE model developed to describe the Naze shore by Walkden and Hall (2005). The simulated recession rate was calibrated to match historic observations by varying the rock strength term *K*. The model was then tested through comparison of the emergent profile forms against survey and bathymetric data. This comparison, which is reproduced in Fig. 9, is close, despite the abstract nature of the model. Its ability to reproduce the current shore profile lends confidence to our subsequent predictive simulations.

For the new simulations presented here, model parameters were selected to reproduce the conditions in the centre of the Naze model. Each simulation was run until the profile shape reached dynamic equilibrium to identify the equilibrium retreat rate (ε). It should be noted that although the work includes simulations over millennia, no attempt was made to replicate variations in the input conditions over such timescales. Instead the tide and wave input files were continuously recycled and historic sea level rise was assumed to be constant to provide a rough approximation of conditions at the Naze.

4.1 Parameter space

The model parameters include: (1) rock strength, (2) sea level rise, (3) wave height, (4) wave period, (5), cliff height, (8) proportion of the rock comprising sediment suitable for building a beach (9) tidal range and (10) beach volume. The last of these is treated as a parameter in this application because we deal with a 2D coast, in other SCAPE applications this would be a variable that fluctuates with sediment transport and supply from rock erosion, obeying mass conservation. The purpose of this study, to use SCAPE to explore shore dynamic response to increased sea level rise, implied the exploration of a very large parameter space. Efforts were therefore made to explore whether any of these parameters were redundant, i.e. did not influence equilibrium recession rates.

4.2 Elimination of parameters

The profiles in Fig. 10 demonstrate how the platform responds to the introduction of the beach. Initially the beach slope is steeper than that of the platform so it forms a thick layer close to the cliff toe, protecting the part of the platform that it covers from erosion. The platform seaward of the beach continues to lower. As the platform erodes the seaward edge of the beach migrates down the profile and so covers and begins to protect a wider portion of the upper platform. This process continues until the beach becomes so wide and thin that waves can erode the profile through it and new dynamic equilibrium conditions are established.

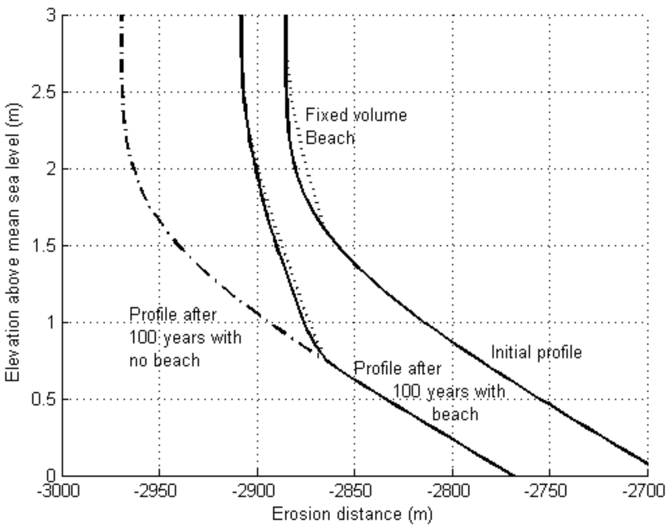

Fig. 10. Shore profile adaptation to the introduction of a beach.

Walkden and Hall (2005) demonstrated a case in which shore equilibrium recession rates were insensitive to the presence of a beach and so a series of tests were conducted to explore whether the beach volume could be considered redundant in this study. An equilibrium profile was simulated using the default (Naze Peninsula) parameters. In a series of tests different volume beaches were added to the profile and subsequent recession rates were recorded. In the decades following the introduction of the beaches the recession rates fell. However, once each profile had adapted to the beach (as in Fig. 10) and dynamic equilibrium conditions had emerged, the recession rate was found to be almost independent of beach volume below approximately 30 m^3/m, as shown in Fig. 11. This model behaviour was investigated and found to be due to the limited protective coverage provided by the beach. In the model any erosion event removes material offshore to the point on the profile where it reaches the depth z_{lim}:

$$z_{\lim} = MSL - \xi - \gamma H_b \tag{5}$$

where *MSL* is the mean sea level, ζ is the tidal amplitude, γ is the wave breaking index and H_b is the wave height. A beach has to be sufficiently big (approximately 30 m^3/m in this case) to provide protection as far seaward as this. Otherwise it merely causes the upper shore platform to steepen (temporarily retarding cliff recession as it does so), whilst the eventual equilibrium shore recession rate is driven by erosion of the platform seaward of the beach.

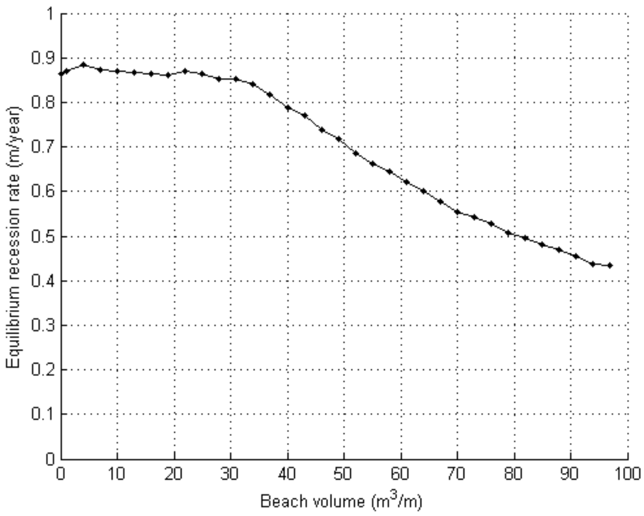

Fig. 11. Sensitivity of equilibrium shore recession rates to the presence of a beach.

This result implies, for the type of shore investigated, the existence of a threshold below which the equilibrium recession rate is unaffected by average beach volume. The actual value of the threshold beach volume (approximately 30 m^3/m in this case) will be dependent on profile shape and therefore the local hydrodynamic conditions, but will also depend to some degree on the model assembly. These results were interpreted as showing that equilibrium recession rate is independent of low beach volumes and therefore beaches were eliminated from subsequent models. The cliff height and sand content were also eliminated since they only influence the shore profile dynamics through their effect on beach volume.

4.3 Parameter tests

Model sensitivity to the remaining parameters were tested by applying perturbations to the default (Naze Peninsula) data. For each perturbation factor the equilibrium recession rate was found for a range of rates of sea level rise. Table 2 contains the input perturbation factors and rates of sea level rise that were tested, e.g. in test series 10 every tidal amplitude read into the model was multiplied by 1.5. In addition, more extensive sea level rise rates were tested on the basic Naze model with unperturbed parameters.

Test series	Input perturbation factors				Rates of sea level rise
	Rock strength	Wave height	Wave period	Tidal amplitude	(mm/yr)
TS1	1	1	1	1	0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16
TS2	0.25	1	1	1	2, 4, 6, 8, 10, 12, 14, 16
TS3	0.5	1	1	1	2, 4, 6, 8, 10, 12, 14, 16
TS4	2	1	1	1	2, 4, 6, 8, 10, 12, 14, 16
TS5	4	1	1	1	2, 4, 6, 8, 10, 12, 14, 16
TS6	1	0.5	1	1	2, 4, 6, 8, 10, 12, 14, 16
TS7	1	1.5	1	1	2, 4, 6, 8, 10, 12, 14, 16
TS8	1	1	0.75	1	2, 4, 6, 8, 10, 12, 14, 16
TS9	1	1	1.25	1	2, 4, 6, 8, 10, 12, 14, 16
TS10	1	1	1.5	1	2, 4, 6, 8, 10, 12, 14, 16

TS11	1	1	1	0.5	2, 4, 6, 8, 10, 12, 14, 16
TS12	1	1	1	1.5	2, 4, 6, 8, 10, 12, 14, 16

Table 2. Test conditions.

5 Results and discussion

5.1 Equilibrium profile shapes

Fig. 12 shows the equilibrium profile shapes reached by the baseline test series (i.e. with unperturbed parameters). It can be seen that the equilibrium profile becomes steeper for higher rates of sea level rise. This behaviour can be understood by considering that increased sea level rise reduces the period that any individual element experiences wave attack and therefore how gentle its gradient becomes. The difference between this behaviour and the unvarying profile form described in Bruun's conceptual model is discussed below.

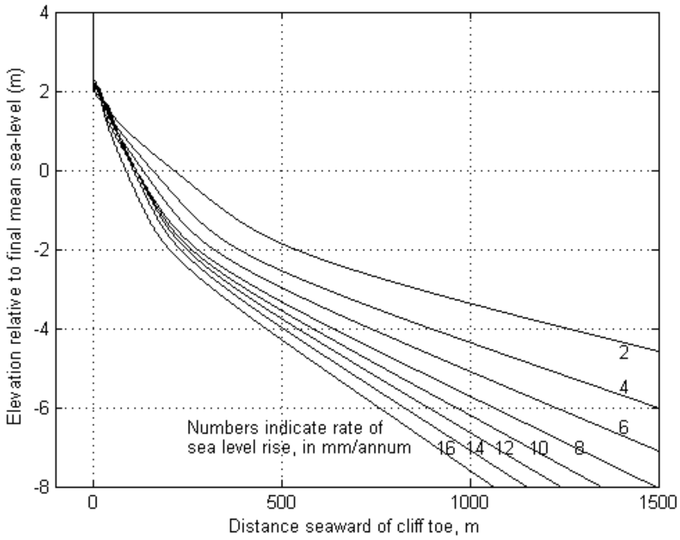

Fig. 12. Equilibrium profiles under a range of sea level rise rates.

5.2 Equilibrium recession rate

Fig. 13(a) shows the equilibrium recession rates from each of the twelve test series. Rates of sea level rise and equilibrium recession are clearly linked, although the relationship is complicated by the variations in rock strength, wave period, wave height and tidal amplitude. A normalisation process was used to clarify the dependence of recession on sea level rise. The normalisation constants chosen were ε_1 and S_1, i.e. historic rates of equilibrium recession and sea level rise respectively. For each individual test series S_1 was assumed to be 2 mm/yr, and ε_1 was the corresponding observed equilibrium recession rate. S_l = 2 mm/yr was chosen simply because it is typical for southern Britain, and many other regions during the 20th Century. The normalised results are shown in Fig. 13(b).

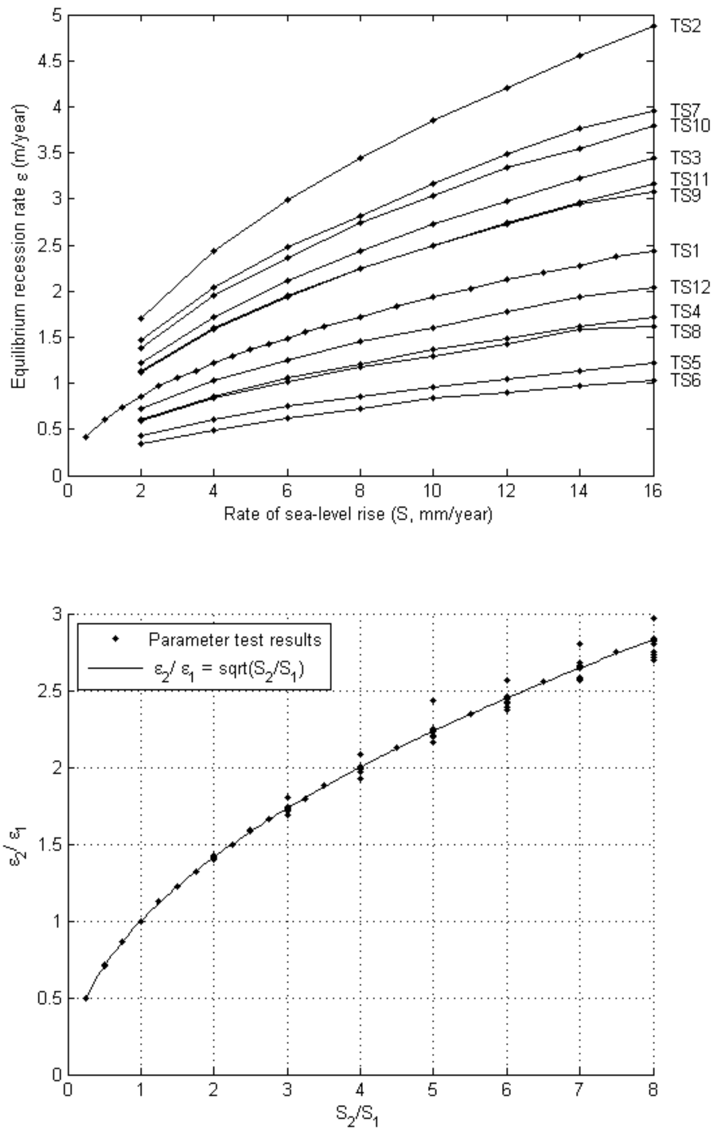

Fig. 13. Parameter test results: (a) raw data, (b) normalised results.

The following expression fits the data in Fig. 13(b) with an r^2 value of 0.96:

$$\varepsilon_2 = \varepsilon_1 \sqrt{\frac{S_2}{S_1}} \tag{6}$$

Hence, Eq. (6) may be used to express the model's response to increased sea level rise, within the parameter space tested for the case of a composite soft rock/ low volume beach shore. This equation is essentially a numerical solution to Eq. 3 that is valid only over extended timescales. It could be used instead of a model like SCAPE under certain constraints. First, Eq. (6) describes the relationship between future and historic *equilibrium* retreat rates, and equilibrium conditions take some time to emerge following a change in the rate of sea level rise. For example, Fig. 14 shows results for a model in which a step acceleration in the rate of sea level rise from S_1 = 2 mm/yr to S_2 = 6 mm/yr was introduced at 6000 years (results have been averaged within 100-year windows). It can be seen that the recession rates take around 1000 years to stabilise at 1.47 m/yr from the prior rate of 0.85 m/yr. Eq. (6) only describes recession rates after this transient stage. However, in this context it should be noted that approximately half of the total increase in retreat rate is achieved by the middle of the first century following the step change.

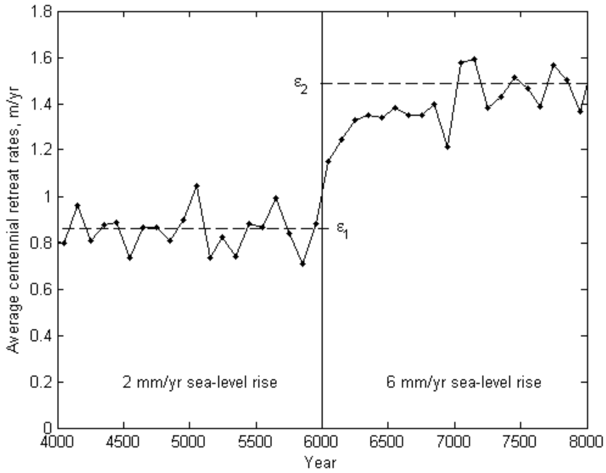

Fig. 14. Example model recession rates before and after a step change in sea level rise from 2 mm/yr to 6 mm/yr at 6000 years (averages of 100 year segments).

Second, Eq. (6) does not describe future recession at sites with no historic sea level rise. Model results not described here indicate that such shores may not achieve a state of dynamic equilibrium and so the concepts used to develop Eq. (6) would not apply. Exploration of this condition would require further work, but the limitation that this constraint imposes on the applicability of Eq. (6) may not be severe since the average global sea level is rising.

6 Conclusions

Traditionally recession predictions for eroding coastlines have been based on the extrapolation of historic observations. This assumption is reasonable for a natural coastal system in dynamic equilibrium, but this is not appropriate with accelerating sea level rise. This is an important issue that lends itself to exploration through numerical model studies. While few data are available to test such models, a range of possible responses of shore profiles can be usefully examined by assuming scenarios of sea level change and testing sensitivity to various model parameters. We have conducted one such study using a process-based numerical model to investigate the equilibrium profile response and recession rate of composite soft rock and low volume beach shores.

In these numerical experiments the equilibrium recession rate proved to be insensitive to beach volumes below 30 m^3/m. This value will be site specific, and will also depend to some degree on model assembly, but is proposed as a tentative first estimate of the beach volume below which the relationship applies. Subject to this condition the relationship should also be independent of cliff height and sand content of the rock as well as to alongshore exchange of sediment.

Equilibrium profiles were found to vary with the rate of sea level rise. They became steeper with higher rise rates because of the associated reduction in duration of wave attack. Once (dynamic) equilibrium had emerged following a step increase in rate of sea level rise the recession rates were found to be well represented with a simple relationship across all parameter values tested (Eq. 6). This relationship is proposed as a means of rapidly estimating future equilibrium recession rates for soft rock shores overlain by a low volume (or absent) beach in which the profile is subjected to an increase in the rate of sea level rise. The relationship is not appropriate in the case of non-equilibrium conditions, including accelerating sea level rise and zero sea level rise. Within these constraints, this work indicates the existence of a remarkably simple relationship governing the response of composite soft rock/ low beach volume shore profiles to increased sea level rise.

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