Available online at www.sciencedirect.com
SCIENCE DIRECT®
Coastal Engineering 52 (2005) 535–563
Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers
www.elsevier.com/locate/coastaleng

A predictive Mesoscale model of the erosion and profile development of soft rock shores

M.J.A. Walkden*, J.W. Hall[1]

School of Civil Engineering and Geosciences, Cassie Building, University of Newcastle upon Tyne, NE1 7RU, UK

Received 13 April 2004; received in revised form 27 January 2005; accepted 11 February 2005
Available online 10 May 2005

Abstract

The development, application and behaviour of a generic model of retreating soft rock (e.g. clay) shores is described. This represents a broad system, in coastal modelling terms, comprising shore platform, beach, tidal range, wave transformation, cliff and talus. The coast is divided into a series of representative cross-shore profiles, each of which is discretised into a column of elements. Erosion of a platform element at each timestep depends on its gradient. Material strength is dealt with as a calibration constant, wave forces are averaged over durations of a tide or hour and sediment transport is represented in bulk terms. Attention has been focussed on interaction between system parts and the emergence of system properties, in particular profile shape. This is allowed to develop towards dynamic equilibrium and is the principal means of model validation. The emergence of the profile shape is dominated by the distribution of wave scour by the tide and by interaction with a beach, if present. Because the model is process-based, it may be used to model the effects of climate change and engineering intervention. Yet it is also computationally inexpensive, so may be used to explore uncertainty through probabilistic application. The breadth of the included system, coupled with short run-times, enables predictions over timescales of decades, which we refer to as the Mesoscale. The model is used to explore the dynamics of retreating soft rock shore profiles and to predict future behaviour of a study site.

Keywords: Erosion; Soft rock; Foreshore; Profile dynamics; Sea-level rise; Cliff

1. Introduction

Soft rock shorelines are vulnerable to erosion yet are often inhabited and developed. The coast can be engineered to lessen this vulnerability and, at least temporarily, reduce coastal recession. The geomorphic implications, and therefore the true benefits and costs of such intervention are not always clear; for example a seawall can prevent subaerial cliff recession but is

* Corresponding author. Tel.: +44 191 222 6259; fax: +44 191 222 6502.
E-mail addresses: mike.walkden@ncl.ac.uk (M.J.A. Walkden), jim.hall@ncl.ac.uk (J.W. Hall).
[1] Tel.: +44 191 222 3660; fax: +44 191 222 6502.

0378-3839/$ - see front matter
doi:10.1016/j.coastaleng.2005.02.005

unlikely to reduce shore platform lowering. Ultimately this may lead to undermining and seawall failure followed by rapid cliff retreat. Similarly, protected cliffs release less sediment, which may cause lowering of local and down-drift beaches.

Engineers responsible for the design of coast protection schemes need tools to explore the geomorphic consequences of potential options. A more general need for such modelling capability arises from the expectation that the rate of global sea-level rise and the magnitude and direction of storm waves will change as a result of global warming. If sea-levels rise more quickly and storminess increases then erosion is expected to increase, but it is not clear whether this will happen at all locations or how extreme the effects might be. Process-based geomorphic models are needed to address these issues and provide quantitative predictions of the effects of natural and anthropogenic changes, which cannot be predicted from statistical analysis of historic recession data. A statistical model can only predict behaviour under conditions that are well represented in the historic record (see, for example, Dolan et al., 1991; Hall et al., 2002), whilst a Bruun-rule model only deals with changes in the rate of sea-level rise; consequently both were rejected in this study. The timescale of interest, from around 1 to 100 years, is long in modelling terms, and is referred to here as the Mesoscale.

In this paper we demonstrate how it is possible to make predictions of soft rock coast erosion over Mesoscale durations by representing dominant coastal characteristics that determine behaviour, for example beach volume and tidal range. Relatively simple formulations of the hydrodynamic, sediment transport and material processes have been adopted on the basis that effective Mesoscale prediction can be achieved by appropriate representation of the feedback between dominant processes rather than by elaborate (and data-intensive) representation of processes at, say, a wave-by-wave scale. In particular, it is argued that the shore platform shape acts as an important regulator of erosion and recession. The processes and dynamic relationships from which the shape of the platform emerges provide the key to Mesoscale prediction of erosion both in undisturbed conditions and in the presence of natural or engineering changes to the system. Adopting a relatively simple formulation of the erosion system brings the added advantage of reasonably short model run-times, so it becomes possible to explore uncertainties and sensitivities in a comprehensive way over the Mesoscale.

We begin by identifying the type of eroding coastal system that our model endeavours to represent. We go on to describe the formulation of our erosion model, which draws on theoretical and empirical work in the literature. Attention is focussed on the interconnections between the parts of the type of coastal system in question. Model behaviour is then explored, and comparisons made with examples from the literature, where they are available. Our emphasis here is on generic features of the type of eroding coast we aim to represent, so that readers can assess the potential applicability of the approach to similar sites world-wide.

A model of a specific site is then prepared and validated against field measurements. Potential futures of the study site are then explored, including engineering options and possible climate change effects. The Monte-Carlo technique is employed to illustrate sensitivity, and to demonstrate the models capability in this respect.

2. Geomorphic system

The erosion model described in this paper is intended to represent coasts developed in soft erodible materials, i.e. materials with strength in the range between a soft mudstone and soft clay. Long sections of the east and south coasts of England are made of eroding cliffs in glacial tills, clay and mixed sands and gravels. These cliffs vary from a few metres to over 50 m in height and have been eroding over the Holocene due to wave action and rising sea levels. Similar coastal forms are widespread in northern Europe, North America and elsewhere.

Fig. 1 illustrates the main features of soft eroding shores that influence coastal recession. The processes of upper cliff erosion and landsliding are of relevance in determining the instantaneous position of the cliff edge, which is the point of interest in determining the risk to cliff-top assets. However, we proceed with the assumption that the long term rate of recession of the cliff top is primarily determined by the rate of recession of the cliff toe, justifying our focus on the shore platform. This assumption is based on the observation

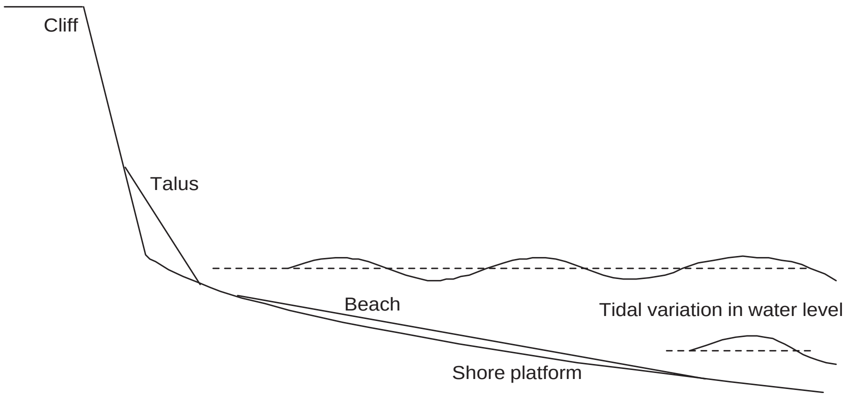

Fig. 1. Schematic profile through an eroding soft shore.

that a far higher proportion of incident waves energy is expended on the shore platform compared to the cliff face, and is supported by earlier work. Kamphuis (1986, 1987) studied the retreat of bluffs on cohesive shores and concluded "...the controlling factor for actively eroding bluffs is related primarily to foreshore erosion rate which in turn controls the recession of the bluff toe." He also develops an equation describing the relationship between foreshore erosion and incident wave conditions, which is used below.

Erosion processes on the upper cliff are only of relevance to the prediction of soft shore evolution in that they deposit material, as fallen talus, at the cliff toe, which is then worked by waves and may bulk beaches. Talus cones of soft material are ineffective at resisting wave attack due to both their disturbed, discontinuous structure and their steep sides. Consequently they have little effect on recession rates. The talus materials are likely to have more effect if and when they pass into a beach. A beach may provide protection to its underlying platform, where and when it is sufficiently thick relative to the waves passing over it.

Although the shore platform and lower cliff are usually carved from the same material, they have very different forms; the former approaches the horizontal, whilst the latter is almost vertical. This means that they experience different types of wave attack. The platform is eroded by breakers under which wave forces are distributed over length and time scales of the order of the wavelength and wave period. In contrast to the shore platform, the cliff toe experiences steep wave fronts that tend to generate higher, more localised and more transient impulse loads (see Walkden et al., 1995). These concentrated wave loads are effective in removing cliff and talus material. However, most waves do not reach the cliff toe, which is only wetted by some high tides. Not all of these tides will coincide with significant wave action. Consequently erosion tends to be more episodic at higher elevations in the profile.

The junction between the cliff and platform emerges for hydrodynamic, rather than geological or geotechnical reasons. The tidal cycle plays an important role in its formation since the junction tends to appear slightly above the mean high water of spring tides.

Shore profiles appear to tend towards dynamic equilibrium in which the average retreat rate equalises across all elevations. If one part accelerates for a time then its subsequent recession is reduced until the rest has caught up. For example, if the cliff retreats rapidly due to some unusual wave loading then this makes the platform wider and the cliff toe rises. Subsequent waves are less able to reach the cliff toe until they had worn the platform down. Similarly, temporary excessive platform downwearing results in lowering of the cliff toe, exposing it to greater and more frequent wave attack and therefore accelerated erosion. Such feedback is important in maintaining the dynamic equilibrium of the profile shape and controlling the overall recession rate. In this study the representation of this feedback is viewed as central to solving the problem of understanding and predicting shore recession.

There appear to be multiple feedback paths that regulate shore erosion. Cliff recession releases sediment which, at least temporarily, provides protection against further erosion, either as talus which protects the cliff toe, or as a beach protecting areas of the platform. Horikowa and Sunamura (1968) noted this behaviour in physical model tests in which sand released from wave-cut notches formed a protective beach. This highlights the importance of sediment transport, which may remove such material and allow erosion to continue.

Kamphuis (1990) described positive feedback in which small amounts of sand, perhaps released by erosion, increase the erosive capability of waves. He also described negative feedback in explaining observations that cohesive shores with a beach, even the ones that were insubstantial, had profiles that were very similar to those of a full beach of the same material. He argued that:

"Any deviations in the cohesive sediment profile from a natural sandy profile are adjusted through abrasion of protrusions and protection of depressions, resulting in a profile in the cohesive sediment which actually resembles a sandy beach profile."

Feedback also influences sediment transport rates. If sediment transport differentials reduce the volume of a beach then it tends to become narrower. It therefore occupies less of the surf zone and the proportion of the potential sediment transport that actually occurs is reduced.

3. Characterisation of the geomorphic system

A number of the characteristics and processes identified above have been in the literature. Not all of this work relates to soft eroding coasts as described above, and some has involved laboratory studies, but the observations and insights are nonetheless of relevance in the development of models of these coastal systems.

3.1. The relationship between eroding forces, shore resistance and slope

Sunamura (1992) observed that the erosion vulnerability of a rock shore can be expressed through its factor of safety:

$$\frac{F_W}{F_R} \tag{1}$$

where F_W represents wave eroding forces and F_R the material resisting forces. There is considerable uncertainty over the physical properties that these terms represent. Various attempts have been made to associate F_W and F_R with measurable characteristics, which can be related empirically to recession rate. Mano and Suzuki (1999) studied erosion of the soft rock cliffs at the Fukashima coast in Japan. They represented the wave eroding forces with the wave energy flux at the breaking point and the material resistance by the product of the cliff height and the Young's Modulus. Trenhaile (1983), in a study of the development of shore platforms in hard rock cliffs defined F_W as the wave energy, and F_R as the wave energy required to cut a notch of a unit length. Jones et al. (1993) studied the shear strength and exposure to wave attack of soft glacial cliffs around Thompson Island in Boston Harbour, Massachusetts. They demonstrated that cliffs with a low shear strength and high exposure to wave attack tended to experience high recession. Wilcock et al. (1998) studied the Maryland coast in the USA. They defined a relative 'wave strength' as the ratio of wave pressure (T) to the cohesive strength (S). They found that sites which experienced a high T/S most often were those with the highest erosion rates. They also acknowledged the importance of the topography of the platform on breaker shape, and impact load and erosion rate. Sites with gently sloping foreshores were deemed to be less likely to erode because waves broke more gently.

The importance of wave dissipation was also noted by Stephenson and Kirk (2000) who studied the shore platforms of the Kaikoura Peninsula in New Zealand and concluded that the passage of waves across the platform reduced their energy by as much as five orders of magnitude. A link between cliff recession and runup, which is controlled by the topography of the platform and beach, was recognised by Shih et al. (1994). Kirk et al. (2000) studied erosion at Lake Hawea in New Zealand. The site was particularly interesting because in 1961, it was converted into a reservoir and the water level was raised by 30 m. Subsequent erosion at this new high level resulted in the rapid formation of beaches, which then reduced runup and acted as a barrier to erosion, in some respects similar to the physical models of Horikowa and Sunamura (1968).

The importance of the shore slope α can be recognised by employing it as a term to reduce wave energy (e.g. Trenhaile and Byrne, 1986). Although the platform slope can be measured, it is not trivial to represent since it varies over both the surface of the platform and through time. This, coupled with uncertainty associated with F_W and F_R, complicates efforts to predict erosion at a particular site. This difficulty is compounded by the dynamic relationship between platform slope and erosion rate. Although it seems true that steeper slopes increase recession rates, it also seems to be the case that high recession rates cause flatter slopes. Field observations reported below in Section 6 indicate steeper platforms associated with slower recession rates. The association between slope and retreat rate seems to depend on causality, whether one views platform slope as a cause of recession or a result of it. Capturing the nature of the relationship between the slope and erosion appears to be an important key to the prediction of retreat and is a focus of this paper.

3.2. Prediction of recession based on volumetric principles

Bray and Hooke (1997) reviewed methods that might be used for predicting soft cliff retreat resulting from accelerated sea-level rise, including historic trend analysis, the Bruun model, sediment budget methods and the shore platform geometrical model proposed by Sunamura (see below). They studied eight soft cliff sites along the south coast of England and the Isle of Wight, and concluded that a modified version of the Bruun rule was the most suitable for predicting the influence of changed sea-level rise rate on recession rate. A particular reason for its suitability was that it represented feedback, in that sediments released through accelerated recession acted to reduce subsequent erosion. Bray and Hooke (1997) do, however, highlight problems with the modified Bruun method including its requirement for a defined closure depth, its assumption of a constant equilibrium profile and its assumption of instantaneous profile response to any change in rate of sea-level rise. They also investigated numerical models but found none based on functional relationships between the dominant physical processes that were reliable.

Meadowcroft et al. (1999) developed a model, named CLIFFPLAN, which described processes affecting a two-dimensional slice of cliff, beach and talus. The model calculates runup, links this to erosion which then bulks the beach. As the beach rises, the runup is reduced and this feedback limits erosion rate. Longshore transport moves beach material between sections using a one-line approach; a technique that has been used for many years to assess the consequences of engineering intervention, particularly groyne construction and beach nourishment. CLIFFPLAN should, therefore, be able to take advantage of these capabilities. A trade-off is explicitly made between model complexity and run-time to make the model suitable for use in probabilistic analysis. Each process is represented in a consistently simplistic manner so that the demands on processor power are small, and multiple simulations are possible. However, the model assumes the presence of an infinitely deep beach and includes no shore platform, so is unsuitable for the type of geomorphic system being considered in this paper.

3.3. Shore platform models

Sunamura (1992) provides a model of the geometry of shore platforms. The model depends upon the wave height, wavelength, water depth at the breaking point, the maximum depth at which waves can erode the rock (the ‘wave base’), the initial platform width and a coefficient of wave height attenuation. The breaker height and the breaker depth are assumed to be independent of time, whilst tide effects, cliff debris, a beach and longshore sediment transport are not included.

Nairn et al. (1986) developed a numerical model to simulate the processes on a cohesive shore profile. The model empirically relates downcutting to two processes. First, the shear stresses on the bed due to wave orbital velocities. Second, the intensity of wave breaking (as indicated by the local gradients in wave energy dissipation across the surf zone) and associated turbulence and jets (due to plunging breakers) impinging on the bottom. The former is dominant outside the surf zone while the latter is dominant in the surf zone. These concepts are in agreement with the observation that the degree of downcutting increases towards the shore, a result that cannot be sustained by a model based only on shear due to orbital velocity. Two empirical coefficients are used to relate the downcutting to these processes. This model forms part of the shore profile model COSMOS (Nairn and Southgate, 1993). COSMOS describes a two-dimensional shore profile, but includes longshore transport, so it can be used to represent quasi-three dimensional morphodynamics. Tidal variation in water surface elevation is represented and the effect of tidal currents on sediment transport is included. COSMOS deals with storm waves so can only predict over storm durations and cannot represent beach building during calm periods. This limitation, combined with the computational expense of this sophisticated model, seems to preclude, at least at present, its use for Mesoscale predictions.

Trenhaile (2000) described a model of shore platform development in hard rock. The model represents the erosive potential of the waves with their (broken) impact load, and accounts for attenuation across the surf zone. A threshold was introduced into the relationship between force and erosion below which no erosion would occur. An important aspect of the model is the inclusion of tidal effects. Trenhaile recognises that most erosion occurs close to the still water line, and that this line is moved throughout the tidal cycle. This leads to concentrations of wave aggression close to high and low tide levels. Material strength is represented by a factor M, which was used to convert the wave force exerted on the rock into the amount of horizontal cliff and platform erosion. Protection provided by fallen debris was represented as a constant reduction in the amount of erosion that would otherwise have occurred by up to 80%. The model also represents submarine wave erosion up to a depth of one-half the wavelength. Submarine erosion was represented by an exponential decay function of the erosion at the water level.

4. Model development

On the basis of field observations and the literature outlined above, Fig. 2 is proposed as an illustration of the processes and influences that determine erosion in coastal systems comprised of a soft cliff, platform and beach.

System parts are illustrated along with arrows representing their interconnections. For example, profile erosion is affected by wave transformation (breaking), which moves across the shore with different stages of the tide. Both the talus and the beach provide protection against erosion. Erosion releases sediment from the platform, which bulks the beach. Sediment is also released (via the formation of talus) through cliff recession, which is driven by the retreat of the platform/cliff toe. Importantly the slope of each part of the platform influences the erosion that it experiences. The mapping in Fig. 2 represents the new model, which was named Soft Cliff And Platform Erosion (SCAPE).

SCAPE is composed of primary modules that represent wave transformation, beach evolution and insitu shore profile development, and secondary modules describing the cliff and talus. Each process in this system is represented in relatively simple terms in order to minimise input data requirements, improve computational efficiency and assist understanding of the emergent properties of the system behaviour.

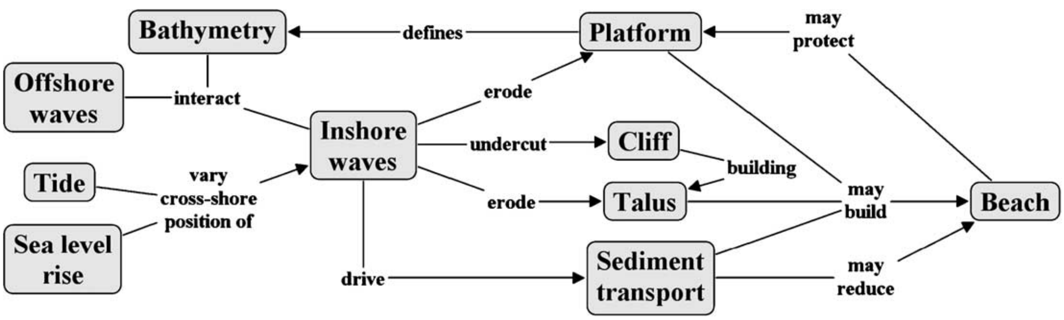

Fig. 2. Map of the interactions within SCAPE.

The approach has aspects in common with the recession models of Kamphuis (1987), Trenhaile (2000) and Meadowcroft et al. (1999), but also significant differences. Like CLIFFPLAN (Meadowcroft et al., 1999), it represents the sediment budget relationship between cliff and beach and the planshape evolution of the beach. However, unlike CLIFFPLAN the beach rests on a shore platform, which is a major determinant of shoreline behaviour. The model of Kamphuis (Eq. (3)) was preferred because it was developed to describe cohesive shore recession. Its disadvantages were that it did not include tidal effects (it was developed for lake shores) and did not describe a beach or allow variation in platform gradient across a shore profile or through time. This function was adopted but adapted to allow cross-profile variations in slope.

The tidal cycle is represented in Trenhaile's model and the platform slope emerges as the model iterates, effecting recession rate as it does so. However, recession is only calculated at a small number of points and the model is focussed on hard rock shores and processes acting on the near vertical cliff toe rather than the gently sloping platform.

The shore was simplified in SCAPE by dividing it into representative 2DV sections. Quasi-3D representation was then achieved by describing a series of these and allowing them to interact. The insitu cohesive material was represented as a column of horizontally aligned thin layers, typically from 5 to 50 mm tall. The face of the lower cliff and platform is composed of the seaward surface of these layers, as illustrated in Fig. 3. Erosion and sediment transport are calculated once per timestep (dt), which may be either 1 h or one tidal period.

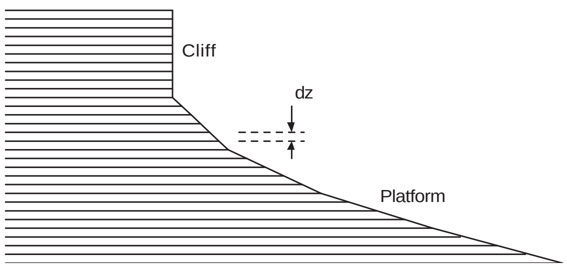

Fig. 3. Descretisation of a shore section.

4.1. Wave transformation and sediment transport

Wave transformation including refraction, diffraction, shoaling and setup was represented using linear wave theory (see Kamphuis, 1992, 2000). Wave diffraction was only used in models that included groynes or hard-point structures.

The beach evolution module was developed using the one-line approach. Bulk sediment transport between shore sections was calculated with the CERC equation (Hanson, 1989). The beach surface was assumed to comprise a flat berm, at the limit of wave runup, fronted by a Bruun profile, of the form:

$$d = ax^{\frac{2}{3}} \tag{2}$$

where d is the depth below the berm level, x is the distance seaward of the berm edge and a is a constant.

This curved profile was used rather than a single gradient, which is more normal in a one-line model, because it is more realistic. Because the SCAPE beach is perched on a platform that defines its lower boundary, the beach volume, depth and width are quantified. Beach volumes are used to ensure continuity in the sediment budget whilst beach depths contribute to the calculation of the cross-shore distribution of platform erosion; where the beach is thick it provides protection, as described below. The beach location and width is used in the calculation of sediment transport; it is compared to a cross-shore distribution of alongshore drift to determine the proportion of the potential bulk transport that is realised. This cross-shore distribution of sediment transport is calculated at every timestep by integrating over a tidal cycle a quasi-instantaneous distribution describing sediment transport on Bruun beach profiles (McDougal and Hudspeth, 1984).

The depth of beach that is sufficient for it to act as a protective barrier against erosion does not appear to have been studied directly. Some work has focussed on the depth of beach disturbance under wave breaking, which may be used to indicate maximum erosion depths. Ferreira et al. (2000) studied the depths to which waves disturbed

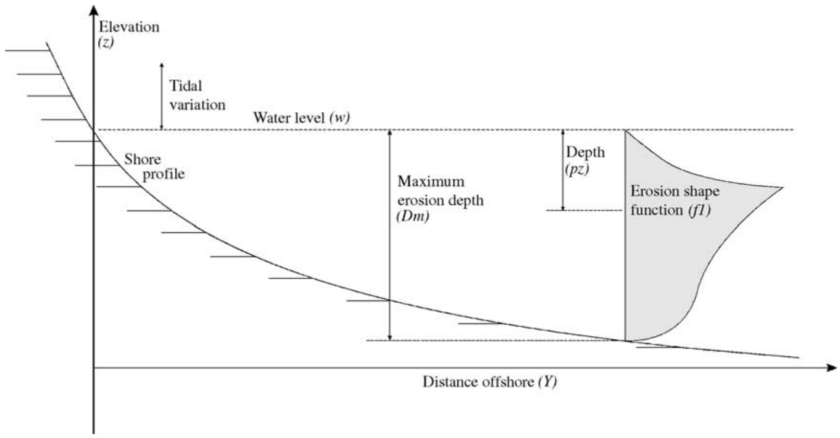

Fig. 4. Representation of cliff/platform erosion.

seven sand beach sites in southern Portugal. They found that the average and maximum depths of disturbance were 0.23 H_{bs} and 0.39 H_{bs}, respectively, where H_{bs} is the significant breaking wave height. In SCAPE 0.23 H_{bs} was assumed to be the maximum depth of beach that waves can penetrate to erode a platform. For depths less than this, the beach protective ability was assumed to vary linearly.

4.2. Erosion module

The description of erosion rate (E) was based on the following expression provided by Kamphuis (1987):

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

where H_b is the breaking wave height and T is the wave period. R represents material strength and some hydrodynamic constants, and is found through calibration. This was developed during a study of recession of glacial till bluffs at the Great Lakes and was based on consideration of the wave power in the breaking zone, the rate of energy dissipation and the energy contained in each breaking wave. α is the average slope across the surf zone. In SCAPE α is allowed to vary across the profile and through time as described below. Moreover, rather than being an input parameter, α is allowed to emerge, influencing retreat rates as it does so.

4.3. Numerical description of erosion

The equation describing the erosion rate in SCAPE is:

$$\frac{dy}{dt} = \frac{F}{R} \tan\alpha \tag{4}$$

where y is the retreat distance and:

$$F = H_b^{13/4} T^{3/2}$$

The erosive forces (F) under random waves in the absence of tidal variation was assumed to vary with depth (p_z) in a manner described by a shape function $f_1(p_z)$ with area equal to 1, which is illustrated in Fig. 4.

$$\int f_1 dz = 1$$

If w is the water level and z is elevation then;

$$p_z = w - z$$

Inserting the shape function into Eq. (4):

$$\frac{dy}{dt} = \frac{F}{R} f_1(w - z) \tan\alpha$$

The platform slope varies with elevation so;

$$\alpha = f_2(z)$$

and;

$$\frac{\mathrm{d}y}{\mathrm{d}t} = \frac{F}{R} f_1(w - z)\tan(f_2(z))$$

w is a function (f_3) of time (t), due to the tide;

$$\frac{\mathrm{d}y}{\mathrm{d}t} = \frac{F}{R} f_1(f_3(t) - z)\tan(f_2(z))$$

If we deal with a unit run of platform then the rate of volume (V) of material lost is

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{F}{R}\int_{w-D_\mathrm{m}}^{w} f_1(f_3(t) - z)\tan(f_2(z))\mathrm{d}z$$

where D_m is the lower limit of f_1, and the total volume lost per tide period (T) is

$$V = \frac{F}{R}\int_0^T \int_{w-D_\mathrm{m}}^{w} f_1(f_3(t) - z)\tan(f_2(z))\mathrm{d}z\mathrm{d}t. \quad (5)$$

The calibration term for material resistance (R) is found by comparing model predictions of recession to observations. The tide (f_3) is represented as a sinusoid, which oscillates about mean sea-level with a period of 12.46 h. Realistic tidal amplitudes are read from an input file. Sea-level change is represented as a small shift in the elevations of the cliff elements at every timestep. The profile slopes (f_2) are calculated by the model at every timestep.

The tangent in Eq. (4) causes erosion to tend to infinity as α approaches vertical (90°). At the start of the modelling process, the cliffs are assumed to be vertical and in deep water with no platform. To prevent excessive erosion during this early stage, α is limited to a maximum of 50°. In practice the platform slope typically assumes a maximum of only 10°.

The erosion shape function f_1 was found by analysing laboratory results published by Skafel (1995). He conducted experiments in a wave tank in which pseudo-random waves shoaled and broke over a model shore composed of intact glacial till (see also Skafel and Bishop, 1994). The model was given a realistic profile of $y=0.18x^{2/3}$ and two water depths were tested. This meant that the platform at the waterline was steeper in the deeper water tests, causing the waves to plunge. The breakers in the shallower water test were classified as 'spilling'. Skafel published the distributions of erosion rate that resulted from these experiments, and these are reproduced in Fig. 5a.

These distributions are significantly different; the plunging waves show larger erosion rates, particularly

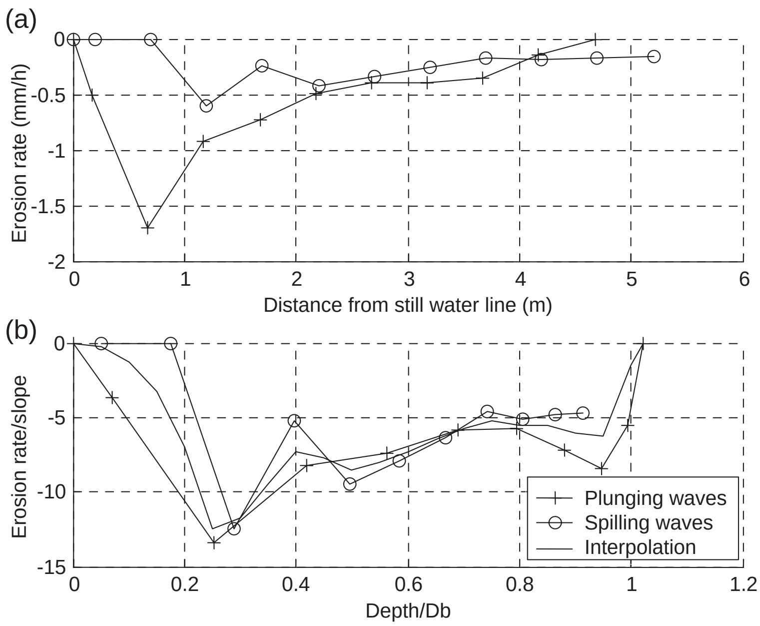

Fig. 5. (a) Distribution of erosion rate under breaking waves, data from Skafel (1995). (b) Variation of erosion rate/platform slope with elevation.

close to the still water line. Neither was considered to be appropriate for f_1 because they are subject to the influence of the platform shape. Both distributions were therefore divided by the local slope and the results are shown in Fig. 5b. In this figure the distance from the still water line has been converted to water depth and normalised by the depth at which the waves began to break.

The resulting distributions are similar, and so an interpolated distribution was produced to represent them both and was adopted as the shape function f_1. Clearly the peak in this distribution tends to amplify erosion at around at $d/d_b = 0.25$. This does not, however, ultimately result in excessive mining at this level because of the $\tan\alpha$ term in Eq. (4). As the slope of the base of any 'hole' approaches zero, so does its subsequent erosion.

4.4. Secondary modules

Simple modules were added to SCAPE to describe the cliff collapse and talus erosion. The cliff was treated as a block of material that sheared to maintain a vertical face when undermined and form a talus wedge, with a surface slope of 45°. All material that shears off the cliff face adds to the talus volume, but only a proportion of the material eroded from the talus bulks the beach; the rest is assumed to be carried away in suspension and lost from the system. Talus material was assumed to have a strength of $0.1R$. To save processor time, the collapse of the cliff face was assumed to take place every ten erosion events.

4.5. Engineering interventions

In its current form SCAPE may be used to explore the effects of some engineering interventions. Seawalls can be represented as positions behind which the platform may not retreat. Groynes are barriers aligned perpendicular to the baseline through which sediment may not pass and around which waves diffract. The proportion of sediment blockage is estimated by integrating the cross-shore distribution of longshore drift over the length of the structure. Beach nourishment can be represented by artificially bulking the beach volume. Examples of engineering intervention are provided in the case study in Section 6.

5. Model behaviour

SCAPE is a geomorphic modelling tool intended to represent the main processes that cause the shape of an eroding shore to emerge and develop. In this section it is used to explore shore morphology and dynamic response. Most of the models used to contribute to this section were given the same starting profile, a vertical cliff in deep water. Wave and tide records (20 years and 11 years, respectively) were adopted from a case study, which is described below in Section 6. Although the models describe very long periods, no attempt was made to represent the extreme events beyond those within the adopted records.

As the model behaviours described below are for idealised cliffs the quantified recession rate predictions are not of significance. Of interest are the rates of change and the emerging shore shapes.

5.1. Initial stages of profile development

A simple model was prepared involving one shore section with no beach or talus. The horizontal cliff elements were all 50 mm high and the initial shape was a vertical cliff. Profile development during the first model timesteps was strongly influenced by the steepness of the cliff, which induced high erosion.

Fig. 6 shows the profile development (from right to left) during the first 10 recession events, i.e. the first 10 tides with active waves. A notch was formed in irregular sized steps, with erosion concentrated at the tidal extremes. After 10 recession events, the model removes any overhanging material, which produces the final vertical cliff in the figure.

Fig. 7 shows 10 further profiles from the same model, each representing development over 10 erosion events. The first profile is the same as the ninth in Fig. 6. It can be seen that the shape continues to develop with the platform left by the retreating notch becoming wider and the cliff toe rises.

Seven profiles are shown in Fig. 8, each 100 tides apart. In the last profile (representing almost 1 year of erosion), the junction between the top of the platform and the cliff toe has risen to approximately 1.3 m above mean water level. Surface irregularity has decreased.

Figs. 9 and 10 show model output every 10 years and 2000 years, respectively, and demonstrate the

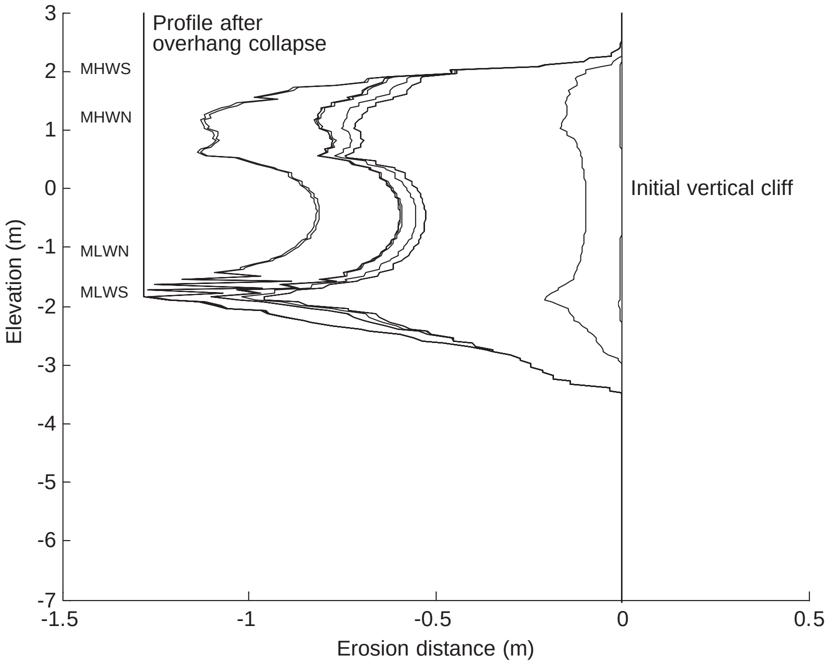

Fig. 6. Early stages in the development of a model notch.

emergence of a characteristic smooth profile. This development is remarkably similar to that hypothesised by Sunamura (1992, his Fig. 7.11). Over time the overall slope of the profile reduces, and this is accompanied by a fall in the average retreat rate, which decays asymptotically as can be seen in Fig. 11.

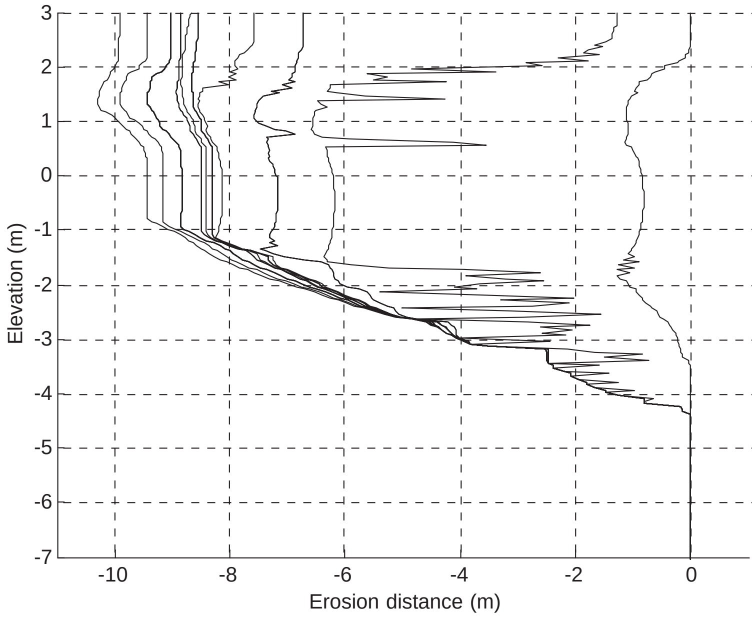

Fig. 7. Early emergence of a model shore platform and cliff.

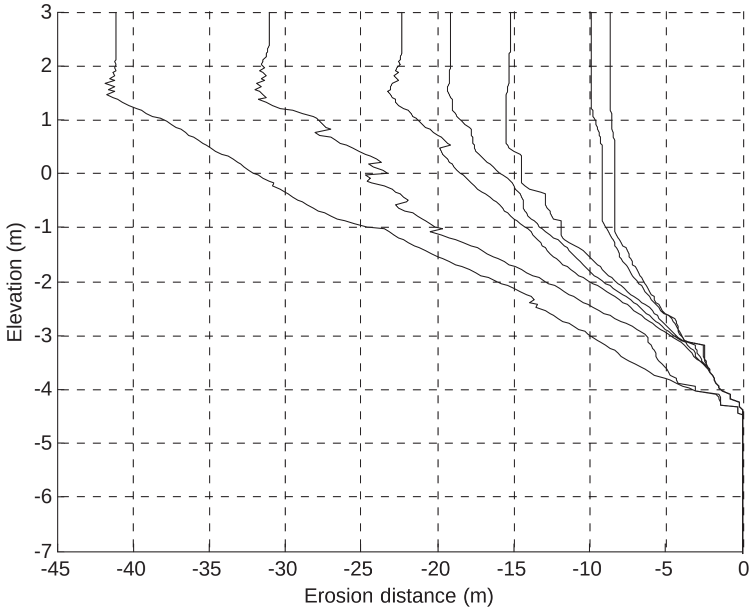

Fig. 8. Continuing demarcation between platform and cliff.

5.2. Influence of rate of sea-level rise

The results shown above were generated assuming static average sea-level; this is not normally the case. Whilst relative sea-level rise is not experienced throughout the globe, it is observed at most sites in temperate and lower latitudes (Church et al., 2001). Rising relative sea-levels increase water

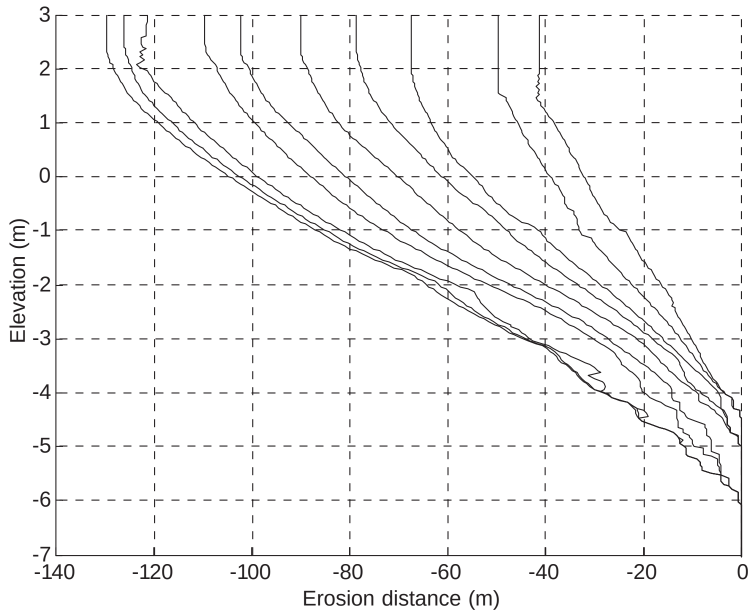

Fig. 9. Stabilisation and smoothing of model profile shape over 10 years, in 1-year stages.

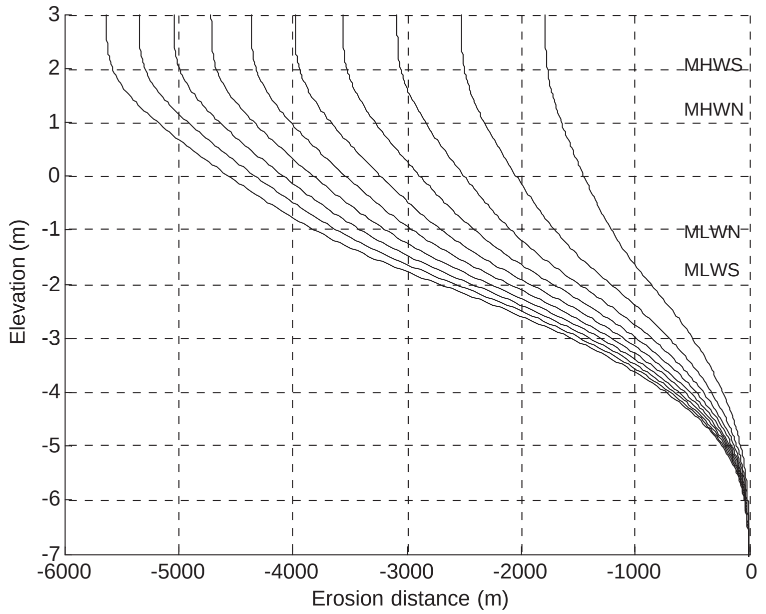

Fig. 10. Stabilisation and smoothing of model profile shape over 20,000 years, in 2000-year stages.

depths over platforms and allow larger waves to attack it and the cliff toe. SCAPE was used to explore profile sensitivity to differences in rate of sea-level rise.

Fig. 12 shows how cliff toe recession distance varies with rate of sea-level rise. As would be expected, the higher rates of inundation caused more recession. Each line, except the one associated with no

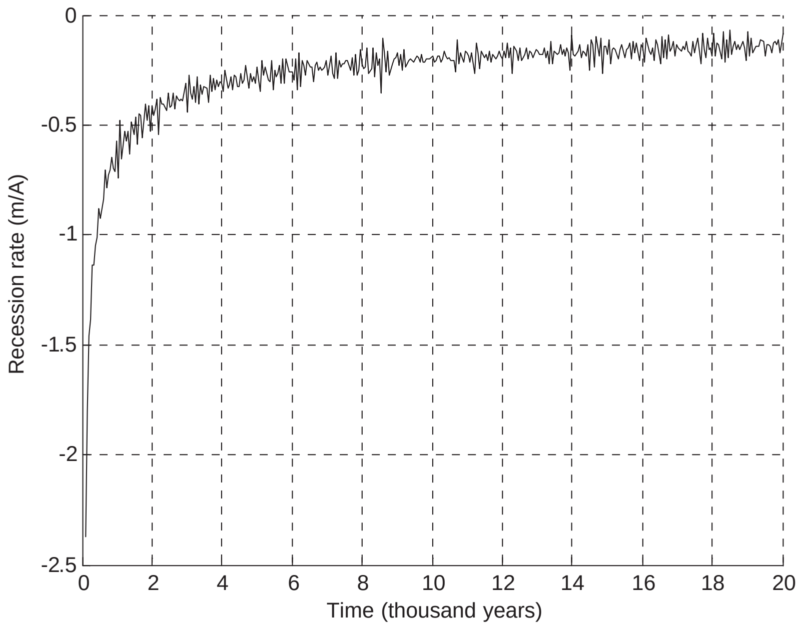

Fig. 11. Asymptotic decay of recession rate with time.

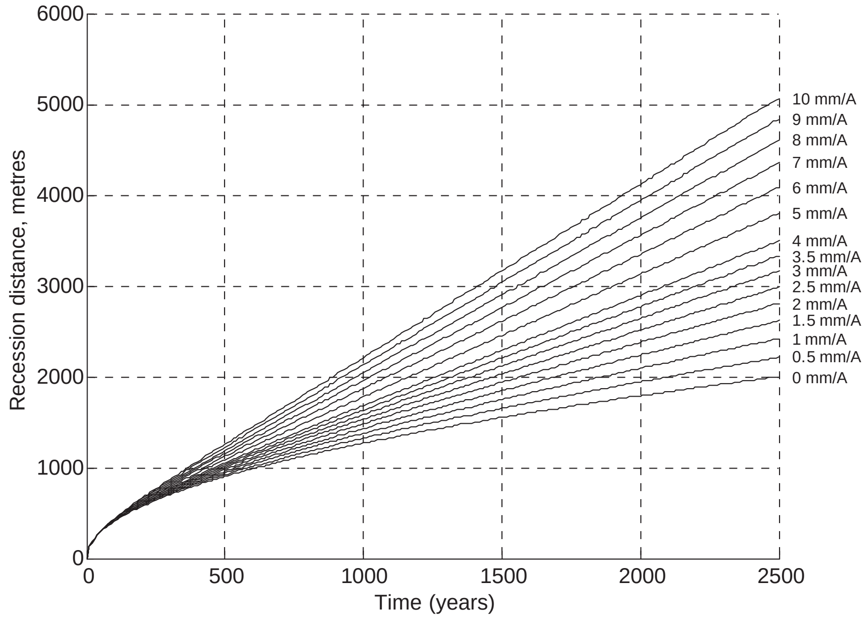

Fig. 12. Variation of profile retreat with rate of sea-level rise.

sea-level rise, is initially curved but becomes straight. These represent stages of profile development before and after dynamic equilibrium is reached.

Fig. 13 illustrates the effect rising sea-levels have on profile development; the dots indicate the rising tidal levels. Whereas the static average sea-level

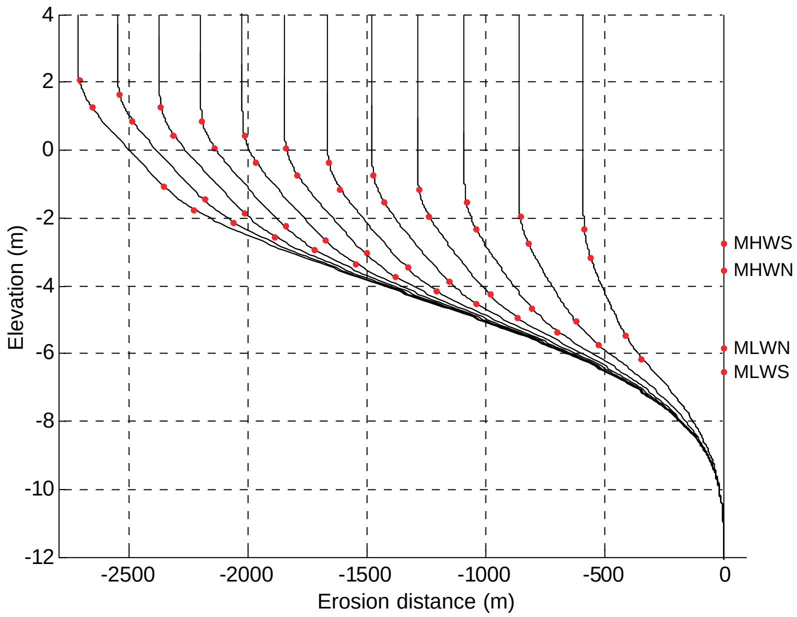

Fig. 13. Profile development with sea-levels rising at 2 mm/A, over 2400 years, in 200-year stages.

causes profiles to become increasingly gently sloping, rising sea-levels allow the retreat rate to equalise across all elevations so that, relative to the rising water levels, the profiles becomes self parallel. The average cliff toe level rises at the same rate as the sea. Over the last 200 years of the model represented in Fig. 13, it fluctuated around 0.69 m above the mean high water level of spring tides with a standard deviation of 0.11 m.

The actual retreat at any level within the limits of wave action is composed of both erosion and inundation (I) by the rising water, equal to:

$$I = \frac{S}{\tan\alpha}$$

where S is the rate of sea-level rise.

At depths below the limit of wave action, the recession is entirely due to inundation.

5.3. Strength representation

Model behaviour depends upon the representation of the strength of the insitu material (R). In the above examples, R was assumed to be 1.27×10^6, a value adopted from a study of a particular site, which is described below. A set of seven models were run to explore sensitivity to R, and the results are shown in Fig. 14. In each case the rate of sea-level rise was assumed to be 2 mm/A. As would be expected from Eq. (3), smaller values of R cause greater recession.

In addition to allowing greater recession, lower R values also cause more gently sloping platforms, as illustrated in Fig. 15, which shows the profiles at 1000 years from three different models.

All the models shown above were allowed to develop towards equilibrium forms. When such a shore is close to equilibrium its future behaviour is reasonable predictable, i.e. it will be similar to its average past behaviour. Interest in modelling such sites mainly arises when the coastal system has changed or is expected to. This may involve anthropogenic forcing of the profile. Fig. 16 shows the results of a model used to simulate the response of a shore to the installation and failure of a small temporary revetment at the cliff toe. The effect of the structure is represented by preventing the profile retreating beyond a specified position. This condition is held for 15 years, after which the structure is assumed to fail and the profile is freed.

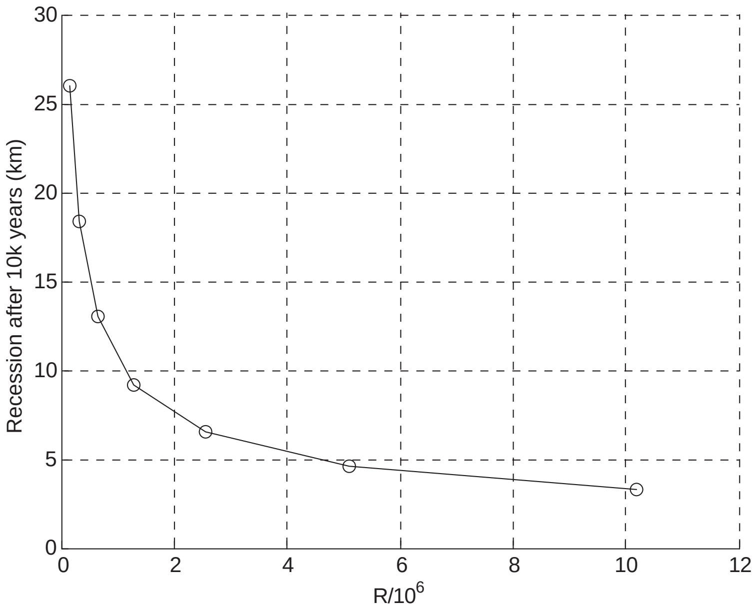

Fig. 14. Variation of recession distance with material strength parameter (R).

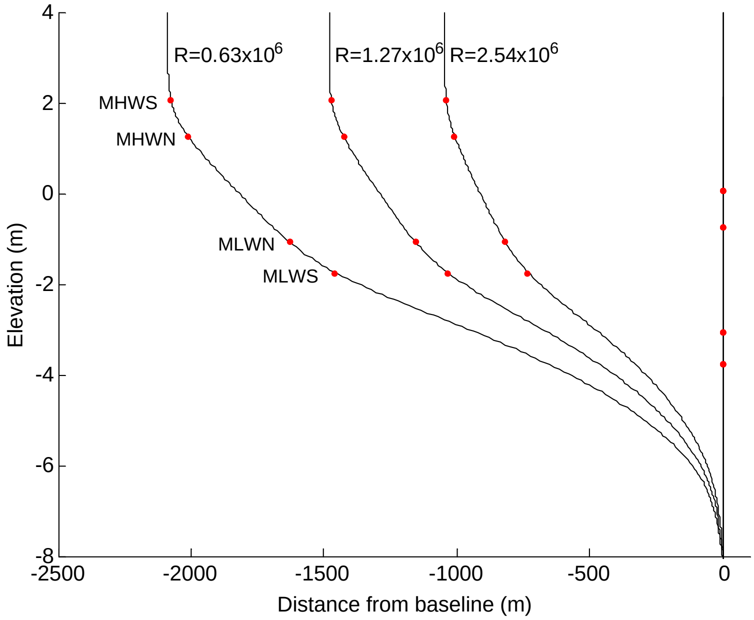

Fig. 15. Variation of profile shape with material strength parameter (R).

It can be seen that although the structure temporarily prevents cliff erosion, it provides no net benefit. After it fails, the cliff erodes rapidly as the profile moves towards its dynamic equilibrium form, which it achieves in approximately 5 years. The average retreat rate then returns to the historical level.

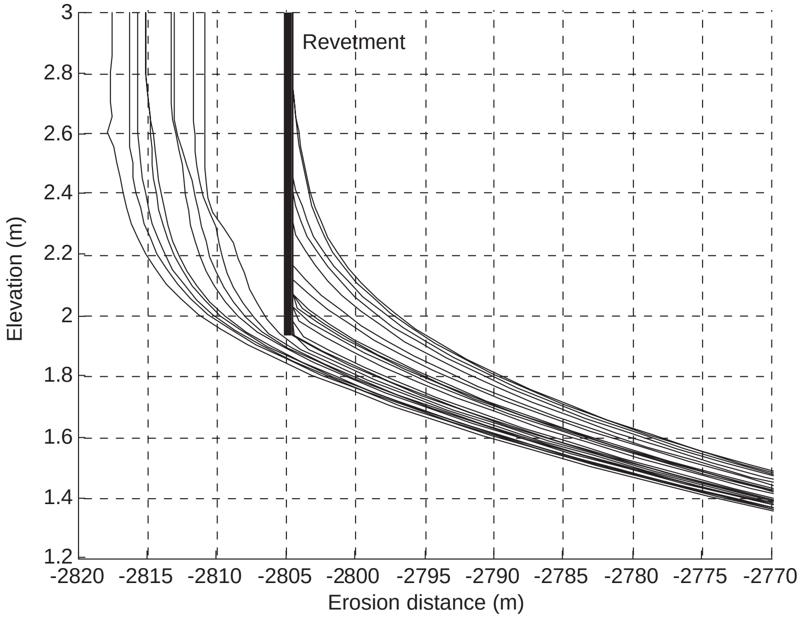

Fig. 16. Yearly model profiles showing response to the temporary presence of a seawall.

5.4. Profile development with a beach

As described above, Kamphuis (1990) observed that the presence of a beach has a strong effect on a shore platform by providing differential protection to the underlying material. This was simulated using SCAPE by introducing a beach to a shore profile. The beach volume was kept at a constant 5 m^3/m to clarify its effect on the shore profile and the Bruun constant of the beach profile was assumed to be 0.16. Fig. 17 shows the results.

Initially the beach is approximately 20 m wide, with a maximum depth of 0.3 m. After 100 years, the width has doubled and the depth reduced, to a maximum of 0.1 m. The upper platform profile has become similar to the beach surface. Approximately 60 m of recession has been prevented by the beach.

Fig. 18 illustrates how the profile adapts to the presence of the beach over the 100 years described in Fig. 17. For the first 30 years, erosion of the profile above approximately 1.7 m above datum is slowed dramatically, lower down the profile erosion rates are unaffected. This vertical gradient in erosion rate leads to a general steepening of the profile, and the downward migration of the seaward limit of the beach. As the beach spreads, it also becomes thinner, allowing more waves to erode the region of the platform upon which it rests. Ultimately the profile shape achieves a new equilibrium form as the retreat rates equalises at all levels. It should be noted that the retreat rate across the profile returns to its pre-beach values, i.e. the introduction of a beach only caused a temporary slowing of recession.

These results are simplistic, and are not intended to predict precise geometries. They are intended to accurately represent geomorphic behaviours and illustrate SCAPE's dynamics and the sorts of coastal issues it can be used to explore. The following section demonstrates application to a specific site.

6. Model application to the Naze

SCAPE was used to model the shore of the Naze peninsula (see Fig. 19), which is on the Essex coast of England and is composed of soft rock.

6.1. Location and history

The site is a roughly triangular peninsula. Its north shore faces across a large bay towards

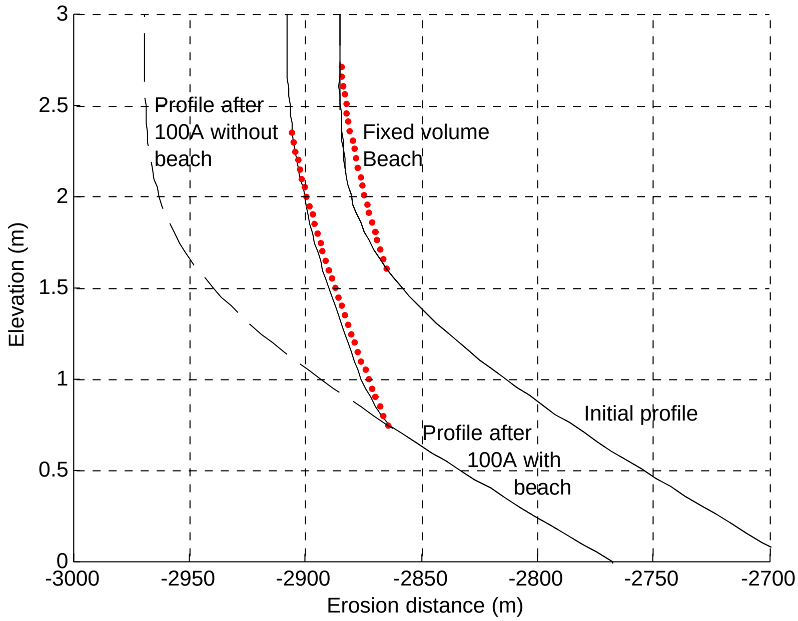

Fig. 17. Profile development over 100 years with, and without, the introduction of a fixed volume beach.

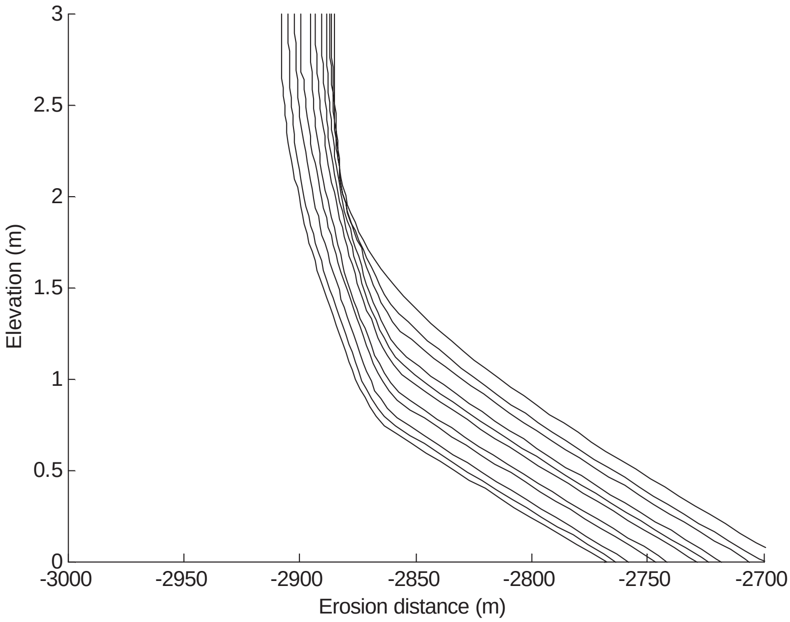

Fig. 18. Profile development, every 10 years, resulting from the introduction of the fixed volume beach.

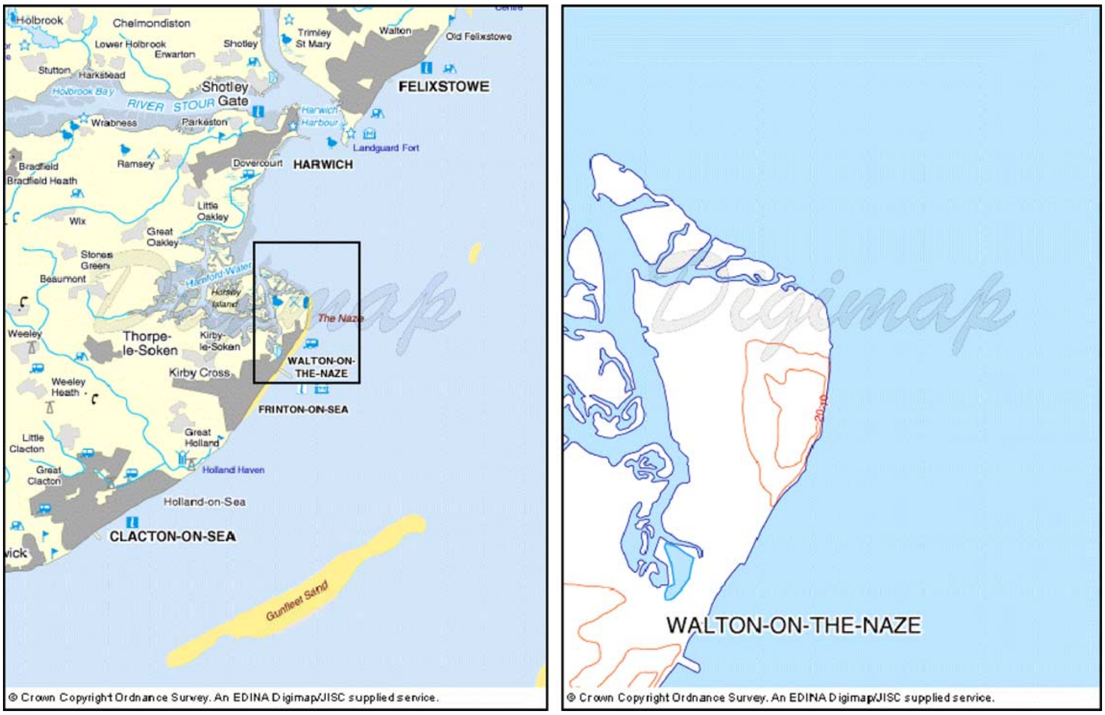

Fig. 19. The Naze peninsula, Essex.

Harwich and the west-facing shore forms the boundary of a small estuary called Hamford Water. The region of interest to this study, referred to below simply as 'the Naze', is the 1-km length of retreating eastern shore north of northing 223 400. The Naze cliffs vary in height, rising from beach level in the north to approximately 22 m at the south.

The shore is currently unprotected, but structures have been placed there in the past. In the late 19th century, a timber groyne field existed. This fell into disrepair and was replaced with two massive rock groynes. These were severely damaged during the extreme 1953 storm surge event and were subsequently left to disintegrate. It is believed that there is little or no residual effect of these structures and that the current shore can be regarded as being in a substantially natural state. The shore south of the Naze is protected by seawalls and groynes fields. A rock revetment has been placed at the junction between the static protected cliffs and the exposed eroding cliff to prevent outflanking of the seawall. The groyne nearest the Naze cliffs at the southern end is a substantial rock and timber construction. The beach on the southern side of this is fuller than the beaches in front of the Naze, and the platform there is normally hidden. The groyne acts as an effective, though not complete, barrier to longshore transport.

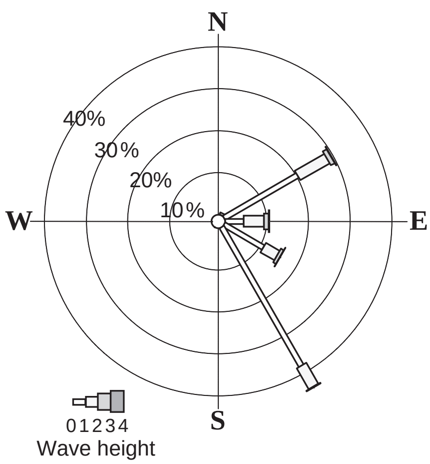

Fig. 20. Wave conditions at the Naze.

Table 1
Tide characteristics at the Naze

Tide characteristic	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

6.2. Hydrodynamic climate

Because the Naze foreshore is gently sloping, it is mainly subjected to gently spilling waves. The wave climate is not severe. Hindcast analysis over a 20-year period has shown only 0.2% of significant wave height conditions over 3 m, and none greater than 4 m. There are two dominant directions of wave approach, north-east and south-east, as illustrated in Fig. 20. The characteristics of the tide are shown in Table 1.

Sea-levels have been rising at the Naze at a rate of approximately 2 mm/A due to combined eustatic and isostatic effects. The rate of relative sea-level rise is projected to increase to 7 mm/A under some climate change scenarios (Hulme et al., 2002).

Although a beach can normally be found at the Naze, it is not always present. When present, it tends to be shallow and does not cover the whole of the platform. Though most of the beach is sand, it also contains diverse material released from the upper cliff. The beach is occasionally thick enough to protect areas of the underlying clay platform from erosion.

Net wave driven sediment motion in the area is towards the north, and most of the beach material at the Naze appears to arrive by longshore drift from the south. Once sediment reaches the northern point of the peninsula, it tends to continue west into Hamford water and cannot return. Cross-shore sediment motion affects the location of the beach but does not appear to remove significant volumes of material.

The potential sediment transport over an area of shore is dictated by the waves impinging on it. The low volumes and narrow width of the Naze beach mean that the actual transport is normally much less than this potential.

The platform and lower cliffs of the study shore are composed of Eocene London Clay, which is overlain with Pleistocene Waltonian Red Crag (see Daley and Balsan, 1999; Flory et al., 2002). The Crag has a ferruginous orange sandy matrix with varying amounts of shelly material. The Naze has been designated a Site of Special Scientific Interest because of geological interest in the Crag and fossils contained in the clay. This is one of the reasons why no shore protection work has been conducted for many years. The lower surface of the crag is at or above the cliff toe, so that the platform is composed entirely of clay.

The lower cliff contains fissures due to stress relief and desiccation cracking. These fissures are, in places, covered by debris left after the passage of mudflows. Piles of clay and crag talus cover other parts. Areas in which stress relief fractures have been enhanced by desiccation are extremely weak and collapse either under their own weight, or under minimal wave attack. Similarly talus piles are rapidly washed away when reached by waves.

The Naze has been retreating over the Holocene, presumably due to wave action and rising sea-levels, leaving behind a relatively shallow and uniform seabed.

Erosion of the foreshore occurs through a variety of processes. The presence of sand and a reasonably energetic wave climate implies abrasion due to corrosion by sand particles saltating or being carried within turbulent water. High wave impact pressures within irregularities or fissures in the platform material, or low pressures above induced within breaking wave turbulence can remove fragments of material from the platform, sometimes assisted by bio-erosive mechanisms.

Although the form of the Naze shore is quite uniform, some variation can be observed. The platform is generally slightly steeper and deeper in the south. Shore retreat rates are higher in the north than in the south. This relationship between retreat rate and cross-shore profile is a feature that our application of SCAPE has been able to demonstrate, as explained below.

6.3. Model application to the Naze

A model was constructed to represent the state of the Naze shore in 1970 and its development over 22 years. This period was chosen because the position of the coast was known in 1970 and 1992 and because wave data were available for most of this period.

Table 2
Input parameters for the Naze model

Purpose	Input	Value	Units
Inputs required for a generic one-line beach module	Run duration	Variable	A
	Step size	One tidal period or 1 h	
	Baseline angle	195	deg
	Offshore contour depth	5	m
	Angle of offshore contour	225	deg
	Wave heights	Variable with time	m
	Wave periods	Variable with time	s
	Wave directions	Variable with time	deg
	CERC coefficient	0.4	
	Runup limit	2.195	m
Defines the steepness of the (sloping) beach	Beach Bruun constant	0.22	
For the cross-shore distributions of longshore transport and erosion	Tidal amplitude	Variable with time	m
Rate of sea-level rise	2 (historic) or 6 (future)	mm/A	
For calculation of beach sediment volumes released from cliff	Cliff top elevation	Variable	m AOD
	Cliff sand contents	50	%
Calibration variable	Material resistance	1.272×10^6	$m^{9/4}\ s^{3/2}$

6.4. Model input

Table 2 summarises the parameters input to the Naze model. They have been grouped by those required for any one-line beach module, and those additional parameters required by SCAPE.

Hourly wave data including significant wave height, period and direction were hindcast from wind records made between May 1973 and December 1994. These waves represented conditions at UK grid reference 628287 mE, 217854 mN where the sea is approximately 10 m deep. Tide level data recorded every 15 min from December 89 to November 2000 were available at Holland-on-sea, approximately 9 km south of the Naze. These data were filtered to obtain the high tide values, which were then used as model input. The wave and tide records were shorter then the longest modelling period (50 years), so the files were recycled; no attempt was made to represent extremes not already in the records.

The slope and curve of the beach was defined by setting a, in Eq. (2) to 0.22. This value was chosen through examination of local beach profiles.

Cliff heights and shore positions were obtained from digital terrain models, which were constructed by the British Geological Survey from aerial photographs taken in 1970 and 1992. It was estimated that potential beach material comprised 50% of the volume of the crag upper cliff, and 0% of the volume of the clay lower cliff and platform.

A single profile was allowed to develop towards equilibrium without a beach, as described above in Section 5. Different values of R were tried to establish one that provided approximately correct average retreat rates.

Once the general two-dimensional form of the Naze shore had emerged, it was copied to produce a series of model sections that were arranged along a baseline to form a quasi-3D form. Eight model sections were used, which were spaced 50 m apart. As is normal when using a one-line approach, boundary regions were added. These were 650 m long and reduced the influence of the boundaries on the beach sediment behaviour in the model. The plan-shape of the cliff toe of the Naze in 1970 was observed from a digital terrain model and used to obtain appropriate offsets for each of the model sections.

The beach was then allowed to change; its volume was controlled by the release of beach material from the cliff and sediment transported in through the model boundaries. A range of boundary conditions were tested before settling on the rules described in Table 3.

The calibration process was then continued by making finer adjustments of the material strength parameter R until the recession rates averaged across all of the model sections matched observations over the chosen period.

6.5. Model validation

Confidence in the model cannot be based on its average recession rate since this is fixed by the calibration process; instead emergent model features are examined and compared to observations. The features used to validate this model were alongshore differences in recession rate and the shapes of the profiles.

It can be seen in Fig. 21 that the alongshore variation in recession rate is well represented. Since R is constant throughout the model, this variation must have other causes. It is explained by the relatively larger beach volumes that appear in the south of the model (represented by lower section numbers), which provide more protection against wave attack. This variation in beach volume affects the profile shapes. This can be seen in Fig. 22, which shows the final profiles of the eight model sections, which have been aligned by the cliff toe position. Lighter grey lines indicate higher (more northerly) profile numbers. The northern profiles tend to be higher than those in the south.

In Fig. 23, these model profiles are compared to observations. The observations dated from 2000, after the end of the validation period, so are not the ideal basis for comparison since it has had to be assumed that the platform shape has been relatively steady whilst retreating since 1992. This assumption

Table 3
Model sediment boundary conditions

Boundary	Feature	Northerly sediment transport	Southerly sediment transport
Northern	Headland	Sediment motion unaffected	No sediment movement
Southern	Substantial groyne, slight embayment on Northern side. Beaches fuller on southern side.	Up to 30% of potential sediment transport allowed	No sediment movement

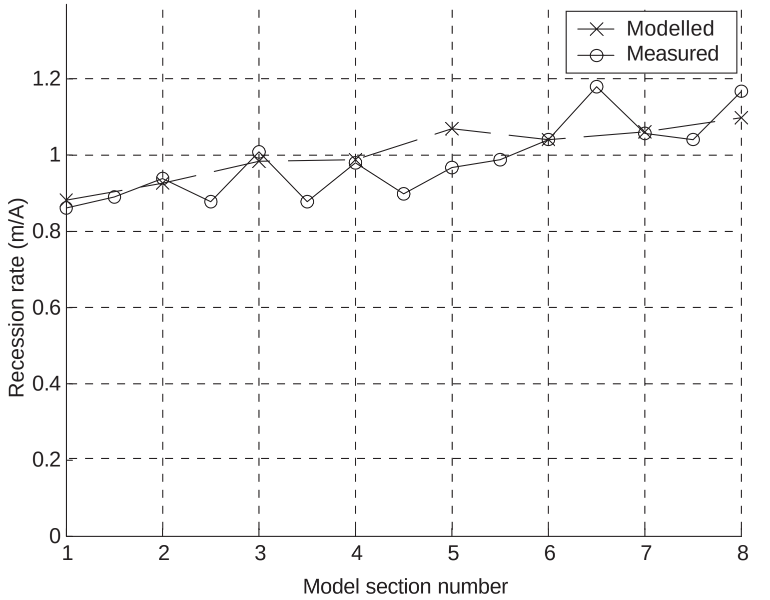

Fig. 21. Model validation, comparison of predicted and measured recession rates.

is not, however, unreasonable. The modelled profiles are slightly high compared to the observations and do not contain as much cross-shore detail, but are good enough to indicate that the principal shore erosion processes have been adequately represented.

Little bathymetric data was available to check the profile shapes further offshore. A single bathymetric

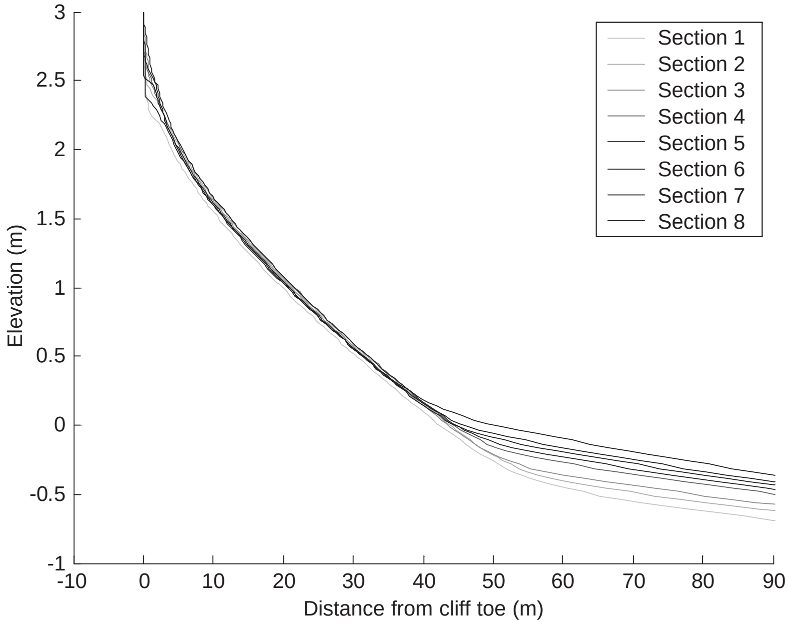

Fig. 22. Naze model shore profiles.

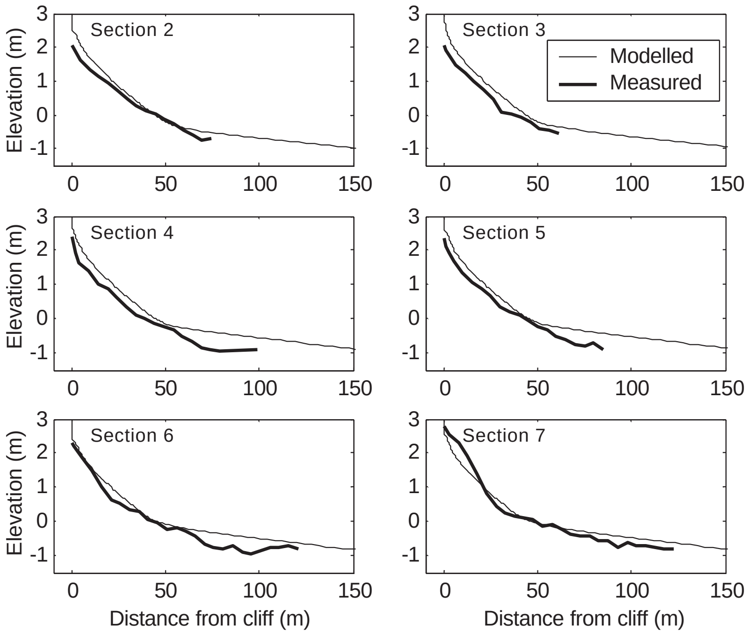

Fig. 23. Model validation, comparison of predicted and measured shore profiles.

point was read from a local chart, from which it was estimated that the predicted profile elevations were within 0.5 m of the measured platform levels up to 2.5 km offshore.

6.6. Potential Naze futures

Having calibrated the Naze model and established some confidence in its process representation, it was

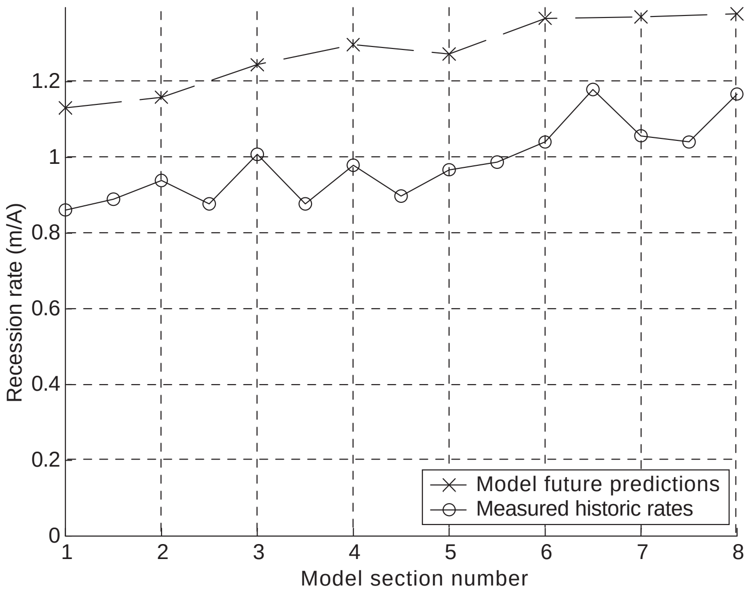

Fig. 24. Predicted average recession rates over 50 years resulting from a 6-mm/A rate of sea-level rise.

used to explore potential future erosion of the Naze under different conditions of climate change and anthropogenic forcing.

6.7. Sea-level rise

The Naze SCAPE model was used to explore the implications of acceleration in rate of sea-level rise at the site from 2 mm/A to 6 mm/A. The results are shown in Fig. 24.

It can be seen that the model recession rates have increased. On average the recession associated with the 6 mm/A rate is 15 % greater than those associated with the 2 mm/A rise. This is associated with a change in profile shape, as has already been explored in Section 5. There is considerable uncertainty surrounding future sea-levels. To explore this, the model was used in Monte-Carlo mode to map the relationship between the rates of sea-level rise and recession. Five hundred simulations were run, and each time the rate of sea-level rise was sampled from a normal probability distribution of mean 4 mm/A and standard deviation 0.5 mm/A, providing a reasonably broad range of values. The results from model section 4 are shown in Fig. 25. The relationship is relatively linear, with higher rates of sea-level rise leading to greater recession.

The Bruun rule was used to provide a prediction of future recession at the Naze for comparison with model output. Many shortcomings of this method have been identified (see, for example, Bray and Hooke, 1997; Kamphuis, 2000; Pilkey and Cooper, 1994), and it was not proposed for profiles that included rock exposures, however after studying various methods for predicting soft cliff retreat with accelerated sea-level rise Bray and Hooke found that, in the absence of process-based models, the following equation, a version of the Bruun rule proposed by Dean (1991), is most suitable for soft cliff shores:

$$R_2 = R_1 + (S_2 - S_1)\frac{L*}{P(B + h*)} \tag{6}$$

where the subscripts 1 and 2 denote historic and future conditions, respectively, R and S are rates of recession and sea-level rise, $L*$ is the length of active coast, $h*$ is the closure depth, B is the height of eroding beach berm, dune or cliff and P is the proportion of sediment eroded that is sufficiently coarse to remain within the equilibrium shore profile. This equation was used to provide predictions of

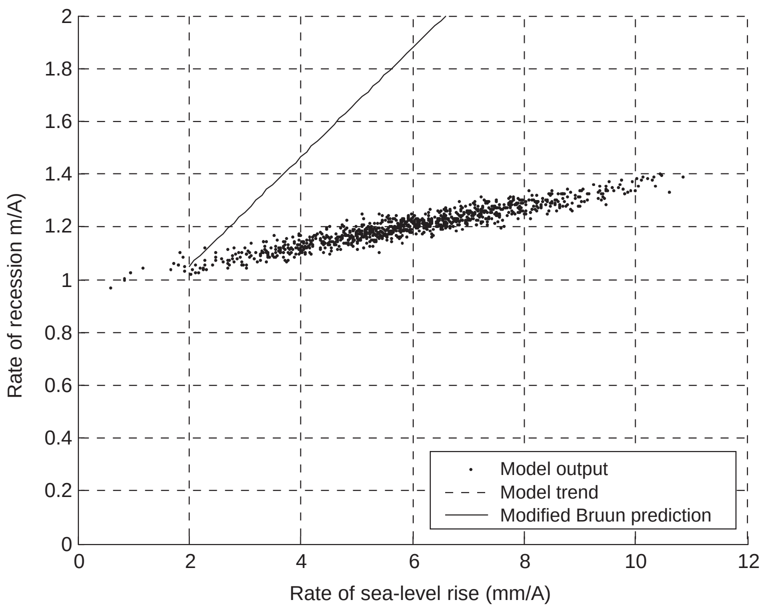

Fig. 25. Monte-Carlo simulation of the dependence of recession rate of model section 3 on rate of sea-level rise.

future recession at the Naze for comparison with model output. Section 3 was chosen as an example, where R_1 is approximately 1.05 m/A. P has been estimated as approximately 0.5. B varies significantly along the site, so an average of 10 m is assumed, S_1 is 2 mm/A and S_2 is assumed to be 6 mm/A. The closure depth and involved length have been estimated using the observation that a relatively flat seabed fronts the Naze. This is roughly 4.5 m below mean sea-level and begins around 1.5 km offshore. Taking these values for h_* and L_*, respectively, and inserting them in Eq. (6) provides:

$$R_2 = 1.9 \text{ m/A}$$

Modified Bruun predictions for a range of rates of accelerated sea-level rise are shown in Fig. 25. In fact there is uncertainty over the appropriate values for the terms in this equation and 1.9 m/A represents a low value in the possible range. It is nevertheless still significantly higher than the model prediction of 1.2 m/A. The differences are due, at least in part, to the fact that the model represents feedbacks through reduction in upper profile shape that mitigate shore response to accelerated sea-level rise.

The model was also used to explore the potential effects of engineering works at the Naze to install rubble mound hard-points at the ends of the shore with a third structure in the middle. In a first scenario, this central structure was assumed to be a groyne, in the second it was another hard-point. These coastal management options were chosen because they were being considered by the council with responsibility for the Naze shore. In the model both these structure types were represented as barriers that absorbed wave energy and around which waves diffracted. The hard-point was also assumed to protect the cliff toe from direct wave attack.

6.8. Construction of two hard-points with a central groyne

Fig. 26 shows the plan-shape development of the Naze cliff toe over 50 years following the construction of two end hard-points and a central groyne. Each line represents the cliff toe position at 5-year intervals. Changes increase with distance north, so that the point of the Naze peninsula would be to the right of the figure.

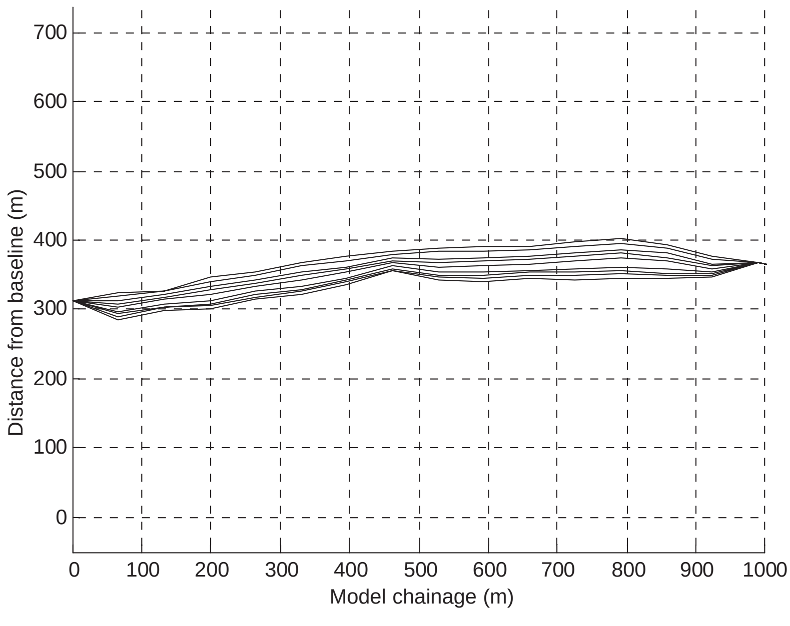

Fig. 26. Prediction of the development of the Naze cliff toe line in 5-year stages over 50 years following the introduction of two hard-points and a central groyne.

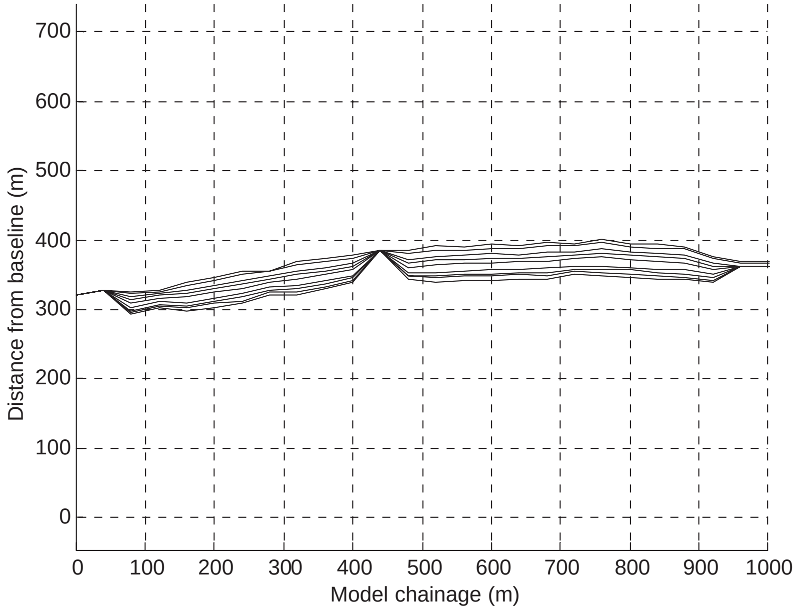

Fig. 27. Prediction of the development of the Naze cliff toe line in 5-year stages over 50 years following the introduction of three hard-points.

Except where the hard-points fix the shoreline, the structures do little to resist cliff recession. There is no significant impact on average recession rates at the site over 50 years.

6.9. Construction of three hard-points

In Fig. 27, the consequences of constructing three hard-points are illustrated. The additional hard-point

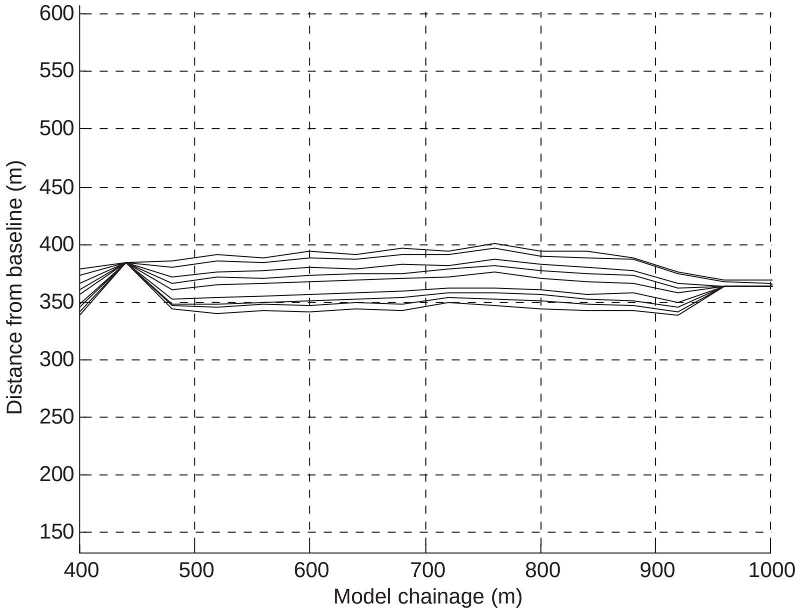

Fig. 28. Detail of the Southern embayment in Fig. 27.

fixes the cliff-toe in the centre of the model but, as before, there is no significant impact on the recession rate within the embayments.

This can be seen more clearly in Fig. 28, which shows an expanded view of the northern half of the model. If the bays were having any protective effect then the distance between the lines would decrease as time progressed. This is not the case.

The model indicates that both engineering solutions would be ineffective in reducing recession rates over a 50-year period. In addition, platform lowering in front of the hard-points, as illustrated by the behaviour in Fig. 16, would be likely to lead to undermining and structural disturbance.

The lack of influence of the scenarios of engineering intervention on the recession rate over 50 years can be attributed to the shortness of the structures and a lack of sediment in the bays. Because the structures are short they do not extend into deep water and diffraction effects are small. The scheme does not therefore benefit from beach-normal wave orthogonals that would minimise longshore sediment transport (see Silvester and Hsu, 1997). The low beach volumes mean that even if longshore sediment transport rates were reduced to zero, shoreline retreat would continue through erosion of the exposed platform.

7. Conclusions

The development and application of a model of 2D/Quasi 3D shore evolution modelling tool called Soft Cliff And Platform Erosion (SCAPE) has been described. The model is based on a study of the behaviour of eroding shore systems in general and platform evolution in particular. Insights into the relevant behaviours are drawn from the literature and site studies. The model structure includes both established techniques, e.g. a one-line beach module, and new methods. The most significant of these is a platform erosion module. SCAPE has been used to explore how shore evolution may depend on various parts of the system such as rate of sea-level rise and the presence of a beach. It has been used to model a specific soft shore site in Essex and to explore its possible futures.

This study shows that it is possible to represent and predict important cross-shore and alongshore behaviours with a set of fairly simple process-based relationships. It has been demonstrated how lower cliff/platform forms emerge through these relationships and are maintained by feedback despite perpetual small-scale disturbance.

The primary feedback path controlling the development of the shore shape is:

Aggressive breaker shape→high erosion→
gently sloping platform→
less aggressive breaker shape→less erosion.

This negative feedback occurs at all levels in the profile that are acted on by breaking waves. If sea-levels do not rise then the average slope always decreases and the retreat rate drops asymptotically to some positive value.

Under the condition that the sea-level is rising, some shore retreat (apparent erosion) will occur as a result of inundation. This couples with the erosion due to wave attack and results in a state of dynamic equilibrium in which average retreat rate equalises across the whole profile. The profile shape then reaches some stable form and the average retreat rate becomes constant. The model provides evidence (Fig. 25) that the modified Bruun rule overpredicts the acceleration in erosion resulting from an increase in the rate of sea-level rise. This seems to be because it does not account for adaptation in the profile form, which becomes more gently sloping as the sea level accelerates, and so dissipates a greater proportion of the wave energy.

The long-term retreat rate at any level tends to be determined by the retreat of the platform below it so long as this is still within the limit of wave action. Thus anthropogenic forcing of the upper platform, for example by the construction of a revetment, will only have a temporary effect on the cliff recession, which will, upon removal or collapse of the structure, accelerate to the position determined by the overall equilibrium form (e.g. Fig. 16).

Interaction between the beach and platform has a strong effect on the profile shape. Beach profiles tend to be steeper than the surface of bare rock platforms; consequently when a beach is introduced to such a shore it tends to rest close to the cliff toe. It is therefore able to protect only the highest parts of the platform. In front of it, the rock wears down normally.

As it does so, the beach spreads forward and begins to protect more of the rock. This behaviour continues until the beach is spread so wide that it has become thin enough for the waves to erode the rock on which it rests. When this state is reached, the original retreat rate (in the absence of the beach) is resumed. This may seem counterintuitive, since the presence of the beach must promote dissipation of wave energy and therefore provide some protection. However, this is exactly countered by the increase in steepness of the rock under the beach. The beach provides a layer of protection but it also makes the rock more vulnerable by increasing its slope.

SCAPE is intended for generic applicability for certain types of coast and lake shore. Its use should be limited to sites at which a one-line beach module can adequately represent sediment transport. In addition the eroding waves should not generate significant impulse loads. SCAPE uses a distribution of erosion under breaking waves provided by physical model tests on glacial till. Clearly this distribution will be less appropriate for other types of rock. However it seems reasonable to suppose that the distribution of wave scour, the principal driver of erosion, will be similar regardless of the content of the rock. Consequently is seems appropriate to attempt to apply SCAPE generically to soft rocks.

It has been shown that SCAPE is a useful tool to address some fundamental engineering and geomorphic questions concerning soft coast recession. It can be used to explore the mesoscale consequences of engineering interventions and climate change. It can also develop understanding of the long-term effectiveness of engineering options. Because it describes a broader system than, say a one-line model, it can map out more geomorphic implications of systemic changes. This results in longer-term model stability than smaller-scale sediment transport models, giving the capacity for predictions over timescales of decades. The value of this capability is enhanced by the expectation that the climate is changing and that shore systems will respond. SCAPE is capable of providing quantified predictions of the consequences for soft shore sites. An additional benefit of the approach used to develop SCAPE is that model run times are short, which enables multiple simulation and therefore eases analysis of the many uncertainties. For these reasons, SCAPE is a useful new geomorphic modelling tool for the management of soft eroding shorelines.

Acknowledgements

The authors would like to thank Tendring District Council for the financial and logistical support they gave to this research and also the Environment Agency for provision of aerial photographs and background data. Hindcast wave data were provided by HR Wallingford. Funding for the research was provided by the Engineering and Physical Science Research Council.

References

Bray, M.J., Hooke, J.M., 1997. Prediction of soft-cliff retreat with accelerating sea-level rise. Journal of Coastal Research 13 (2), 453–467.

Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D., Woodworth, P.L., 2001. Changes in sea level. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom (881 pp.).

Daley, B., Balsan, P., 1999. British tertiary stratigraphy. Part of the Joint Nature Conservation Committee Series (15). ISBN: 1 86107 469 7.

Dean, R.G., 1991. Equilibrium beach profiles: characteristics and applications. Journal of Coastal Research 7 (1), 53–84.

Dolan, R., Fenster, M., Holme, S., 1991. Temporal analysis of shoreline recession and accretion. Journal of Coastal Research 7 (3), 723–744.

Ferreira, O., Ciavola, P., Taborda, R., Bairros, M., Dias, J.A., 2000. Sediment mixing depth determination for steep and gentle foreshores. Journal of Coastal Research 16 (3), 830–839.

Flory, R., Nash, D., Lee, E.M., Hall, J., Walkden, M., Hrachowitz, M., 2002. The application of landslide modelling techniques for prediction of soft coastal cliff recession. Proc. Conf. Instability—Planning and Management, Ventnor, UK, pp. 249–256.

Hall, J.W., Meadowcroft, I.C., Lee, E.M., Van Gelder, P.H.A.J.M., 2002. Stochastic simulation of episodic soft coastal cliff recession. Coastal Engineering 46 (3), 159–174.

Hanson, H., 1989. GENESIS: Generalised Model for Simulating Shoreline Change: Report 1, Technical Reference. Technical Report, CERC-89-19.

Horikowa, K., Sunamura, T., 1968. An experimental study on erosion of coastal cliffs due to wave action. Coastal Engineering in Japan 11, 127–147.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate Change Scenarios of the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Research, University of East Anglia, Norwich, UK (120 pp.)

Jones, J.R., Cameron, B., Fisher, J.J., 1993. Analysis of Cliff Retreat and Shoreline Erosion: Thompson Island, Massachusetts, USA. Journal of Coastal Research 9 (1), 87–96.

Kamphuis, J., 1986. Erosion of cohesive bluffs, a model and a formula. Proceedings Symposium on Cohesive Shores. National Research Council, Canada, pp. 226–245.

Kamphuis, J., 1987. Recession rates of glacial till bluffs. Journal of Waterway, Port, Coastal, and Ocean Engineering 113 (1), 60–73.

Kamphuis, J.W., 1990. Influence of sand or gravel on the erosion of cohesive sediment. Journal of Hydraulic Research 28 (1), 43–53.

Kamphuis, J.W., 1992. Computation of coastal morphology. Proc. Short Course on Design and Reliability of Coastal Structures, Attached to the 23rd Int. Conf. on Coastal Engineering. Venice, Italy, pp. 211–257.

Kamphuis, J.W., 2000. Introduction to Coastal Engineering and Management. World Scientific Publishing Co., ISBN: 981 02 3830 4.

Kirk, R.M., Komar, P.D., Allan, J.C., Stephenson, W.J., 2000. Shoreline erosion on Lake Hawea, New-Zealand, caused by High Lake Levels and Storm-Wave Runup. Journal of Coastal Research 16 (2), 346–356.

Mano, A., Suzuki, S., 1999. Erosion characteristics of Sea Cliffs on the Fukushima Coast. Coastal Engineering Journal 41 (1), 43–63.

McDougal, W.G., Hudspeth, R.T., 1984. Longshore sediment transport on dean beach profiles. Proc. 19th Int. Conf on Coastal Engineering, pp. 1488–1506.

Meadowcroft, I.C., Hall, J.W., Lee, E.M., Milheiro-Oliveira, P., 1999. Coastal Cliff Recession: Development and Application of Prediction Methods. HR Wallingford Report SR549.

Nairn, R.B., Southgate, H.N., 1993. Deterministic profile modelling of nearshore processes: Part 2. Sediment transport and beach profile development. Coastal Engineering 19, 57–96.

Nairn, R.B., Pinchin, B.M., Philpott, K.L., 1986. A cohesive coastal development model. Proc. Symposium on Cohesive Shores. Burlington, Ontario, Canada, pp. 246–261.

Pilkey, O.H., Cooper, J.A., 1994. Society and sea level rise. Science 303, 1781–1782.

Shih, S.M., Komar, P.D., Tillotson, K.J., McDougal, W.G., Ruggiero, P., 1994. Wave run-up and sea-cliff erosion. Proc. 23rd Int. Conf. on Coastal Engineering, pp. 2170–2184.

Silvester, R., Hsu, J., 1997. Coastal stabilisation. Advanced Series on Ocean Engineering, (14). World Scientific Publishing, ISBN: 981 02 3154 7.

Skafel, M.G., 1995. Laboratory measurement of nearshore velocities and erosion of cohesive sediment (Till) shorelines. Technical note. Coastal Engineering 24, 343–349.

Skafel, M.G., Bishop, C.T., 1994. Flume experiments on the erosion of till shores by waves. Coastal Engineering 23, 329–348.

Stephenson, W.J., Kirk, R.M., 2000. Development of shore platforms on Kaikoura Peninsula, South Island, New Zealand: Part I. The role of waves. Geomorphology 32, 21–41.

Sunamura, T., 1992. The Geomorphology of Rocky Coasts. John Wiley and Sons, Chichester, UK, ISBN: 0 471 91775 3.

Trenhaile, A.S., 1983. The width of shore platforms; a theoretical approach. Geografiska Annaler 65 (A), 147–158.

Trenhaile, A.S., 2000. Modelling the development of wave-cut shore platforms. Marine Geology 166, 163–178.

Trenhaile, A.S., Byrne, M.L., 1986. A theoretical investigation of rock coasts, with particular reference to shore platforms. Geografiska Annaler 68 (A), 1–14.

Walkden, M.J.A., Crawford, A.R., Hewson, P.J., Bullock, G.N., Bird, P.A.D., 1995. Wave impact loading on vertical structures. Proc. Coastal Structures and Breakwaters, London, UK, pp. 273–286.

Wilcock, P.R., Miller, D.S., Shea, R.H., Kerkin, R.T., 1998. Frequency of effective wave activity and the recession of coastal bluffs: calvert cliffs, Maryland. Journal of Coastal Research 14 (1), 256–268.