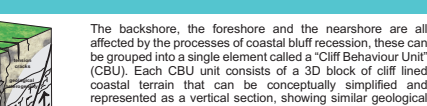
Process–Response Coastal Bluff Recession Model, Application to Holderness Coast (UK)

Ricardo Castedo [1], Carlos Paredes [1], William Murphy [2], James Lawrence [2]
(1) School of Mines and Energy, Universidad Politécnica de Madrid, Spain
(2) School of Earth and Environment, University of Leeds, UK

1 INTRODUCTION

Coastal erosion and coastal instability, threatens property, businesses and life. Because of the great concentration of natural resources in coastal zones, it is imperative that coastal change is well understood to allow for effective management and, where necessary, engineering intervention.
In this context, the development of tools to explore different scenarios under different conditions can be useful. To do this effectively, it is necessary to represent adequately the processes involved, especially where the shoreline responds in a non-linear fashion due to variations in geology, the environment, the hydrodynamic regime and changing climate. Process – Response Models or PRM (Trenhaile, 2009; Walkden, 2011) are therefore needed to address these issues and provide quantitative predictions of the effects of natural and human-induced changes, which cannot be predicted from statistical analysis of historic recession data. Usually, PRM have been based on functional relationships between the dominant physical processes covering the shoreface, beach and bluff, avoiding the geotechnical retreat mechanisms and behaviour within the bluff, a new characteristic of the present model. Under this procedure, the resulting simulations of bluff of differing behaviour can produce identical annual retreat characteristics despite the potential responses to a changing environment being unequal.



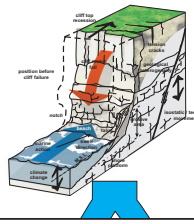
2 CONCEPTUAL MODEL

Bluffs are defined as a geographical feature in the form of denuded coastal escarpment and shaped by the simultaneous and successive action of two processes:

1) Marine, acting under the water depth at the base with the dual role of erosion and transport.

2) Subaerial, that act on the material that is above sea level producing gravitational movements i.e. landslides.

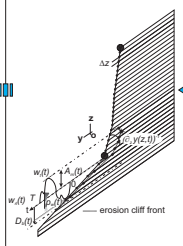
Changes on coastal bluffs are not easily predicted because recession is the cumulative result of numerous complex interacting phenomena, which are mostly non-linear, variably continuous and sporadic.



The backshore, the foreshore and the nearshore are all affected by the processes of coastal bluff recession, these can be grouped into a single element called a "Cliff Behaviour Unit" (CBU). Each CBU unit consists of a 3D block of cliff lined coastal terrain that can be conceptually simplified and represented as a vertical section, showing similar geological and oceanographic behaviours.

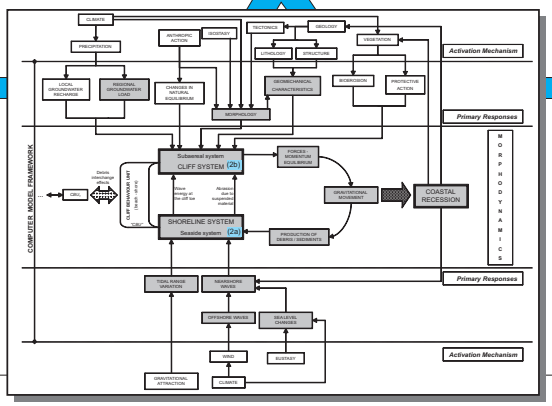
Each vertical section is a reflection of the interrelationships between the morphodynamic processes and resultant changes in form over time along the coastline.

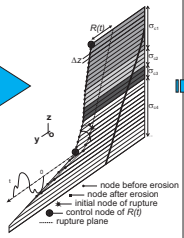
The process-response recession model (PRM) developed includes the shaded boxes in the flowchart presented.



This model is a geomorphic tool representing the main processes, in relatively simple terms, which cause and determine the topography of an eroding shore that emerge and develop for geometrically simple or idealized cliffs.

The in-situ cohesive material is represented as a column of horizontally aligned thin layers, of 5 mm tall. Erosion, bluff stability, and debris deposition are calculated one per tidal cycle *T* which is considered as one time step in the computational procedure of the global simulation time(12.46 h).





On the basis of field observations and the literature reviewed, this flowchart (left) is proposed as a conceptual diagram of the activation mechanism and their primary responses that determine recession in a CBU.

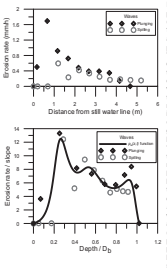
This illustrates the principal interactions within two main sub-systems:
1) the shoreline
2) the bluff
The nature of coastal change at any place or time results from combinations of these factors.

(2a) MECANICAL WAVE EROSION

The PRM considers a global constant *OZY* reference system. The origin is fixed on the point where the mean sea level contacts the bluff at the initial time. The profile motion is modelled as a function of displacement for each point of the profile in the bluff with height *z* at each instant of time *t*: $y(z,t+T)=y(z,t) + \delta y(z,T)$. In the description of erosion rate $\delta y(z,T)$, a modified relationship of Kamphuis (1987) and Walkden (2011) formula was used:

$$y(z,t+T)=y(z,t)\pm\frac{H_b^{15/4}(t)T_b^{3/2}(t)}{K\sigma_s(z)}\left(\frac{\partial y(z,T)}{\partial z}\right)^{1.7}\int_0^T p_{y_i}(w_i(t)-z)dt$$

A Simpson quadrature rule (to solve the integral) and backward-forward finite difference approximation (to solve the partial derivative) are the best solutions regarding the efficiency and accuracy of the numerical results (Paredes, 2012).

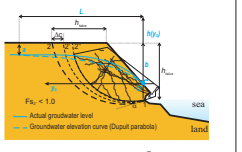


Following the model presented by Walkden (2011), the erosion shape function $p_y(z,t)$ was found by analysing laboratory results published by Skafel (1995). The latter work published the distributions of erosion rate that resulted from experiments in a wave tank with pseudo-random waves that shoal and broke over a model shore composed of intact glacial till from the Great Lakes. To obtain a generic expression of $p_y(z,t)$, both axis were transformed. The vertical axis was transformed form erosion rate to erosion rate divided by the slope, and the horizontal one, was transformed from horizontal distance to depth divided by D_b. The results of the two wave type are similar, and so an explicit expression (rational Chebyshev polynomial of order 5/6) was produced to represent them both and was adopted as the shape function $p_y(z,t)$.

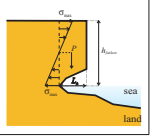
(2b) BLUFF SLOPE FAILURE

After each tidal cycle the geomechanical equilibrium conditions are evaluated to determine the slope stability of the exposed rock mass against slumps (*Fellenius Method of Slices*) and topples (*Cantilever beam model*). Both slope failure mechanisms introduced into the model are projected to characterize coastlines with relatively unjointed soils with an uniaxial compressive strength up to 2.5 - 5 Mpa.

Groundwater elevation curve	$h(y_w)=+\sqrt{(y_w/L)(b-a)}$
Factor of safety against slumps (*FS*)	$FS=\frac{\sum(c'\cdot\Delta L+(W\cdot\cos\theta_i-u_i\cdot\Delta L)\cdot\tan\phi')}{\sum W_i\cdot\sin\theta_i}$
Topple occurs when	$\sigma_{t\,max}>\sigma_t$
Maximum bending stress ($\sigma_{t\,max}$)	$\sigma_{t\,max}=\frac{3\gamma L^2}{h_{failure}}$



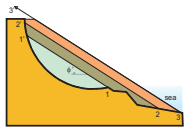
As the foot erosion progresses, the notch becomes deeper and increasing the volume of the overhanging material. When some of the forces exerted on the material cannot be balanced, the limits of rock mass strength are exceeded, resulting in the breaking and removal of material, causing the loss of some coastline and consequently the coast retreats.



3 DEBRIS MATERIAL

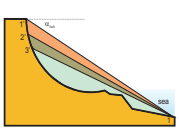
Following a failure event, colluvium is deposited at the foot of the bluff acting as a natural protection, reducing the sea wave impact at the bluff face. This talus material is highly disturbed and can be considered to be in a fully softened state and is less resistance to erosion. After a failure occurs, the model solves the colluvium wedge based on the material balance between the volumes of erosion and deposition. Three different solutions are implemented following 3a, 3b, 3c.

(3a) FRICTION ANGLE



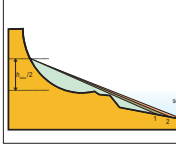
The debris shape is determined by the friction angle for weathered materials ϕ'_w (Wyllie, 2004). From point 1, talus is created. If the volume obtained is not the same as the volume of debris the point 1 is moved over the profile (2', 3' ...) to find the desired volume. If this solution does not find the required volume, the formation of talus piedmont is solved with the next alternative (3b).

(3b) ANGLE OF REACH FOR LANDSLIDES (α_{lnds})



Following Corominas (1996), the regression equation for landslides used in the model is: $log(\alpha_{lnd}) = -0.07log(vol) - 0.214$. Once the angle α_{lnd} is determined, the point 1 is calculated. From point 1, the model creates a first attempt to solve the talus piedmont with a small slope (3', 2', ..., 1'), until the desired talus is obtained. If not, the formation of talus piedmont is solved with the next alternative (3c).

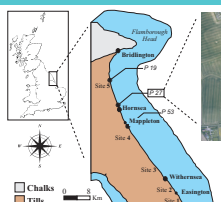
(3c) FIELD OBSERVATIONS



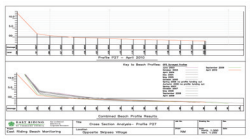
The debris talus is created starting from the half cliff height ($h_{cliff}/2$) with a small slope, increasing it, until the desired talus is obtained, achieving point 3 as the end / reaching point of the talus piedmont (Bird, 2008).

4 MODEL APPLICATION

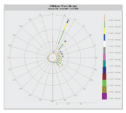
This model has been tested against the bluffs of the Holderness Coast, UK. This area is one of the youngest natural coastlines of England, a 61 km long stretch of low glacial drift bluffs ranging from 3 m to 35 m in height. This coastline is one of the fastest eroding coastlines in Europe with an average rate of 1.55 m/year along the entire coast, and it is estimated that more than 200 km² of land has been lost since Roman times. Oceanographic (4a) and geological (4b) conditions control the shape and dynamics of the receding coast.



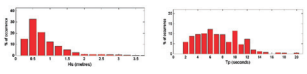
Monitoring of the East Riding coastline began in 1951 with the establishment of over 100 bluff erosion monitoring posts. Since 2001, the authority also uses a differential GPS surveing methodolology to record bluff profiles at 500m centres along the entire coastline.



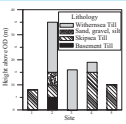
(4a) OCEANOGRAPHIC CONDITIONS



The environment is primarily one of fetch-limited wind wave development, the dominant wave direction is north-easterly, creating a north-south orientated net long shore current. Waves during normally occurring storm events can reach up to 4 m, and very high tidal range up to 7 m.



(4b) GEOTECHNICAL AND LITHOLOGICAL CONDITIONS



It was estimated for the Holderness Coast area (Bird, 2010) that potential talus material comprises 70% of the fallen volume after a circular failure event and 0% of the fallen volume after a toppling failure.

For modelling purposes the groundwater level used here is 2.5m under the surface at about 250m landward (Quinn, 2010).

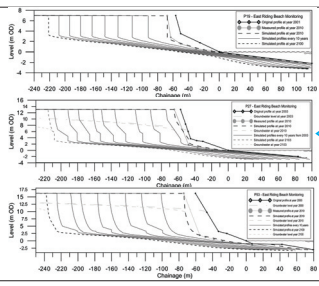
TILL UNIT	γ (kN/m³)	σ_c (kPa)	$\sigma_{c\,sat}$ (kPa)	σ_t (kPa)	c' (kPa)	ϕ' (kPa)	ϕ_w' (kPa)
Withernsea	23.1	160	136	2.3	23	25	16
Skipsea	23.4	182	164	2.6	26	23	21
Basement	23.9	186	156	3.4	34	29	23

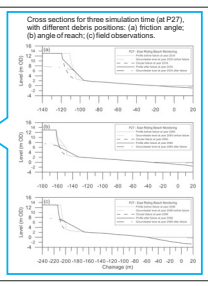
Data used in the model from Bell (2002)

5 RESULTS

The three real profiles (their first GPS surveyed profile) are introduced into the model. Then, the model runs for several years and the simulated profiles are compared with the real ones. The rate of relative sea level rise (Quinn, 2010) incorporated is 6 mm/year. In all cases the assessed hydrodynamic constant (*K*) has a value of 10^2. Once the model is calibrated with available real results, the simulation is extended to a century.

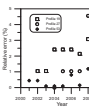
- **P19**: Presents a topple type failure. The simulated recession rate from the next century is 1.65 m/year, similar to the measured historical one 1.54 m/year.
- **P27**: Presents a topple and slump type failure. The simulated recession rate from the next century is 1.59 m/year, similar to the measured historical one 1.23 m/year.
- **P53**: Presents a topple and slump type failure. The simulated recession rate from the next century is 1.77 m/year, very close to the measured historical one 1.78 m/year.





Cross sections for three simulation time (at P27), with different debris positions: (a) friction angle; (b) angle of reach; (c) field observations.

MODEL VALIDATION



Confidence in the model calibration cannot be based on the position of the bluff edge between the first and last field profiles since this is fixed by the calibration process, instead the relative errors which occur in the profiles measured between these times is examined.

As can be seen, the relative errors between the first profile and last profile do not exceed 4.56%, and most of the values are below 3%.

6 CONCLUSIONS

The process-response model presented was developed to investigate the relationships between variables that affect the erosion, recession and development of cohesive clay coasts. The main relevant conclusions from the model application at Holderness, are:

1. slope oversteeping and groundwater content appears to be key factors of instability in coastal bluffs;
2. the model is geotechnically based avoiding the common assumptions in stochastically-based or process-response evolution;
3. the model can replicate the morphology of clay coast profiles, along with the erosional behaviour and groundwater changes at Holderness;
4. clay coasts maintain a state of quasi-equilibrium as they retreat landwards, with parallel slope retreat in the upper part of the profile, and slope decline in the lower part, producing concave submarine profiles that are similar to those in the field;
5. higher bluffs present less stability with respect to rotational failure, obtaining higher erosion rate, but, in some cases higher bluffs produce more debris material at each failure so the time between failures is higher obtaining lesser erosion rates;
6. to generalize the results, the model should be used under different conditions at other sites.

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NOTATION

A_i: tide amplitude (m)
c': effective cohesion (kPa)
D_b: depth at which the waves began to break (m)
H_b: mean breaker height (m)
K: hydrodynamic constants ($m^{15/4}s^{3/2}$/kg)
$p_y(z,t)$: erosion shape function (m / s)
T_b: mean breaker period (s)
u_i: pore water pressure of the i-slide (kPa)
W_i: weight of the i-slide (kg)
$w_i(t)$: tide function (s)
$w_s(t)$: sea level rise (mm / year)
ΔL_i: length of the bottom of the i-slide (m)
$(\partial y(z,t))'$: local slope
γ: material unit weight (kN/m3)
θ_i: inclination of the bottom of the i-slide
$\sigma_t(z)$: UCS (kPa)
$\sigma_{t\,sat}(z)$: UCS for fully softened remoulded material (kPa)
$\sigma_t(z)$: uniaxial tensile strength (kPa)
ϕ': effective friction angle
ϕ_w': effective friction angle for weathered materials

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