PREDICTING BREACHING OF SHINGLE BARRIER BEACHES - RECENT ADVANCES TO AID BEACH MANAGEMENT

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Abstract

Shingle barriers and ridges provide a natural line of coastal protection and flood defence for many sites around the coast of England. Examples include: Chesil Beach, Porlock, Hurst Spit, Medmery and Cley. Long term barrier evolution is linked with sea level rise, longshore transport rate and sediment supply, local geomorphology, incident hydraulic conditions, and the barrier geometry. Changes in any combination of these controlling variables may result in either building or degrading of the barrier; the latter may result in periodic overtopping, overwashing and landward migration.

The evolutionary process is a significant management issue, particularly when an increasing frequency of barrier overwashing results in migration towards coastal developments or important habitats. Intervention in the natural evolutionary process is commonplace, yet there is little practical management guidelines available. Management strategies vary considerably; some barriers are artificially managed by beach recharge, or reforming of the crest following storms, whilst others have been allowed to develop naturally. Regular breaching and extensive storm damage has occurred at many sites, but limited scientific guidance is currently available to provide beach managers with operational management tools, to predict the response of these beaches to storm conditions. Some sites are currently the subject of high profile strategic management reviews, or have already incurred high capital or maintenance expenditure costs; significant decisions must currently be made with a limited understanding of the way that these beaches perform under storm attack.

This paper examines the relationship between the geomorphological barrier response, hydraulic conditions, and the pre-storm barrier geometry at a temporal scale based on typical storm events. A wide range of geometric configuations have been examined. Key variables which affect the profile response of shingle barriers to storm activity are identified and their influence is quantified. An empirical framework, based upon an extensive series of physical model and field studies has been analysed to develop a dimensionless predictive threshold model. The empirical framework has been tested and partially validated within the development of coastal strategy plans and in operational beach management, at several sites.

1 Introduction

Varying definitions of breaching have been used in context with shingle barrier beaches, within geomorphological and engineering communities. The definition commonly used within an engineering context, and within the current investigation, describes breaching as the short term lowering of the barrier crest, resulting from wave induced overwashing.

Evolutionary processes associated with the mechanics of crest evolution of shingle barriers are well documented, although these have been confined to descriptive conceptual models (Orford et al 1991). Despite numerous field based studies, which have examined barrier evolution, none have quantified the effects of individual storm events, on the basis of measured wave and tidal variables, immediately adjacent to the sites (Horn et al 1996). The significance of storm activity and other allogenic controls is well recognized however (Carter et al 1989) and the limitations of earlier conceptual models are highlighted, in context with near shore spatial variability of wave conditions (Carter et al 1990). Although it has been suggested that the catastrophic transition between crestal build up and barrier break down domains may occur over a narrow range of conditions(Carter and Orford 1993; Carter et al 1993), the threshold conditions have never been quantified, by reference to local hydrodynamic and geometric controls.

The profile characteristics of shingle beaches alter at a near instantaneous temporal scale, in response to wave activity, acting on a passive water level datum (Powell, 1990). Crest and back barrier evolution of shingle barrier beaches, resulting from overtopping and overwashing, is usually confined to storm events or exceptional swell wave condtions, with durations of several hours. Such conditions occur when water levels and wave condtions are "extreme" relative to the particular site (Nicholls and Webber, 1989). The significance of these short term events is often masked within the mesoscale signatures of sub-decadel barrier migration rates, which are often linked with sea level rise (Orford et al 1995); both of these temporal scales of evolution are of significance to barrier stability in context with shoreline management.

The dynamic response of shingle beaches to wave attack has been described within a patametric model, which links profile response with a series of wave driven functional relationships (Powell, 1990). This model can be used to predict the short term profile response of shingle beaches, provided that overwashing of the beach does not occur. In theory, a dynamic equilibrium profile should form for any given combination of wave conditions, at a constant water level (assuming that sufficient sediment is available for the profile to form). This limitation means that the model cannot be valid for prediction of overwashing and breaching on shingle barriers of finite cross sectional area, although it may be used erroneously to provide a first estimate of profile performance in these cirumstances.

No predictive models are currently available to provide either prediction of breaching, or overwashing thresholds. No nationally funded research programmes have been conducted to provide a strategic systematic examination of shingle barriers to storm conditions. Given the high cost of reactive maintenance to these beaches, the need for a strategic approach to beach management, and the spectacular and damaging dynamic response of shingle barriers to storm conditions, this is somewhat surprising.

2 Factors affecting barrier evolution

Shingle barriers move hotizontally and vertically (Orford et al 1995) in response to overwashing or overtopping; a series of evolutionary domains have been identified. Vertical oversteepening of the profile, due to crestal build up by overtopping, may result in substantial failure of the barrier and dislocation landwards over time (Forbes et al 1991; Orford et al 1991). The lack of net input of sediment to barriers often results in a declining volume of barrier relative to mean sea level; this effect can be exaggerated in the presence of channels which lie to landwards of the barrier (Bradbury 1998). By contrast, a rising solid geology to landwards of the barrier can enable the effective barrier inertia to become greater, or to maintain pace with migration. The rate of overtopping experienced by a barrier, relative to the rate of overwashing, expressed as a function of wave climate and barrier geometry, is the key to understanding barrier retreat at scales less than a sub-decadel mesoscale (Orford et al 1995. Conceptual hypotheses (Carter and Orford 1993, Carter et al 1993) discuss the transitions between the evolutionary domains, emphasizing the importance of wave conditions in the change of the morphodynamical status of the barrier, between overtopping and overwashing; this suggests that changes occur at abrupt thresholds.

The primary forcing variables acting on a shingle barrier are the wave climate, superimposed on the tidal elevation; this can be affected by storm surges and local wave set up, as well as astronomical effects. Wave climate characteristics are described here, by reference to a series of standard variables, including: wave perios (Tm) significant wave height (Hs) wave approach angle and dimensionless wave steepness (s). Although the effects of standard spectral shapes ie JONSWAP have been shown to have a limited effect on shingle beach profile response (Powell 1990), more complex bi modal spectral shapes can have a more marked effect on profile response (Bradbury 1998; Nicholls and Webber 1989): the latter is difficult to analyse in a quantitative manner, but should be considered when examining barrier response, particularly with respect to long period components of the wave energy spectrum.

The impact of storm surges within the UK can be profound, particularly at mesotidal or mirotidal sites. Extreme tidal surges, with typical return periods of 50 years, may increase the tidal elevation by more than 50% of the astronomical tidal range (Nicholls and Webber 1989). The effects of such a surge advance the point of wave attack on the barrier to landwards, by the ration of the mean beach slope cotangent to the surge residual: a 1m surge on a beach with a mean slope of 1:7 will move the point of attack landwards by 7m; this is highly significant on a barrier which is only 30m wide at mean high water. Secondly, the increased water depth at the beach toe allows larger waves to attack the beach prior to breaking.

If the magnitude of local hydrodynamic conditions resulting in an overwashing event can be quantified (relative to a given barrier geometry), this can be expressed in probabilistic terms: regional wave climate statistics can be used to determine the statistical return period frequency of a defined storm event. A sufficiently large data set of conditions and responses will allow an empirical relationship to be derived, to enable threshold prediction for each of the evolutionary states. Joint probabilities of occurrence of combined wave climate conditions and water levels can be expressed in such statistical terms for any site, to determine a standard of defence.

Spatial variability of the barrier cross section is considered also, to be of significance. Low points on the barrier crest my provide preferential flow paths for the formation of washover throats (Orford et al 1991). Relict run up berms, which lie between the barrier crest and the lowest run up ridge, are ephemeral features; these represent the signatures of events which have occurred between overtopping events and the most recent wave activity. Other peripheral geometric and geological variables, such as the sub barrier platform, foreshore slope, and the shape and composition of the back barrier, also effect the rate of barrier migration. Controls on the surface emergent barrier cross sectional area include: the geotechnical properties of the barrier substrate (Nicholls 1985); relict recurve spits; and the geometry of back barrier channels (Bradbury 1998). Grain size distribution and permeability are issues which are of considerable importance

(Carter and Orford 1993), but which have not been examined systematically within the current investigation.

Conceptual models of barrier evolution (Orford et al 1991) focus upon wave overtopping, resulting from wave run up which exceeds the elevation of the barrier crest. Instantaneous variations in foreshore profile response, which may arise from wave activity are also important. The effects of local wave period and dimensionless wave steepness have largely been ignored hitherto, in context with barrier evolution. The concept of barrier intertia (Orford et al 1995) has been presented previously, by reference to the base of the barrier and mean sea level. This framework can be modified to examine the short term profile response, by reference to the storm peak static water level datum and the barrier cross sectional area above this datum.

Undermining and cut back through the barrier can occur in response to waves of high amplitude and wave steepness; these result in short term widening of the profile to landwards of the water level datum (Bradbury 1998). Run up levels need not exceed the initial barrier crest elevation for the overwashing threshold to be exceeded under these cirumstances.

3 Methodology

Ideally, an investigation of barrier crest evolution should be based upon extensive field measurements which examine the response of a range of barriers to a large number of extreme events. In reality this is impractical. This investigation is based upon a combination of fieldwork and 3 dimensional mobile bed physical model studies, conducted under random wave conditions (Bradbury 1988). Initial design of the laboratory experiments was based upon the geometry of Hurst Spit, and the initial model tests calibrated using the results of field measurements undertaken during severe storm events (Bradbury and Powell 1990). Subsequently, a wide range of geometric and hydrodynamic conditions have been tested (Table 1). Aditionally, the effects of variable back barrier geometry and longshore spatial variability of the barrier geometry have also been investigated. Model test conditions were run over a standardized 3 hour storm period peak and profiles measured pre and post storm. Field data has been collected using pre and post storm beach profile data, together with wave and tidal conditions; these have been derived by both direct measurement, and by numerical modeling of synthetic wave data. Validation work has been conducted on range of shingle barriers, to a series of storms.

Variable	Abbreviation	Range Tested
Significant wave height	Hs	1.0 to 4.1m
Mean wave period	Tm	7.4 to 10.9 s
Incident wave angle (rel, to beach normal)	0	0 to 15 degrees
Freeboard	Rc	-0.4 to 7.8m
Beach width at static water level	SWLs	0 to 110m
Barrier cross section area (above still WL	Ba	0 to 400m2
Storm peak static water level	SWL	1.4m

Table 1 Summary of the ranges in variable used in the model tests and field studies

4 Numerical schematization of a barrier profile

A shingle barrier profile is punctuated by a series of clearly defined points, linked by curves; these can be described in numerical terms relative to a fixed datum, defined here as the intersection of the seaward static water level (SWL) with the beach profile. Part of the shingle barrier geometry can conveniently be described, using the profile descriptors defined within an earlier parametric framework (Powell 1990). Additional profile descriptors have been added, for this investigation, to describe the back barrier geometry (Figure 1): beach span at static water level (SWLs) surface emergent cross sectional area (Ba) back barrier toe (Pbb2 Hbb); and crest freeboard (Rc).

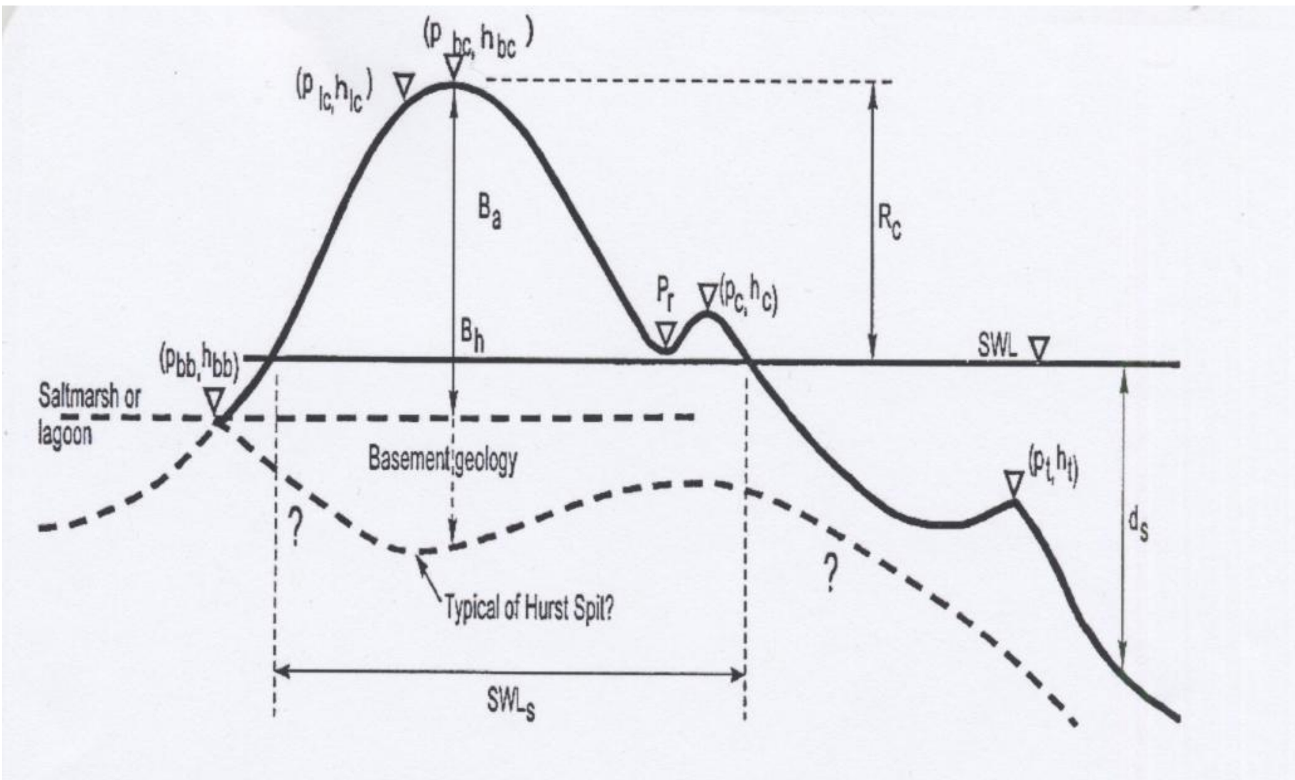

Figure 1. Schematic representation of a shingle barrier profile, annotated with numerical profile descriptors (Vertical exaggeration x 10)

Wave conditions must be measured or predicted at a consistent location relative to the beach, for analytical purposes. The most suitable position is at the toe of the active beach (closure point), where conditions are relatively unaffected by the dynamic response of the beach profile; this is in suitably deep water for the waves to be unbroken, yet not too far offshore for shallow water transformations to futher modify the waves on their approach to the beach. Ideally the measurement point (ds) can be located (Figure 1) on the basis of the analysis of a time series, comprising several years of monitoring data of bathymetric profiles.

5 Categorisation of barrier crest evolution response

A series of alternative types of barrier response have been identified previously, in context with barrier crest evolution (Carter and Orford 1993, Carter et al 1993).

Observations made during model testing have identified a series of beach crest responses, to hydrodynamic conditions (Figure 2); these are consistent with earlier conceptual models (Orford et al 1991), but also provide further detailed evidence for refinement of the response categories. Earlier conceptual models suggest that overwashing occurs only when the wave run up exceeds the pre storm crest elevation. Observations made within this investigation have suggested that a break through breach may also occur, when wave run up elevation is at a much lower level than the pre storm crest. An additional evolutionary category has also been identified; this results in an overwashed barrier crest reforming at a higher elevation than pre storm, although this combination is relatively rare. The evolutionary modes discussed above can be described in numerical terms by reference to profile descriptors (Figure 1).

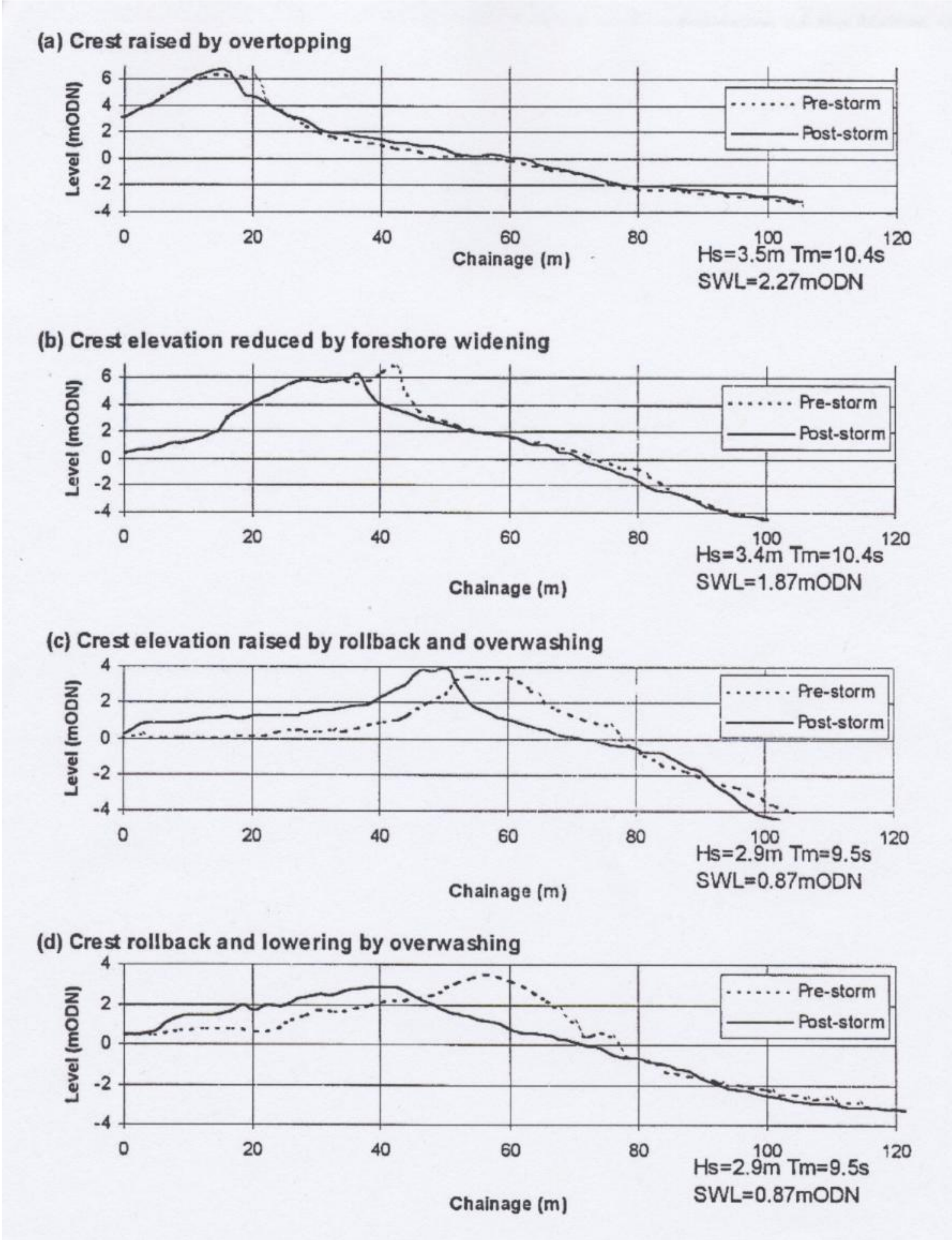

Figure 2 Categorisation of barrier crest evolution, based upon physical model results

The response categories identified are described below.

(a) The crest elevation is raised, in response to overtopping, when limited overtopping of the barrier occurs (Figure 2 (a)). Waves modify the crest, by depositing a run up berm comprising thin layers of shingle. Finally, the supratidal beach becomes higher and, usually, narrower. This response is often associated with long period swell waves.

(b) The crest elevation is reduced, due to cut back and undermining of the barrier crest , but with no overtopping (Figure 2 (b)) this profile response is similar to that observed in earlier investigations (Powell 1990). Waves do not exceed the barrier crest, but the active profile widens (between the run up crest and the breaking point). This response may evolve further to form a break through breach, at which point fan formation and roll back (Figure 2 (d)) occurs. Such a response is characteristic of a situation where differential longshore transport results in local beach starvation, or of high amplitude waves with a high wave steepness (>0.04).

(c) Roll back occurs and the crest is raised by overwashing. Wave run up exceeds the crest level, resulting in destructive modification of the crest profile. The crest is lowered initially, then migrates landwards; it subsequently rebuilds in a new position, at a higher elevation than the pre storm level (Figure 2 c). This condition is associated with low wide barriers.

(d) Roll back occurs and the crest elevation is reduced by overwashing. Waves exceed the crest line, resulting in destructive modification of the profile (Figure 2 (d)). The crest is lowered and migrates landwards, whilst deposition occurs on the back barrier and further to landwards.

(e) No change occurs to the crest elevation and the profile is contained to seawards of the barrier crest. The beach responds n a similar manner to that described by the functional relationships observed in earlier studies (Powell 1990) (not present on figure).

6 Barrier confined profile evolution

A comparison between measured field profile response data and an earlier predictive model (Powell 1990) demonstrates that, when overwashing occurs, the measured response function is quite different to that predicted for a beach of unrestricted cross section area. (Figure 3).

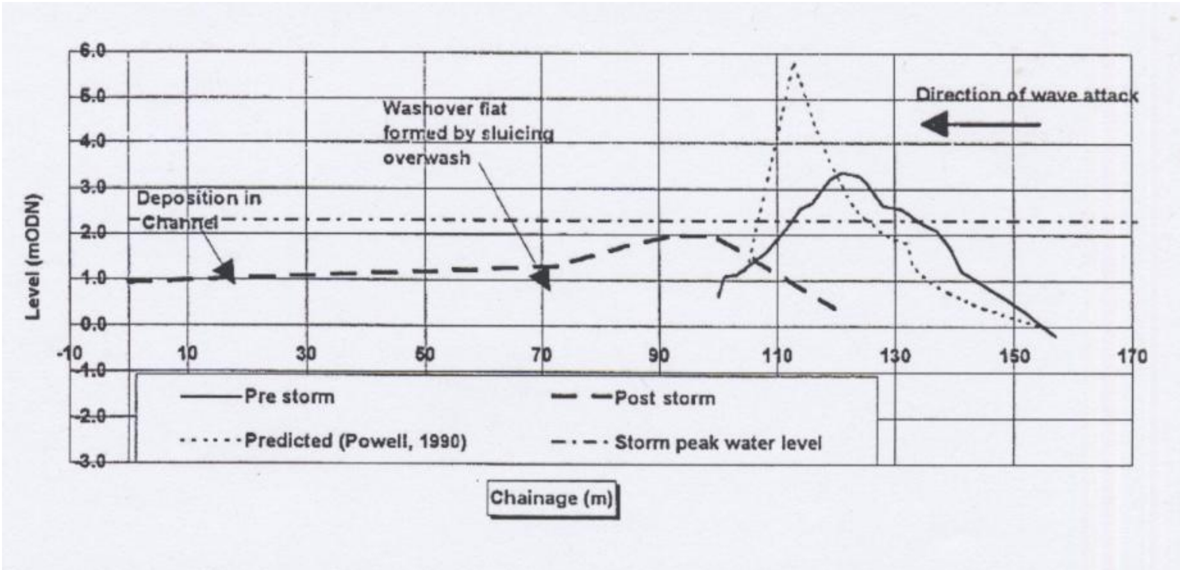

Figure 3. Application of Powell's (1990) parametric model to a shingle barrier profile; comparison between measured and pre and post storm profiles and the predicted response for: Hs = 2.58m; Tm = 7.7s; SWL = 2.27mODN

This response is not surprising since Powell (1990) works on the basis of an infinite availability of sediment and a requirement for a mass balance of pre and post storm profiles in order to locate the profile. It has been suggested that the pre storm beach geometry affects the length of time taken (but not the final shape) for the dynamic equilibrium profile to form (Powell 1990): this is clearly not the case for a barrier beach. Data derived for non – overtopping conditions provided a much better fit, although results were rarely within the tightly banded confidence limits of the predictive equations. Profile prediction equations may be valid therefore, within certain geometry controlled limits, on barrier beaches.

7 Variables controlling crest evolution

The primary controlling geometric and environmental variables, have been derived on the basis of a systematic assessment of each environmental and geometric variable, isolated over the full range of conditions measured. The key hydrodynamic variables are SWL, Hs and Tm. Wave conditions can be non dimensionalised using the wave steepness parameter (Hs/Lm).

The choice of dimensionless structure groupings is introduced here, by reference to the group of dimensioned structure variables (Figure 1). Dimensionless freeboard (Rc/Hs) is a commonly used parameter, in studies of wave overtopping: it has a significant effect on the final form of the post-storm barrier profile. The barrier crest is, typically, sufficiently low to permit wave overtopping to occur (approx) when Rc/Hs <1.1. Although it is insufficiently well refined to examine whether overwashing will result, in isolation, dimensionless freeboards is an important parameter; as such it must form part of a dimensionless structure grouping.

A barrier with a small cross section area is found to be more likely to be subject to crest lowering by overwashing, than one with a larger cross section area but with the same freeboard. The effects of a large cross section area, but low freeboard, can result in overwashing and an increase in crest elevation. However, for this to occur, the volume of the barrier must be sufficiently large to permit the dynamic equilibrium profile to form within the barrier. The influence of the barrier cross section has been considered only rarely in studies of barrier evolution, although it has been suggested that sub-decadel evolution may be a function of cross section area and barrier height (Orford et al 1995). This dimensioned relationship makes no reference to hydrodynamic variables; it refers to the use of mean sea level (as opposed to storm peak water level), and barrier height (as opposed to freeboard). Barrier freeboard (Rc) is often, although not necessarily, linked with barrier cross section (Ba); hence, these two variables must be considered separately. When combined, the two variables provide a barrier inertia grouping; this can be non-dimensionalised by wave height, to provide a proposed dimensionless barrier inertia parameter: Bi = RcBa/Hs3.

The combined influence of freeboard (Rc) and surface emergent cross section area (Ba) is examined, by comparison of data for the dimensionless barrier inertia parameter (Bi), with the wave steepness parameter (Hs/Lm) (Figure 4). Summary data sets are shown. Data points lying below the lower regression curve indicate conditions where overwashing is likely to occur. The higher curve represents the upper confidence limit threshold. Conditions resulting in points lying above this curve are unlikely to result in overwashing:

$$\frac{RcBa}{Hs3} = 0.0006 \left(\frac{Hs}{Lm}\right)^{-2.54}$$

The whole data set comprises a population of over 2200 data points, many of which represent profile containment (these are not shown on the graph). Non overwashing data generally lie on the correct side of the proposed dimensionless barrier inertia parameter threshold curve, although some scatter appears around the overwashing threshold; this is a function, largely, of spatial variation of the barrier geometry. Most data sets relate to a narrow range of geometric conditions, providing a high level of confidence in the results; others are more widespread, reflecting greater spatial variability. Error bands associated with each data set reflect this variability of individual profiles, and provide an indication of the spatial spread of results. Confidence limits for the regression curves take into account the effects of spatial variation, observed in the present investigation, but may not be representative of all shingle barriers. It is suggested that the upper bound confidence limit is used for prediction purposes; this will provide a margin of safety. The influence of spatial variation in barrier geometry cannot be ignored, although a clear relationship has not been determined between such variability and other controlling variables.

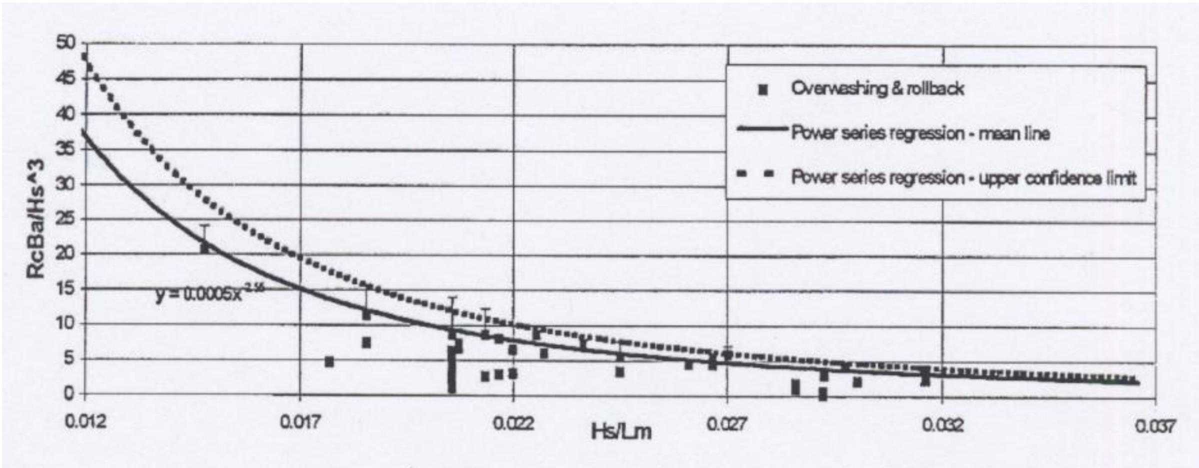

Figure 4 Determinatiion of functional relationships between the barrier inertia parameter and steepness parameter using averaged data sets.

The valid range of the relationship is controlled further, by the limitations of the test programme (Table 1); these limits should be observed strictly, for predictive purposes. Scatter is more evident over the lower range of the wave steepness parameter (>0.018). Further data collection is necessary within this range, to provide more confidence in the response of barrier beaches to swell conditions. Although a swathe of data describing overtopping conditions lies immediately above the overwashing threshold curve, the barrier inertia parameter cannot be used to predict overtopping and build up. This limitation is demonstrated by scattered data, well above the overwashing limits; these data represent a large, but low, barrier.

Barrier elevation responses indicate that hydrodynamic conditions become the more important governing variables (than barrier geometry) following the first overwashing event. However, initial changes to the crest elevation are likely to occur when the wave energy is at a maximum and the freeboard is at a minimum. Such a response suggests that a barrier with a large (overwashed) freeboard is likely to be lowered more than one with an initially low freeboard. Once the overwashing threshold has been exceeded, the crest may evolve rapidly.

Shingle barriers undergo two alternative responses, following overwashing: (a) the beach may roll back, lowering the crest; or (b) the crest may roll back, reforming at a higher elevation than the pre storm barrier. The response is strongly dependant upon the surface emergent cross section area and the back barrier geometry. A two stage conceptual model is proposed for overwashing. The beach will initially attempt to reach a dynamic equilibrium profile, as suggested by Powell (1990). If the critical barrier inertia is exceeded, then the beach crest will be lowered by overwashing and a second stage process begins. Provided that sufficient volume is available within the overwashed beach, the barrier crest will reform farther to landwards; this may be to a higher elevation than the pre-storm profile, to a similar dynamic equilibrium profile to that predicted by the earlier functional relationship (Powell op cit). Such conditions may occur under the following circumstances: (a) where additional sediment is made available, in terms of longshore transport; (b) where pre-storm conditions are marginal to the overwashing threshold; or (c) as a result of spatial variability, when the overwashed profile forms as a result of outflanking of a topographic low, in a zone which is close to the overwashing threshold.

8 Validation

The predictive framework has been tested by reference to field data gathered at Hurst Spit, both prior to and upon completion of a beach recharge scheme (Bradbury and Kidd, 1998). (Figure 5). The field data for the overwashing events are scattered, largely about the predicted overwashing threshold regression curve. Regrettably, the model data are limited to the range Hs/Lm<0.032; the regression curve has been extrapolated (to 0.057), to cover the full range of field data. Notwithstanding potential error over this range, the field data are largely consistent with the predicted response over the range of the extrapolated curve. Additional data are required to improve the validity of the framework; likewise, to define the overwashing threshold more precisely for Hs/Lm>0.032.

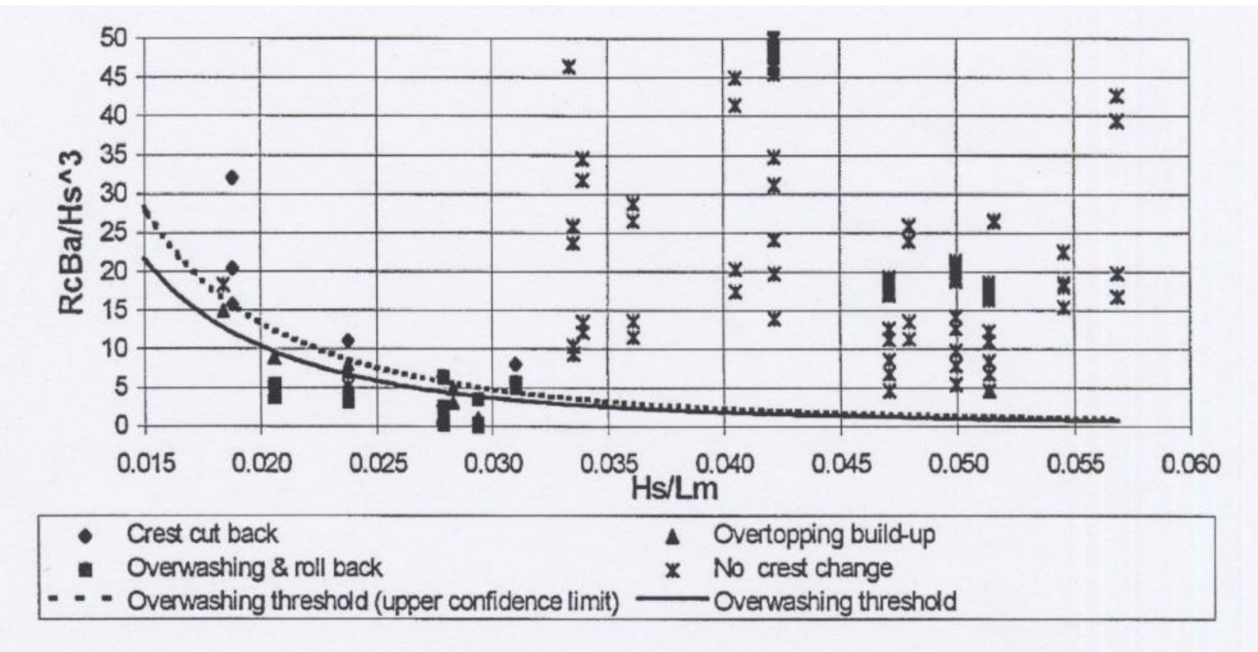

Figure 5 Validation of the barrier inertia threshold framework for Hurst Spit

Although the proposed parametric framework appears to be valid for a range of conditions at Hurst Spit, it should be applied and tested at other sites under carefully controlled measurement conditions. Tidal height measurements are required at, or very close to, the site: small errors in water level measurement can have significant effects on the outcome of the results. The hydrodynamic conditions used in the empirical framework (Tm, Hs) are based upon measured wave conditions, in a 6-8m water depth. Predictions for shingle ridge profiles at Reculver (Kent) and at Seasalter (Kent) are examined. (Figure 6). Both sites are shown to be vulnerable to overwashing, within the context of defined extreme conditions. Assessment of the predictions, based upon the analysis of beach profile records, suggest that the results are representative.

An application of the parametric framework, based upon data relating to Chesil Beach (Dorset) is shown also in Figure 6. Conditions for a wave steepness of 0.01 (Hs = 3.6m; Tm = 15.5s), resulted in occasional waves reaching the crest of the barrier (at a level of 14.7m ODN), but no overwashing; this suggests that conditions were close to the overwashing threshold. The data presented lie outside the range of conditions examined within the present investigation. However, extrapolation of the predictive curve to a steepness of 0.01 suggests that the proposed relationship is also reasonable. The curve becomes very steep over the lower range of wave steepness (<0.015); any inherent errors may be accentuated by this trend. No overwashing occurred for the other data set, shown for a wave steepness of 0.045 (Hs=7.0m; Tm=10.0s); this is consistent with the predicted response.

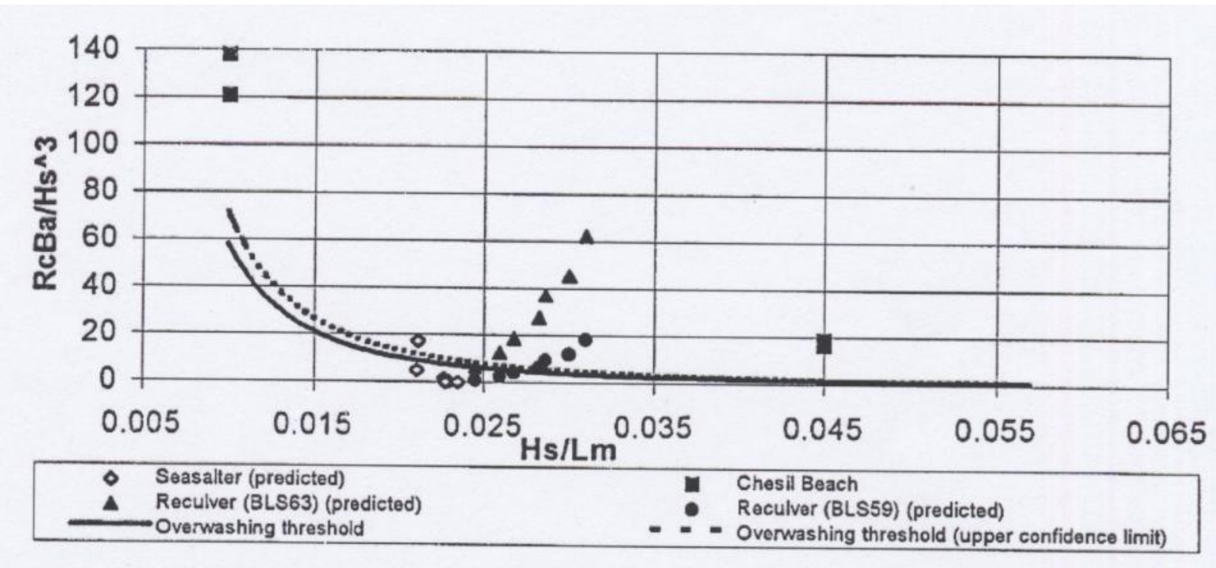

Figure 6 Application of overwashing threshold prediction, to Chesil Beach; Reculver (northern sea wall) shingle bank and Seasalter shingle bank

9 Limitations and further research

The effects of spatial variability in the crest geometry eg washover throats are highlighted. Crest responses are likely to reflect the geometry of topographic lows, which may be subject to outflanking when overwashing occurs. A spatially consistent barrier geometry, with longshore transport in equilibrium, is likely to be predicted more reliably.

Results are unable to differentiate between initial overwashing, resulting from profile widening, or from run-up exceeding the crest.

The pre storm foreshore geometry may affect the rate of profile evolution. If the initial beach profile is similar to the dynamic equilibrium profile, less profile evolution will be required to achieve the final profile. An artificially graded beach, with a plain slope may respond initially quite differently to a natural system. In such circumstances, the empirical framework proposed for the present investigation may not predict correctly the barrier crest evolution.

Physical model studies have been confined to the examination of a single spectral shape (JONSWAP), but the field data have demonstrated that local bi modal spectra may occur. Research is needed to extend and refine the validity of the framework to include examination of: spectral shape; grain size and grading; foreshore bathymetry; spatial variability; incident wave angle; and wave measurement point.

10 Conclusions

The overwashing threshold conditions for shingle barrier beaches can be predicted, using barrier profile descriptors and the dimensionless functional relationship derived for the barrier inertia and the wave steepness parameters, within the range of conditions tested. The limits of validity of an earlier predictive shingle profile model (Powell, 1990) have been identified.

Overwashing, resulting from foreshore widening, is an important process in crest development.

Field data provides limited confirmation of the validity of the relationship. The model can be applied to the management of many sites with local calibration.

11 Acknowlegements

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