Geomorphology 243 (2015) 1–13

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Observation and prediction of three-dimensional morphology at a high-energy macrotidal beach

Christopher Stokes *, Mark Davidson, Paul Russell

School of Marine Science and Engineering, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK

ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form 20 April 2015
Accepted 23 April 2015
Available online 1 May 2015

Keywords:
Three-dimensional
Sandbar
Morphology
Equilibrium
Behavioural
Macrotidal

ABSTRACT

Three-dimensional beach features such as crescentic sandbars and rip channels influence beach response to, and recovery from, storm waves, as well as significantly affecting the safety and amenity provided by the surf-zone for beach water-users. In this contribution temporal variations in subtidal and intertidal beach three-dimensionality are observed at a high-energy macrotidal beach, and a simple equilibrium model is developed to predict the changes over multi-year timescales. A dataset of 5.5 years of quasi-weekly bar measurements, and quasi-monthly intertidal surveys from Perranporth beach (Cornwall, UK) were used to quantify seasonal to inter-annual changes in three-dimensionality. The three-dimensionality of the outer bar displayed significant annual periodicity, with annual minima and maxima occurring in winter and spring, respectively. The lower intertidal beach displayed a similar periodicity, but developed three-dimensionality 1–4 months before the outer bar. The model predicts increases or decreases in the scale of three-dimensional features by examining the disparity between instantaneous wave conditions and a temporally varying equilibrium wave condition. A tidally-modulated wave power term determines the rate of morphological change. Negative feedback was found to be an important process governing the changes in three-dimensionality; while free morphological behaviour may drive three-dimensional growth, negative feedback exerts stability in the system, making it inherently predictable using a temporally varying equilibrium value. The model explained 42% and 61% of the overall variability in outer bar and lower beach three-dimensionality, respectively. It skilfully predicted changes outside the training data range, during the most energetic 8-week period of waves measured in the last 65 years off SW England, in winter 2013/14. The model outperformed a simple baseline model (a linear fit), as well as a comparable linearized feedback model from the literature, providing the first long-term (multi-year) predictions of seasonal to inter-annual beach three-dimensionality for a macrotidal beach.

1. Introduction

1.1. Background and rationale

Much of our conceptual understanding about the variability of beach morphology comes from sequential models developed for single-barred microtidal beaches in Australia (Short, 1979; Wright and Short, 1984; Wright et al., 1985). Through extensive field observations made over a number of years, Wright and Short (1984) reduced the natural continuum of beach forms into a sequence of 6 discrete states. The end-members of the model have a shallow gradient in the Dissipative (D) extreme, or a steep gradient in the Reflective (R) extreme, both of which consist of a planar beach face with little alongshore variability. The intermediate stages (Longshore Bar and Trough — LBT, Rhythmic Bar and Beach — RBB, Transverse Bar and Rip — TBR, Low Tide Terrace — LTT) are typified by greatly increased alongshore variability in the form of rip channels, and crescentic bar formations. The general applicability of this sequence has subsequently been verified at other sites and extended to include beaches with meso- and macro-tidal range (Short, 1991; Masselink and Short, 1993; Masselink and Hegge, 1995; Scott et al., 2011; Masselink et al., 2014), double or multi-bar systems (Short, 1992; Short and Aagaard, 1993; Castelle et al., 2007; Scott et al., 2011), and beaches with dominant headlands or geological features (Short, 1996; Castelle and Coco, 2012; Loureiro et al., 2012). Although the intermediate beach forms observed in the different studies vary slightly, they all feature alongshore non-uniformities such as rip channels and crescentic bars, collectively referred to as three-dimensional (3D) morphology (see Fig. 1 for example images).

Beach morphology often becomes 3D during the recovery period following energetic waves, when the straightened, offshore bar(s) migrates back towards shore unevenly under the action of accretive, low-steepness waves (Short, 1979; Wright and Short, 1984; Lippmann and Holman, 1990; Poate et al., 2014). The result is a sinuous, crescentic bar which can either be rhythmic in form, or a range of wavelengths (from 150 m to 2 km) and cross-shore amplitudes (from 5 to

---

* Corresponding author at: School of Marine Science and Engineering, University of Plymouth, Plymouth PL4 8AA, UK. Tel.: +44 1752 586102.
E-mail addresses: Christopher.Stokes@plymouth.ac.uk (C. Stokes), M.Davidson@plymouth.ac.uk (M. Davidson), P.Russell@plymouth.ac.uk (P. Russell).

http://dx.doi.org/10.1016/j.geomorph.2015.04.024

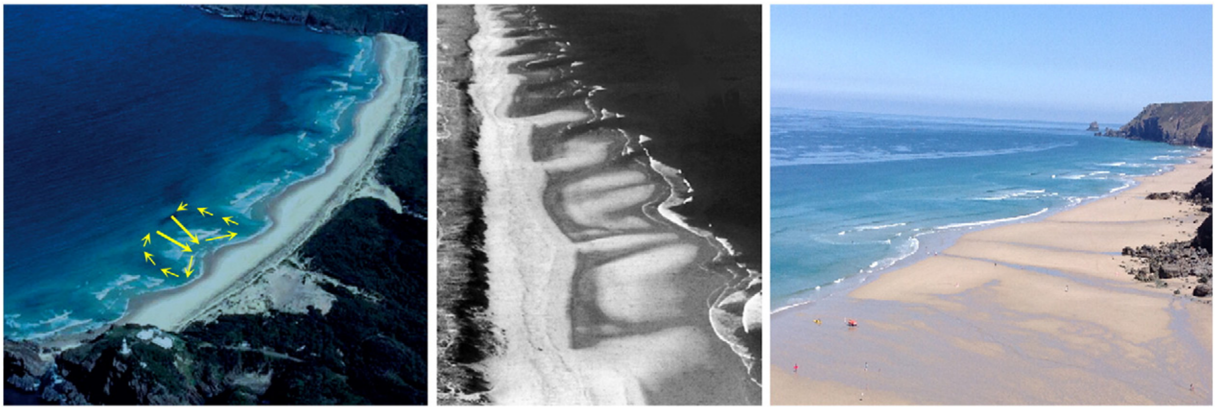

Fig. 1. Examples of three-dimensional beach morphology from the microtidal New South Wales coast, Australia (Price et al., 2014), meso-macrotidal Aquatanian coast, France (Castelle et al., 2007), and macrotidal North Cornwall coast, England (left to right panels respectively). Arrows demonstrate typical wave-driven horizontal cell circulation with seaward directed rip current component.

80 m) can occur (Van Enckevort et al., 2004). Under sustained accretive conditions the shoreward bar horns will eventually weld to the shore, resulting in the highly 3D TBR beach state. The final states in the 'downstate' sequence feature diminishing three-dimensionality, and a bar that is close to shore (LTT and R). The landward return of sediment during this downstate sequence forms an important mechanism for beach recovery following erosive, 'upstate' conditions. Conversely the presence of 3D features such as cusps and rip channels during a storm can potentially allow erosive swashes to reach further landward and undercut the dune foot (Thornton et al., 2007). 3D morphology therefore heavily influences a beach's response to, and recovery from, storm waves.

3D features also significantly affect the safety and amenity provided by the surf-zone for beach water-users. The alongshore varying morphology causes localised refraction and breaking; while these factors improve the amenity provided by waves for popular recreational activities such as surfing (Mead and Black, 2001a, 2001b; Scarfe et al., 2009), they also influence the type and strength of surf-zone currents (Bowen, 1969; Ranasinghe et al., 2004). Rip channels allow water set-up by wave breaking to funnel back out to sea in concentrated offshore flows (Fig. 1) which can take water-users from the shallows out into deeper water (MacMahan et al., 2006; Austin et al., 2010). As a result rip currents are the largest cause of surf-zone rescues and fatalities globally (Scott et al., 2008; MacMahan et al., 2011; Scott et al., 2011; Brighton et al., 2013). In the UK 90% of rip incidents occur during the highly 3D intermediate Low Tide Bar-Rip (LTBR) and LTT with rip (LTT + R) beach states (Scott et al., 2008), which are analogous to the TBR and LTT states.

1.2. Approaches to modelling 3D morphology

Process-based models have shown that horizontal wave-driven circulation in the nearshore contributes to the growth of 3D morphology through positive feedback between the developing morphology and local hydrodynamics, termed bed-surf coupling (Falqués et al., 2000; Caballeria et al., 2002, 2003a, 2003b; Ranasinghe et al., 2004). In the case of subtidal bars, this process starts with waves breaking preferentially over the shallowest bar sections. The dispersion of energy and gradient of the beach decelerates the shoreward flowing water, promoting a decreasing sediment flux and sand deposition directly shoreward of the bar, further reducing the water depth and enhancing wave breaking in that region (Falqués et al., 2000, 2008). The water set-up by the breakers locally increases hydrostatic pressure and forces an alongshore flow away from the region of breaking. These flows converge at points between the shallow regions of wave breaking, and return seaward over the deeper portions of the sandbar crest, creating horizontal circulation (Fig. 1) (Falqués et al., 2000; Ranasinghe et al., 2004). The offshore-directed return flows are coupled with increasing sediment fluxes and sand erosion, enhancing the depth of the channels between the horns. Eventually the developing morphology begins to hinder the sediment transport and the initial positive feedback diminishes as equilibrium is approached (Smit et al., 2008). This 'negative feedback' has been shown to play an important role in controlling free morphological behaviour, making the system inherently predictable (Plant et al., 2006).

Behavioural models provide an alternative approach to process-based modelling of 3D morphology. Although sometimes criticized for consisting of incomplete physical representations (Splinter et al., 2011; Van de Lageweg et al., 2013) or being overly dependent on tuning parameters (Ruessink et al., 2013), behavioural models are often capable of explaining substantial amounts of data variance and accurately forecasting large-scale beach changes over multiyear timescales (e.g. Plant et al., 1999; Yates et al., 2009; Davidson et al., 2010; Splinter et al., 2011; Davidson et al., 2013a), which is presently unachievable using process-based models. Wright et al. (1985) proposed a behavioural beach state model based on the assumption that state changes occur when instantaneous wave conditions differ from the conditions associated with zero change for each state, termed the disequilibrium stress, $\Delta\Omega$:

$$\Delta\Omega = \Omega - \Omega_{eq} \quad (1)$$

where Ω and Ω_{eq} are the instantaneous and equilibrium dimensionless fall velocity respectively (Gourlay, 1968; Dean, 1973):

$$\Omega = H_b / \overline{W}_s T_p \quad (2)$$

H_b is the significant wave height (H_s) at breaking, $\overline{W}_s$ is the mean sediment fall velocity, and T_p is the peak wave period. Large departures from equilibrium (large $\Delta\Omega$) represent an increased potential for change, and upstate and downstate changes occur under positive and negative disequilibrium, respectively. As instantaneous conditions approach the equilibrium condition ($\Omega \rightarrow \Omega_{eq}$) the morphological change appropriately reduces to zero. Although successful predictions of beach state were not achieved by Wright et al. (1985), their approach recognises the importance of negative feedback in maintaining system stability, and the concept may therefore be suited to predicting beach three-dimensionality. Disequilibrium stress has since been used in adapted forms to predict cross-shore shoreline (Yates et al., 2009; Davidson et al., 2010; Yates et al., 2011; Davidson et al., 2013a; Castelle et al., 2014; Splinter et al., 2014) and barline (Plant et al., 1999; Masselink et al., 2014) migration under varying waves, but is yet to be applied to the prediction of alongshore non-uniform changes. Other attempts to behaviourally model three-dimensionality have either been restricted