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On the morphological development of embayed beaches

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ABSTRACT

The typically curved and stable planform shape of embayed beaches is often observed in the presence of rigid headlands. The long-term alongshore equilibrium shape is variable and is controlled by headland geometry, cellular circulation patterns and wave obliquity at the shoreline. We use a process-based morphological model to simulate the development of embayed beaches depending on different environmental conditions and geological settings (i.e., topography and geometry). The embayment is allowed to develop from an initially straight beach to one which is curved under idealized wave forcing conditions and without external sediment input. Bay development can be approximated with an exponential function with coefficients representing rate of growth and bay size. Long-term shoreline cutback is both uniform (shoreline translation) and non-uniform (shoreline rotation) and is parameterized. Alongshore gradients in flow and transport patterns are related to long-term non-uniform shoreline cutback. Rotation of the beach ceases as the bay matures, leading to a curved shoreline planform, which is a remnant of decaying erosion processes.

1. Introduction

A defining feature of embayed beaches is the typically spiral-shaped curvature of their shorelines. Embayed beach shorelines tend to be relatively stable over long timescales (Yasso, 1965; Silvester and Hsu, 1997), typically evolving toward an 'equilibrium' configuration. Periodic rotation occurs on shorter timescales, caused by event-driven or seasonal changes in wave direction that modify longshore currents (Short and Masselink, 1999; Klein et al., 2010) or create longshore gradients in cross-shore sediment transport (Harley et al., 2011). Wave climate characteristics, in particular wave directional variability, are among the main forcing mechanisms that control embayed beach development (Ranasinghe et al., 2004; Littlewood et al., 2007; Daly et al., 2014a, 2014b). In the face of climate change, changing wave climate and increased anthropogenic impact in coastal areas, it is vital that we increase our knowledge and predictive capacity of beach dynamics for informed coastal protection (de Vriend et al., 1993). As such, it is important to understand the trajectory embayed beaches take in reaching their equilibrium shape and the conditions that control this process.

We start by asking the question: how do embayed beaches develop a characteristically curved and stable shape? It is often mentioned in the literature that the geological setting (i.e., topography, geometry, headland position, orientation of the bay) plays a significant role in determining the bay shape (Hsu et al., 2010; Short, 2010) as it is strongly coupled with the steering of wave-driven currents, causing cellular circulation patterns to develop in the bay (Klein and Menezes, 2001; Silva et al., 2010). The development of cellular circulation is shown to be dependent on the length of the bay relative to width of the surf zone (Short and Masselink, 1999) – short, compact embayments generally feature single circulation cells while larger embayments allow room for more normal (open-coast) circulation – and, additionally, the degree of curvature, which affects the indentation of the bay (Silvester and Hsu, 1997).

In terms of long-term stability, equilibrium on embayed beaches occurs as the beach responds in order to achieve zero sediment transport or flux along the shoreline (LeBlond, 1979). This is, of course, dependent on sediment supply at locations within, up-coast and offshore of the bay (assuming the bay to be a closed system on its own). If there is no sediment supplied to the beach, the bay has the potential to reach its maximum size under 'static equilibrium' conditions, i.e. zero-gradient in sediment flux (Hsu et al., 2010). Otherwise, the bay will be in 'dynamic equilibrium' if the rate at which sediment entering the bay exceeds the rate at which it is bypassed, leading to infilling and a reduced equilibrium size. It is often assumed that as a bay develops over time obliquely incident waves will ultimately become shore-normal once an equilibrium state is achieved, producing simultaneous wave breaking around its periphery (Dean, 1978; Silvester and Hsu, 1997).

Circulation patterns vary depending on the spatial dimensions of the bay. In large embayments (~5–10 km), large-scale gyre structures have been observed and linked to surface winds and oceanic currents (Valle-Levinson and Moraga-Opazo, 2006). In small embayments (~100–500 m) cellular circulation patterns and mega-rips are observed

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around headland structures with counter-rotating eddies in the open-coast section of the bay and in the shadow zone (Pattiaratchi et al., 2009; Loureiro et al., 2012). More specifically, within the surf zone, circulation of wave-induced currents is easily affected by the geometry of bay as well as by transient bar-rip nearshore morphology (Short and Masselink, 1999; Gallop et al., 2011; Castelle and Coco, 2012). It can be expected that, as an embayment develops toward an equilibrium state, flow patterns in the bay may change not only due to the fixed bay geometry but also due to feedbacks as the underlying bathymetry changes over time (LeBlond, 1979).

Observations of natural embayed beach development are rare. Terpstra and Chrzatowski (1992) and Lavalle and Lakhan (1997) documented the development of two different embayments of approximately 150 m length over a period of 10 years and 9 months, respectively — the only published works to the knowledge of the authors. In an effort to garner more data, laboratory flume experiments have been conducted which account for circulation effects on embayed beach development. For example, Ho (1971) performed experiments in which an initially straight shoreline is allowed to erode in order to create a curved embayment. Weesakul and Tasaduak (2012) also used flume experiments to investigate several cases of dynamic equilibrium by varying the degree of riverine sediment input. Flume experiments have to contend with scale effects, especially with regard to sediment sizing and reproducing prototype Reynolds numbers (van Gent et al., 2008) and are generally limited to monochromatic, unidirectional wave forcing. However, the results of these experiments nicely show the equilibrium shoreline shape of the bay and also indicate that the rate of development is non-linear over time (Silvester, 1985).

Coastline evolution models have been used to simulate the equilibrium position of embayed beach shorelines using the 'zero longshore transport' and 'uniform wave breaking' assumptions for defining equilibrium conditions (LeBlond, 1972; Rea and Komar, 1977; Weesakul et al., 2010). Turki et al. (2013) present a model which aptly predicts shoreline response to time-varying wave forcing, compared to high-resolution measurements over several years. Still, these models focus on simulating a single contour line and simplify wave-induced sediment transport processes in the surf zone. Medium- to long-term coastal behavior can be investigated in greater detail using process-based morphodynamic models (de Vriend et al., 1993; Winter, 2006; Roelvink and Reniers, 2012). Such models account for the non-linear interaction between currents, sediment transport and bed level changes at real-world scales and may therefore overcome limitations of coastline models and flume experiments. Recent advances in numerical morphodynamic models allow simulations over very large spatial and temporal scales, ~10–100 km and ~100–1000 years, respectively (Roelvink, 2006; Dissanayake et al., 2009; van der Wegen et al., 2010). Therefore, in the absence of sufficient observational data, systematic and schematic numerical simulations are assumed to be able to provide insight into medium- to long-term coastal evolution. Despite this, 2D morphodynamic studies of embayed beaches are still scarce (Daly et al., 2011).

In this paper, a numerical modeling approach is used to examine the processes that cause an embayed beach to develop into a curved and stable bathymetry over small to medium spatial scales and medium to long temporal scales (~0.1–1 km and ~1–100 years, respectively; as defined in Stive et al., 2002). We use a similar model set-up as Daly et al. (2014b), who investigated the effect of various forms of wave forcing on the development of embayed beaches. The simulations start from an initially straight, in-filled bay that is expected to increase in area until static equilibrium conditions are met. In doing so, sediment is expelled from the bay, and there is no sediment supply to the beach during the course of its development. The effect of changes in environmental conditions (sediment size, mean wave energy and tidal range) and geological setting (inclination angle and bay width) is demonstrated by examining how the simulated circulation and transport patterns develop during the evolution of the bay.

2. Methods

2.1. Numerical model description

The open-source, process-based, morphological model, Delft3D (Version 5.00.11) (Lesser et al., 2004) was used in the present study to simulate the morphological development of embayed beaches. A similar model setup is used as described in Daly et al. (2014b). The most relevant aspects of the Delft3D model as it relates to the current work are briefly described below; however, the Delft3D manuals (http://oss.deltares.nl/web/delft3d/manuals) offer a more detailed description of the numerical structure and formulations of the model.

The spectral, phase-averaged, third generation wave model, SWAN, (Booij et al., 1999) is used within the Delft3D wave module to solve the wave action balance equation, which accounts for refraction, dissipation (due to bottom friction, breaking and whitecapping) and non-linear interactions (triads and quadruplets) while transforming input boundary wave conditions across the model domain. SWAN uses an approximation for phase-decoupled wave diffraction (Holthuijsen et al., 2003). The Delft3D flow module solves the Navier–Stokes (non-linear, depth-averaged, shallow water) equations using finite difference methods. The depth-averaged (2DH) equations ignore vertical momentum and accelerations. Hydrodynamics are driven by lateral and surficial boundary conditions; here predominantly by radiation stress gradients calculated in the wave module. Wave-induced mass flux, including the Stokes drift contribution from the waves, is accounted for using a Generalized Lagrangian Mean (GLM) method (Groeneweg and Klopman, 1998; Walstra et al., 2000). The flow and wave modules are coupled at regular intervals to update the wave field. The effect of wave–current interaction is accounted for as, during coupling, SWAN includes the effect of ambient currents (computed in the flow module) on wave propagation.

Non-cohesive suspended transport (a function of inter alia the depth-averaged sediment concentration, GLM velocity and horizontal eddy diffusivity) and bed-load transport (a function of inter alia the bed shear stress, median grain diameter, and bed slope) are computed according to van Rijn (1993). After each time step, bed level changes are determined based on the net suspended and bed-load transport by using a sediment conservation scheme together with a bed level continuity equation. Bed-load transport is enhanced by wave-induced currents, according to van Rijn (1993), and also by avalanching, whereby sediment volumes above a defined critical wet slope is added to the downslope bed-load transport rate. Bed level changes can be up-scaled using the 'morfac' approach (Roelvink, 2006; Ranasinghe et al., 2011) in order to speed up computations. The modeling system includes a dredging and dumping function which can be used to maintain a fixed bed level. The erosion of dry land is simulated by assigning a percentage of the erosion computed in wet grid cells to neighboring dry cells.

2.2. Simulation set-up

2.2.1. Initial bathymetry and simulation setup

The initial bathymetry features a straight plane sloped (1:2.5) beach between +2.2 and −12.8 m elevation created between two headland structures in a similar layout as the flume experiments of Ho (1971) (Fig. 1). One headland is positioned to the north-west and the other to the south-east. The morphodynamic simulations are structured around a base case (M01) in which the lateral bay width between the headlands (W_B) is 140 m and wave obliquity (the angle β at the tip of the south-east headland between the (modal) wave crest and a down-coast control point (DCP)) is 45° (Fig. 1). The significant wave height (H_s) and peak wave period (T_p) were kept constant at 1.25 m and 8 s, respectively, while the peak wave direction (θ) was varied between 0° and 90° 6% of the time. The median grain diameter (D_{50}) was 300 μm and the tidal range (ζ) was zero, hence no variation in water level. Additional simulations, summarized in Table 1, were performed to determine the response of the bay to changes in the value of a particular parameter