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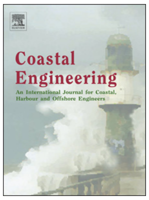

Wave energy distribution and morphological development in and around the shadow zone of an embayed beach

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ABSTRACT

Background: The curved shoreline shape of embayed beaches is one of its most notable characteristics and can be described using the parabolic bay shape equation (PBSE). Wave diffraction in and around the shadow zone is often regarded as the primary forcing mechanism leading to the prominent curvature of the shoreline. However, wave climate variables (wave direction, directional spreading and wave height) are shown to be influential in redistributing wave energy throughout the bay and in the shadow zone.
Methods: In this study, a process-based morphological model (Delft3D) is used for hydrodynamic and morphodynamic simulations of a schematic embayed beach. Wave forcing conditions are systematically varied between a mixture of time-invariant and time-varying cases.
Results: The role of diffraction is shown to be dominant only when the wave conditions are both narrow-banded ($<20°$) and when the PBSE angle β is high ($>30°$). Otherwise, as little as 6% variation in wave direction within a 90° range can account for the shoreline curvature in and around the shadow zone.
Conclusion: The degree to which wave direction and directional spreading vary through time therefore has a large effect on the equilibrium orientation and shoreline planform of the bay.

1. Introduction

Wave-induced flows largely control the morphological development and stability of coastal systems in wave-dominated environments (Wright and Short, 1984). Such environments include embayed beaches, which tend to be stable coastal landscapes over the long term (Silvester and Hsu, 1997), although they may be prone to seasonal or short-term beach rotation events (Harley et al., 2011; Klein et al., 2010; Short and Masselink, 1999). The uniquely curved shoreline planform of embayed beaches is often regarded as being in an equilibrium state and has been characterized empirically (Hsu and Evans, 1989; Moreno and Kraus, 1999; Silvester, 1960; Yasso, 1965). Among these studies, the parabolic bay shape equation (PBSE) of Hsu and Evans (1989) is currently the most widely accepted and is commonly used in coastal engineering practice (Gonzalez and Medina, 2001; Silvester and Hsu, 1997). Empirical formulae, such as the PBSE, generally define the curved planform of embayments using a single representative wave direction, a down-coast control point (DCP, where the curved embayed shoreline is assumed to be tangential to the straight down-coast shoreline) and a focal point (commonly referred to as a diffraction point), as shown in Fig. 1. The use of the term “diffraction point” has resulted in an emphasis on the role of diffraction in shaping embayed beaches in recent research (e.g. Iglesias et al., 2009; Schiaffino et al., 2011; Silva et al., 2010).

Diffraction is regarded as a key process capable of modifying the wave direction around headland structures, which ultimately redistributes wave energy in the shadow zone of embayed beaches thereby causing the curvature of the shoreline (LeBlond, 1979; Silvester and Ho, 1972; Yasso, 1965). Laboratory experiments have been carried out to investigate this hypothesis (e.g. Ho, 1971); however, these experiments are prone to scale effects as the bed slope in the shadow zone is often not reduced below the critical angle of repose of the sediment, indicating that hydrodynamic effects are weak in comparison to bed slope stability effects. Analytical models have also been used to determine the shoreline of embayments, assuming that waves break uniformly around the periphery of the bay (e.g. Dean, 1978; Rea and Komar, 1977; Weesakul et al., 2010). Despite this reasoning, periodic changes in wave climate (wave direction, directional spreading and wave height) can also alter the energy distribution in and around the shadow zone. Therefore, the variability of the wave climate can, hypothetically, have an equally large influence on the equilibrium morphology of embayed beach environments. Many studies have found that the variability as well as the sequencing of wave events can lead to different types of beach response, which can affect the (large-scale) morphodynamic equilibrium of shoreline position (Turki et al., 2013; Yates et al., 2009) and even the (small-scale) development of rip channel patterns (Castelle and Ruessink, 2011; Gallop et al., 2011).

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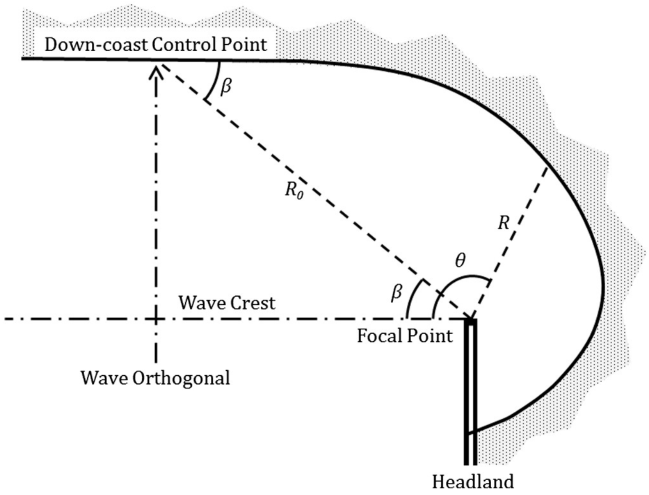

Fig. 1. Definition sketch of PBSE (modified from Hsu et al., 1989).

As the distribution of embayed beaches covers a wide range of geological settings and wave climates, it is difficult to separate the influence of the many interacting processes that affect local sediment transport dynamics, even based on well-structured field campaigns (Daly et al., 2014; Loureiro et al., 2012; Short, 2010). Process-based morphodynamic models are now sufficiently advanced that they can be used as a numerical laboratory to separate and study the interaction and effects of natural processes in relation to various wave forcing scenarios (Castelle and Ruessink, 2011; Roelvink and Reniers, 2012; Smit et al., 2008). These models have already been used to simulate embayed beaches with the goal of understanding their dynamics. For example, Yamashita and Tsuchiya (1992) simulated circulation patterns and sediment redistribution using a single wave condition. Reniers et al. (2004) studied the influence of wave groups and infragravity waves on the development of nearshore morphological rhythmicity induced by rip currents, and Castelle and Coco (2012) investigated how rip currents and circulation patterns are affected by changes in bay width. These studies are restricted to relatively short timescales (in the order of days to months) and feature embayments with limited curvature. Daly et al. (2011) showed how a schematic embayed beach responded to a number of constant wave forcing conditions over a four-year period, but did not investigate the effect of wave climate variability. Despite the many advances in this area of morphodynamic modelling, neither the influence of wave diffraction nor the variance of the wave climate have been systematically investigated together from a process-based perspective.

The aim of this paper is to investigate the role of wave climate conditions (directional variance, wave height variance and directional spreading) in providing forcing in the shadow zone of an embayed beach. Additionally, the role of diffraction is investigated to determine how this process enhances embayed beach development. The study focuses on beaches with high curvature and with a defined shadow zone in the lee of the main headland structures (e.g. Fig. 2) as this area is most affected by diffraction. A state-of-the-art process-based numerical model (Delft3D) is a suitable tool for carrying out such an investigation. Therefore, a systematic numerical modelling approach is taken that uses (i) stationary hydrodynamic simulations to show how the distribution of wave energy and sediment transport vary around the shoreline of an idealized embayed beach, and (ii) morphodynamic simulations to show the evolution of an initially straight, plane-sloped beach over time until it forms a stable embayed shape. The study isolates key processes affecting embayed beach development, from which we can evaluate the role of wave climate variability and diffraction processes in the formation of the typically curved embayed beach shoreline. Details of the setup of the hydrodynamic and morphodynamic Delft3D simulations are given in Section 2. The reader is directed to Appendix A for a brief description of relevant aspects of the Delft3D model to the current work. Results from both types of simulations are presented in Section 3 and discussed in Section 4, followed by conclusions in Section 5.

2. Methods

Two types of Delft3D numerical simulations were used in the current investigation: stationary hydrodynamic (H) and morphodynamic (M). The hydrodynamic simulations were used to determine the instantaneous distribution of wave energy with an embayment. We could therefore easily isolate key wave forcing parameters that affect sediment transport rates throughout the surf zone of the bay, thus underpinning the understanding of how the beach would develop morphologically. The fixed bathymetry used for these simulations was that of an idealized embayed beach (Fig. 3b) and the boundary conditions were kept constant until a steady-state flow pattern was achieved. The morphodynamic simulations modelled the development of an embayed beach under both constant and time-varying wave conditions, thereby adding perspective to the effect of variations in wave forcing. The initial bathymetry in the morphodynamic simulations was a straight plane-sloped beach (Fig. 3c), which was allowed to evolve over time into an embayment in response to the wave forcing conditions. This was seen as a rigorous test of the model as it was expected to reproduce the highly curved shoreline of the embayment. Further details on both types of simulations are given in the following two sub-sections.

2.1. Hydrodynamic simulations

2.1.1. Setup and fixed bathymetry

The hydrodynamic simulations (summarized in Table 1) were structured in order to determine the effect of systematically changing the wave direction (θ) and degree of directional spreading (σ), both ignoring and including the effect of diffraction. In total, there are 9 hydrodynamic cases (18 simulations, considering diffraction). A fixed bathymetry was used under the assumption that bed level changes are much slower than changes in the wave conditions. This allows us to analyse the degree to which wave events that are not in equilibrium with the pre-existing bathymetry force changes on the beach (via beach rotation).

The fixed bathymetry used in the hydrodynamic simulations (Fig. 3b) is based on the combination of the PBSE (Fig. 1) and a simple equilibrium beach profile formula. The PBSE is given as:

$$\frac{R}{R_0} = C_0 + C_1\left(\frac{\beta}{\alpha}\right) + C_2\left(\frac{\beta}{\alpha}\right)^2 \tag{1}$$

where R_0 is the length of the control line joining the DCP to the focal point; β is the angle formed between the incoming wave crests and the control line; R is the radius to the shoreline at an angle α from the control line; and C_0, C_1 and C_2 are polynomial coefficients variously defined by several authors (e.g. Hsu and Evans, 1989; Schiaffino et al., 2011; Wang et al., 2008), but typically a function of β. An equilibrium beach profile (Dean, 1991) is defined as:

$$d(y) = Ay^{2/3} \tag{2}$$

where d is the water depth at a distance of y from the shoreline, and A is a scale parameter taken as 0.43, which is used between 0 and 5 m depth with a relatively plane 1:7 slope thereafter until 12.8 m depth (Fig. 3a). The choice of A and the gradient of the plane slope were based on angles typically associated with a median sediment grain size (D_{50}) of 300 μm, which was used in the model. The shoreline of the bay was drawn based on the position of two headlands spaced 147 m apart in the cross-shore. Both headlands run north–south, parallel to the primary direction of wave approach—a similar configuration as that used in the flume experiments of Ho (1971). The planform was determined using $\beta = 45°$ with the DCP attached to the northern headland. The northern headland extended 30 m seaward from the DCP in order to physically constrain the