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Long-term evolution of nourished beaches under high angle wave conditions

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ABSTRACT

A nonlinear numerical model for large-scale dynamics of shoreline and nearshore bathymetry under wave action is applied to investigate the long-term evolution of a rectilinear coast dominated by high angle wave incidence, which is perturbed by a nourishment or an offshore borrow pit. Previous studies show that a coastline can be unstable due to high angle wave instability, which results from the feedback between shoreline changes and the wave field. In contrast to traditional one-line shoreline models, which always predict a diffusional behaviour, this instability can lead to the growth of shoreline perturbations. Model results suggest that due to high angle wave instability a nourishment or a borrow pit could trigger the formation of a shoreline sand wave train (alternating accretional and erosional zones). Its formation is a self-organised response of the morphodynamic system and can be seen as a spatial-temporal instability. New sand waves are formed downdrift while the old sand waves migrate downdrift and increase in amplitude and wavelength. Instability develops only if the bathymetric changes related to shoreline perturbations extend to a depth where the wave angle is greater than the critical angle of 42°. The potential for coastline instability is therefore limited by the wave incidence angle at the depth of closure and not the angle at deep water as suggested in previous studies. Including a fraction of low angle waves to the wave climate causes saturation of the amplitudes of the sand waves and limits the formation of the sand wave train. Even on a stable coast dominated by low angle waves, the feedback between morphology and the wave field can be crucial for the prediction of nourishment evolution. This feedback leads to relatively slow diffusion of shoreline perturbations and it can lead to downdrift migration. While some existing observations describe downdrift advection, no satisfactory explanation had been provided previously.

1. Introduction

Shore nourishment is used in coastal engineering to mitigate beach erosion. The nourishment can be seen as a perturbation of the dynamic equilibrium of the coastline and since this perturbation is eventually diffused in cross-shore and alongshore directions, nourishment is considered to be a temporary solution. When a net alongshore transport is present, the perturbation can also undergo advection (Hamm et al., 2002).

Within the process of nourishment design and planning, modelling plays an important role. Capobianco et al. (2002) gave an extensive review of different shoreline change models and their applicability on nourishment planning. The increasing understanding of nearshore dynamics has lead to the development of detailed process-based models. These models however still have a low skill in predicting shoreline dynamics. Furthermore they require detailed field data for calibration and they are computationally demanding. Therefore, simple one-line shoreline change models are commonly used for long-term and large-scale simulations. These models are based on the assumption that shoreline changes are caused by gradients in wave driven alongshore (Komar, 1998; Dean, 2002). This alongshore transport is commonly computed with the empirical CERC formula, which relates alongshore transport with the wave height at breaking (H_b) and the angle between the wave fronts and the shoreline orientation ($\theta_b - \phi$), where θ_b is the wave incidence angle at breaking with respect to the shore normal and ϕ is the angle between the local shoreline and the mean rectilinear shoreline. When this approach is applied to small amplitude changes on a rectilinear coastline the Pelnard–Considère equation for the shoreline position can be derived (Pelnard-Considère, 1956). This is a diffusion equation, which predicts a stable coastline and the diffusion of perturbations of the shoreline. The diffusivity coefficient in this equation is called coastline diffusivity. This concept can also be applied in a more general context and the coastline diffusivity can be estimated as the squared length scale of a perturbation divided by its decay time.

In recent years it has been demonstrated that when the wave climate is dominated by high angle waves this situation can be reversed and the coastline becomes unstable (actually, this was previously suggested by Zenkovich (1959)). This instability of the coastline will be referred to as high angle wave instability (from now on called HAWI). Ashton et al. (2001) used a non-linear cellular model

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to explore HAWI. They found that small perturbations on a rectilinear coastline can grow and migrate if the incidence angle of offshore waves with respect to the shore normal (θ_0) is higher than a critical value of 42°. Non-linear effects made the largest perturbations to dominate and they reproduced large scale coastal patterns resembling shoreline sand waves, capes and spits Ashton and Murray (2006a). In the present study we use the term shoreline sand wave field to refer to an undulating shoreline with alternating accretional and erosional zones, like the pattern described by Ashton and Murray (2006a). Falqués (2003) showed that HAWI is the result of the feedback of the shoreline changes into the wave field, a feedback ignored in the traditional one-line models. When shoreline variations extend into the nearshore bathymetry they affect wave transformation. Work and Rogers (1997) and Thevenot and Kraus (1995) already included the effect of wave refraction in their shoreline models, leading to a lower θ_b and a reduction of the coastline diffusivity. The reduction of the coastline diffusivity maybe up to about 50% (Dean, 2002). Refraction also leads to alongshore gradients in H_b through wave energy spreading and focusing. Ashton and Murray (2006b) and Falqués et al. (2011) suggested that it is wave energy spreading that is essential for HAWI. For θ_0 lower than 42°, alongshore gradients in $\theta_b - \phi$ are dominant for alongshore transport and the resulting transport pattern leads to diffusion of shoreline perturbations. For θ_0 greater than 42°, gradients in H_b at breaking become dominant for the alongshore transport and this leads to a different transport pattern, enabling a perturbation to grow and migrate.

List and Ashton (2007) confirmed that a shoreline can potentially be unstable for high angle wave conditions by modelling initial transport gradient patterns with the use of a fully 2DH process-based wave, circulation and sediment transport model. Some discussion exist about the capacity of the CERC formula to correctly predict gradients in alongshore sediment transport that result from wave transformation over bathymetric perturbations (List et al., 2006, 2008). However, the results of List and Ashton (2007) suggest that the CERC formula predicts qualitatively correct transport gradients along large scale shoreline undulations (alongshore lengths of 1–8 km).

The two main limitations of the studies by Ashton and Murray (2006a,b) and Falqués (2003) are that the bathymetric lines are rectilinear and that the perturbations of the shoreline extend offshore in the bathymetry to infinite distance. Falqués and Calvete (2005) developed an one-line model with curvilinear bathymetric lines and a finite extension of the perturbations in the cross-shore direction. They used linear stability analysis to explore the HAWI mechanism. The model was able to predict instability and the formation of a shoreline sand wave field. They found that if the bathymetric perturbation is confined close to the shoreline, no instability develops. This enlightens the importance of cross-shore profile dynamics for the HAWI mechanism. They found typical initial growth times of 1–10 years and wavelengths in the order of 4–15 km for the modelled sand wave field. Since this study used a linear approach it was only valid for small amplitude perturbations. A second limitation was that the cross-shore extension of the perturbation was fixed in time.

In the present study an extension of the one-line model used by Falqués and Calvete (2005) is presented. This model, called Q2D-Morfo, is non-linear, can simulate large amplitude perturbations and treats the cross-shore extension of the perturbations as finite and dynamic. The aim of this study is to understand the long term evolution of nourished beaches under high angle wave conditions. It is expected that, under these conditions, a nourishment can act as a perturbation that triggers shoreline instability and the growth of shoreline sand waves. Two different nourishment scenarios are used for the numerical simulations, a beach nourishment and a shoreface nourishment. A third scenario used is a straight coastline with the presence of a nearshore dredge pit. The three scenarios are expected to respond differently to high angle wave conditions. The influence of the offshore wave conditions and nourishment dimensions on the shoreline evolution are also studied.

2. Nourishment methods and shoreline response

The most traditional nourishment method is beach nourishment. This involves the placement of large quantities of sand on the sub-aerial beach, advancing the shoreline seaward (Dean, 2002). The volume of sand involved in beach nourishment is in the range of one to several million cubic meters spread over an alongshore section of several kilometers. The shoreline advances seaward several tens of meters and the initial nourished cross-shore profile is usually steeper than the original beach profile. This often results in an initially rapid diffusion in cross-shore direction until the equilibrium shape of the profile is restored. The planform diffusion depends on wave conditions and the amplitude and length of the nourishment. Typically the diffusion is slower for a long nourishment with a small amplitude. Grove et al. (1987) suggested that apart from diffusing a beach nourishment can initiate a solitary downdrift migrating shoreline sand wave, i.e. a single accretional zone (crest) sometimes followed by an erosional zone (trough). This suggestion is supported by various studies on other sites where the input of a large body of sand to a coastline appears to initiate a shoreline sand wave. The input of sand can be due to nearshore bar welding (Davidson-Arnott and van Heyningen, 2003), episodic inlet opening (Thevenot and Kraus, 1995), sediment bypass pulses at inlets (Ruessink and Jeuken, 2002) and riverine flood deposits (Inman, 1987). When these natural inputs of sediments are periodic they could lead to the initiation of multiple shoreline sand waves.

A second nourishment approach is shoreface nourishment, in which the sand is placed as a submerged berm (Dean, 2002). The submerged berm is located within the active zone of the cross-shore profile over an alongshore section of several kilometres. This method is gaining popularity as it seems to be effective and is cheaper than beach nourishment. Its effectiveness depends on two mechanisms. The first one is the feeder effect due to onshore transport of sand from the shoreface nourishment to the beach. The second one is the lee effect of the berm, which causes wave shadow and wave focusing leading to gradients in alongshore sediment transport. In particular, when a net alongshore transport is present there will be accretion in the lee of the berm due to a decrease in transport capacity. This can however also cause a down drift zone of erosion due to the subsequent increasing transport capacity (van Duin et al., 2004). The behaviour of shoreface nourishments is usually complex as they interact with bar dynamics (Grunnet and Ruessink, 2004).

Nourishments require a nearby source of good quality sand, which is usually dredged from an offshore location. These borrow pits can affect the shoreline directly by trapping sediment from the nearshore and indirectly through wave transformation and the resulting transport gradients (Dean, 2002). Borrow pits are generally located at depths greater than the depth of closure (D_c). Therefore they fill in very slowly and their forcing on the shoreline can persist for decades. As it has been mentioned in Section 1, there exists some discussion on the capacity of the CERC formula to correctly predict transport gradients due to bathymetric perturbations like borrow pits. On the one hand, Bender and Dean (2004) used an analytical wave transformation and the CERC formula to compute alongshore sediment transport and their predictions showed accretion in the shadow zone of a borrow pit with a downdrift erosional zone, qualitatively in agreement with results of process based models (Benedet and List, 2008; Hartog et al., 2008). These results were only obtained if an additional term, which describes the contribution of alongshore gradients in wave height (Ozasa and Brampton, 1980), was added to the CERC formula. On the other hand, List et al. (2006, 2008) suggested that the transport gradients shoreward of a borrow pit computed with the CERC formula are out of phase with those of a