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Sea bed evolution in the vicinity of longitudinal submerged discontinuous breakwaters - "Acripelagos"

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Abstract

The influence of shore parallel defence structures on sediment transport patterns is numerically investigated, along the coastal zone of Cannes in France. Extreme and long-duration storm events have become more frequent over the last years and they have significantly affected the coastal environment of this densely urbanised area. A landward retreat of the coastline has been observed, which is associated with the presence of high-energy wave-induced currents and coastal defences located on the upper part of the beach. XBeach and Swan, two state-of-the-art numerical models, are coupled in order to transport inshore offshore wave characteristics and evaluate the sediment transport mechanisms in shallow waters. This study enlightens a novel approach for the design of sea structures, providing significant insights into flow-seabed interactions.

Keywords Coastal structures, Breakwater, Numerical simulation, Morphodynamics, XBeach, Swan.

1 INTRODUCTION

The performance of longitudinal submerged discontinuous breakwaters has been investigated as a possible shoreline erosion prevention device, in the coastal region of Cannes in France. This area is particularly vulnerable to coastline retreat due to extreme meteorological conditions that prevailed in recent years. Storm events associated with high energetic waves and intense littoral currents occur frequently in this zone, causing a significant sediment loss. Moreover, coastal defences and vertical-wall structures, located on the upper part of the beach, intensify wave reflection and increase local scour and general reduction in the sea bed levels. The present study explores the overall influence of shore parallel innovative discontinuous double breakwaters on the morphological response of the sea bottom, relying on numerical approaches. The breakwater system is used in combination with mechanical placement of coarse sand sediment (beach nourishment) in order to advance the shoreline and increase the total volume of sand in the littoral system.

Significant efforts have been made in the last decades to investigate hydrodynamics and morphodynamic conditions around low-crested structures (Postacchini et al. 2016) (Kramer et al. 2005) (Losada et al. 2005) (Van Rijn 2011). Submerged breakwaters are widely perceived to be efficient of providing beach protection, avoiding a loss of beach amenity or aesthetic considerations often associated with groins and revetment walls (Ranasinghe and Turner 2006). However, modified hydrodynamics are generated around these submerged structures, as sea level set-up increases, and associated induced pressure gradients generate seaward rip currents through the gaps between contiguous breakwaters (Calabrese et al. 2008) (Vicinanza et al. 2009) (Brocchini et al. 2004). These currents play an important role in coastal erosion as they are associated with rip embayments (i.e. megacusps) that expose the shoreline to high erosion rates during extreme storm events (Thornton et al. 2007) (Michallet et al. 2013). This study suggests an innovative breakwater design solution in order to overcome the adverse impacts of submerged structures. The proposed geometry concerns a low-crested structure composed of two parallel rouble mound breakwaters along the coastline with asymmetric openings (channels). The main function of this optimized configuration is to channelize wave-induced flux offshore so as to limit the sea level set-up in the protected area. Figure 1 depicts the geometry of these structures, located at a depth of about 4m in the coastal zone of Cannes. Furthermore, this structure is characterized by a significant reduced total material volume due to the presence of openings, thus providing a cost-effective solution. For this system a patent is pending under the name "Acripelagos".
Figure 1 a) Illustration of shore parallel discontinuous submerged breakwaters, b) Details of the breakwater form in 3D, c) Cross-section of the double submerged breakwater.

2 METHODOLOGY

The prevailing offshore wave conditions and tide characteristics are analysed in order to determine the input data for the numerical simulation of hydrodynamic and morphodynamic processes. XBeach and Swan, two state-of-the-art numerical models, are coupled in order to transport inshore offshore wave characteristics and evaluate the sediment transport mechanisms in shallow waters. Simulating Waves Nearshore (SWAN) is a third-generation wind-wave model (Booij et al., 1999), which has been utilized for hindcasting surface gravity waves (Rogers et al., 2003) and forecasting future conditions (Rogers et al., 2007) (Mao et al. 2016). This numerical model is based on the spectral action balance equation (Gelci and Cazale, 1953). SWAN evaluates coastal processes, such as the propagation and decay of waves, taking into account current-induced and depth-induced refraction and frequency shifts, wind input, whitecapping dissipation, bottom friction, depth-induced wave breaking, and nonlinear wave-wave interactions (Booij et al., 1999). A triangulated flexible mesh generated on the wet part of the case study area is used to simulate the wave propagation with SWAN model (Figure 2b). This mesh contains 17,056 nodes and 33,400 elements and it is locally refined in the shallow water areas. The wave directions are distributed into 36 bins with a constant bandwidth of 108, and frequencies are discretized over 32 bins with a logarithmic scale over the range of 0.0512–1 Hz. Wave breaking is introduced through the formula of Battjes and Janssen (1978), and the breaker index ($\gamma$) is considered equal to 0.73. Bottom friction is taken into account through the formulation of Hasselmann et al. (1973) and a constant coefficient of 0.067 m²s⁻³ is used. The initial wave conditions applied on the offshore boundary of the numerical model are extracted from provided data concerning wave height, period and direction time series at the reference point shown in Figure 2. Computed wave height distribution and wave-relative streamlines during a storm event are evident in Figure 2a.

Figure 2 a) Map of computed significant wave height and wave-relative streamlines, b) Triangulated flexible mesh of SWAN model.
The SWAN simulation corresponds to a total duration of 1 year, as non-stationary runs with time steps of 24 hours are used in order to provide wave conditions for XBeach model and predict beach morphological response. XBeach solves the time-dependent short-wave action balance, roller energy equations, non-linear shallow water equations of mass and momentum, sediment transport and bed update (Roelvink et al. 2009; Smit et al. 2010; Bolle et al. 2011). The frequency domain is reduced to a single representative peak frequency, assuming a narrow-banded incident spectrum. Radiation stresses are calculated through the wave action balance and roller energy equations. Wave-induced mass fluxes and return flows in shallow water are calculated through the Generalized Lagrangian Mean formulation described in Andrews and McIntyre (1978). Sediment transport rates are calculated using an advection-diffusion equation (Galappatti and Vreugdenhil 1985). XBeach has been widely used for the evaluation of morphodynamic conditions in coastal zones (Vousdoukas et al. 2012) (Afentoulis et al. 2017). The computational grid is constructed with a variable spatial step which decreases progressively shoreward (dx=10 m offshore and dx= 1 m nearshore). The bathymetry extends 1 km and 0.5 km in alongshore and crossshore direction respectively. Figure 3 shows the bottom elevation and irregular computational grid. XBeach simulations are carried out in 2D surf beat mode and in 1D non-hydrostatic mode. Sediment properties represent a uniform sand porosity of 0.4 and a grain size (D50) of 0.8 mm. The grain size (D50) of the coarse sediments used for beach nourishment is considered 2 mm. A constant Chezy number of 32 m0.5s-1 is applied to estimate bed resistance.

3 RESULTS AND DISCUSSION
The complex physical processes in the nearshore area are particularly assessed in order to estimate the final coast shape 1 year after the installation of the breakwater system. The combined action of waves and currents, as well as groundwater flows are evaluated with XBeach model. Figure 5a depicts the maximum wave height distribution during a severe storm (Initial conditions: Hmo = 2 m and Tp = 9 s), superimposed with isobath lines. The wave amplitude decreases notably in the area between the shore and the structures (Hmax = 0.6 m), as detached breakwaters provide shelter from the wave action. Outside of this area the wave height value varies from 2 to 3.5 m. Figure 5b demonstrates the sea bed evolution after 1 year, superimposed with isobath lines. The most striking result to emerge from the graph is that an accretion of 1.5 m is generated in the wave sheltered zones. However, erosive zones are identified in the gaps between the breakwaters and in the non-protected foreshore areas. Changes in seabed morphology are negligible for a water depth greater than 6 m. In order to investigate the effects of swash and groundwater dynamics, XBeach model is utilized in 1D non-hydrostatic mode. For this scope, a representative crossshore profile is chosen with a constant spatial step (dx) of 1 m (Figure 5). After the beach nourishment the seabed in the shoreface consists mainly of coarse sand with a mass median diameter (D50) equal to 2 mm while the layer thickness of nourishment sand is about 1.5 m. The final sea bed geometry of the selected profile, as it is derived from the one-dimensional simulation of morphodynamic processes over a year, is illustrated in Figure 6. The simulation concerns two scenarios: A) seabed evolution under the presence of the breakwater system with initial beach nourishment (Figure 5a), B) seabed evolution without coastal structures with initial beach nourishment (Figure 5b). The obtained numerical results revealed that the proposed structures, offer satisfactory protection to the coastal area, since an overall retention of the nourished sediments is observed, whilst in the case of an equivalent unprotected beach an offshore sediment movement is generated. However, slight erosion is presented near the seaward toe of the structure.
This study enlightens a novel approach for the design of sea structures, providing significant insights into flow-seabed interactions. The submerged discontinuous breakwaters offer a consistent environmentally friendly solution to deal with beach erosion phenomenon, contributing to the long-term stability of the coast. After an initial beach nourishment, it shown that the sediments are retained in the beach system, as the wave climate is modified in the protected area due to the presence of the structures. However, erosive zones are generated in the offshore toe of the structure and in the gap between contiguous breakwaters. Furthermore, the proposed configuration is characterized by a significant reduced volume comparing to traditional hard protection works, providing a cost-effective solution. A dedicated study is underway to evaluate the fluid–seabed-structure system in an interactive mode, in order to optimize the form and performance of the discontinuous submerged breakwaters.

4 REFERENCES


