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Beach Dynamics in the Presence of a Low Crested Structure. The Altafulla case

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ABSTRACT

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Low crested detached breakwaters constitute a promising alternative as a "partial" barrier for Coastal Engineering applications. They block "partially" water/sediment fluxes which should result in a wider range of morphodynamic applications while exerting smaller visual and aesthetic impacts than more conventional groynes. The way these structures work by filtering wave energy and partially constraining the resulting wave-induced circulation is however far from trivial. This explains commonly found functional failures and it is the key question addressed in this paper. The paper starts by showing the limitations of the present state-of-art in terms of conceptual and numerical modeling tools. Based on a field case from the Spanish Mediterranean Coast the paper explains how the wave/current fields are modified by the presence of a low crested detached breakwater. The resulting water/sediment fluxes are discussed in terms of implications and uncertainties for the functional design of this structural type. The emphasis is on the various driving mechanisms generating alongshore fluxes and how they become modified, not only by the presence of the low crested structure, but also by the corresponding beach evolution.

ADDITIONAL INDEX WORDS: *Morphodynamics, hydrodynamics, numerical modeling.*

INTRODUCTION

Coastal erosion acts at two main time-scales (gradual and "impulsive") affecting significant stretches along the Spanish Mediterranean Coast. Because of the effect of both time-scales and the high pressure of use in the region, there is a reduction of available beach width and surface. This affects the economic development of the coastal zone and forces the construction of a number of so called "solutions". These solutions do not always behave as expected (in terms of their morphodynamic impact) and they also produce significant visual and ecological impacts. Low-crested structures (LCS) are detached breakwaters frequently overtopped, offering a number of potential advantages:

i) They exert a partial barrier effect for sediment fluxes (allowing more flexibility in designing the desired coastal response).

ii) They impose a reduced visual barrier effect (producing a smaller aesthetic impact).

iii) They enhance water circulation (around the structure) and wave breaking (over the structure). This leads to increased water quality and biological productivity.

For these reasons LCS have been often used to reduce coastal erosion or mobility. They have been used alone or in combination with artificial nourishment and their degree of success has been, at best, limited.

This can be explained by the complexity of water/sediment fluxes around and above a LCS. This complexity is also illustrated by the high number (up to 14) of variables participating in the functional design of such structures (see e.g. HSU and SILVESTER, 1990; PILARCZYK, 2003).

Within this framework the paper will analyze a "simple" field case (Altafulla beach) in which there is a single LCS built on a microtidal beach and with relatively well defined "boundary conditions" at both ends of the beach. Based and inspired on this field case the paper will address the main hydrodynamic processes controlling the morphodynamic response. These processes, not normally considered in the present design of LCS, allow a better understanding of the observed (and so far unexplained) variability in the coastal response for supposedly similar structures.

The paper will then critically assess the limitations of state-of-art morphodynamic analyses and tools for coastal stretches protected by LCS. The limits of conceptual and numerical models (depending on the weight of the different driving terms) will also be shown to change significantly from the "initial" stage (right after building the structure) to the "final" stage (once the morphodynamic response has set in).

STATE-OF-ART

The morphodynamic functional design of low crested detached breakwaters is extremely difficult due to the large number of different processes contributing to the resulting water/sediment fluxes. Depending on the driving terms and the beach/structure geometry, different processes contribute with different relative weight and the resulting water/sediment fluxes will vary. This means, in practice, that a different morphodynamic behaviour should be expected, depending on:

- Incident wave and mean water level conditions (for medium waves, severe storms or exceptional storms a different morphodynamic behaviour will result).
- Beach state (i.e. the morphodynamic behaviour right after the structure construction or once the salient/tombolo has developed will be different).

The present state-of-art, be it based on diagram, 1-line or numerical morphodynamic models, does not normally consider this richness of mechanisms. This results in a poor understanding of how low crested detached breakwaters function and the commonly observed morphodynamic "misbehaviour".

The most common approach for the functional design of detached breakwaters consists in using diagrams which predict the morphodynamic response as a function of structural parameters, essentially the ratio of structural distance to the coast over structural length. These functional relationships or diagram models are very useful as pre-design tools. Generally these relationships are based on experimental observations and their main limitations are due to the extrapolation of these results without taking into account (in the morphological response) the local wave climate, characteristics and availability of sediment, etc. Among the more commonly employed expressions those of GOURLAY (1980), DALLY and POPE (1986), SUH and DALRYMPLE (1987) and AHRENS and

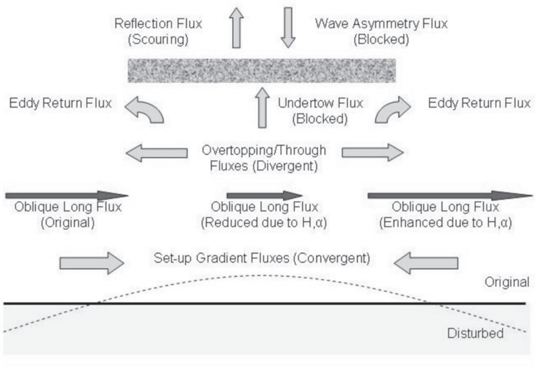

Figure 1. Wave-driven sediment fluxes for an alongshore uniform beach with an emerged LCS.

COX (1990) can be cited. A comprehensive revision of these formulations can be found in USACE (1993), PILARCZYK and ZEIDLER (1996) and HERBICH (2000).

Nevertheless, these criteria are based on geometric ratios without taking into account wave evolution and, in particular, wave transmission, which plays a very important role in the efficiency of LCS and the resulting shoreline response. Different authors have proposed formulations for detached breakwaters considering wave transmission (see e.g. HANSON and KRAUSS, 1990). PILARCZYK (2003), after analyzing the behaviour of submerged breakwaters proposed the correction of previous geometric expressions by introducing a transmission coefficient, Kt, to take into account the actual hydrodynamic conditions.

The next step in sophistication uses 1-line models (e.g.HANSON and KRAUSS, 1989) which predict the morphodynamic response as a function of wave conditions, sediment type and structural geometry. They have been widely employed to design detached breakwaters. However these models are based on the computation and balance of wave-induced longshore sediment transport and do not consider the effect of circulation, overtopping and sometimes even transmission. HANSON and KRAUSS (1990) employed simulations of the Genesis 1-line model and some limited verification from existing data to develop criteria for salient and tombolo formation, including wave transmission. JIMÉNEZ and SÁNCHES-ARCILLA (2002) analyzed with a one-line model the influence of LCS freeboard on the shoreline evolution.

Coastal area morphodynamic models allow the modelling of complex hydrodynamic patterns around a dettached breakwater cosidering the effect of a number of environmental and design variables. Examples can be found in WATANABE *et al*. (1986), GRONEWOUD *et al*. (1996), BOS *et al*. (1996), NICHOLSON *et al*. (1997), ZYSERMAN *et al*. (1999) and ALSINA *et al*. (2003).

In spite of the variety of approaches and design tools, and eventhough the more comprehensive analyses establish that the morphodynamic response should be a function of structural/beach/meteo-oceanographic conditions, these analyses seldom identify (or even less quantify) the resulting water and sediments fluxes. The main processes and associated fluxes have been schematised in figure 1 and have been splitted in two groups related to longshore and cross-shore dynamics. There are four main mechanisms driving alongshore sediment fluxes and associated morphodynamic "responses":

-Fluxes due to oblique wave incidence (and their corresponding reduction in the shadow area of the structure).

-Fluxes due to the gradient in set-up (converging fluxes since the set-up is smaller in the lee of the structure).

-Fluxes to conserve the vorticity of set up gradient flows and to preserve the overall mass balance (which are, thus, diverging fluxes that "close" the eddies formed at both ends of the structure).

-Fluxes due to overtopping or transmission through the structure (divergent fluxes due to mass conservation).

There are 3 main mechanisms driving cross-shore sediment fluxes and associated morphodynamic "responses":

-The reduction/blockage in undertow (in the lee face of the structure).

-The reduction/blockage in wave asymmetry near bed flux (in the seaward face of the structure).

-The generation/enhancement of reflection fluxes (in the seaward face of the structure).

Only the alongshore fluxes will be considered in this paper, with emphasis on the variation of incident wave conditions.

DESCRIPTION OF THE STUDY AREA

Altafulla, is a typical Mediterranean beach located in the touristic coast of Tarragona (Spanish Mediterranean), 100 Km south of Barcelona. The beach of Altafulla is facing south and surrounded by two rocky salients enclosing the considered morphodynamic system. The length of the beach is about 2,300 m, it has a medium grain size of 0.12-0.2 mm, an average slope of 1.6 % and the astronomical tidal range is smaller than 0.3 m.

In 1965 a defence concrete seawall with a length of 250 m was constructed, being extended to 450 m in 1972. In 1983 the seawall was suffering increasing scouring problems and failed. The failure area was then protected with a conventional rouble mound.

However, and due to the high touristic value of the place, in

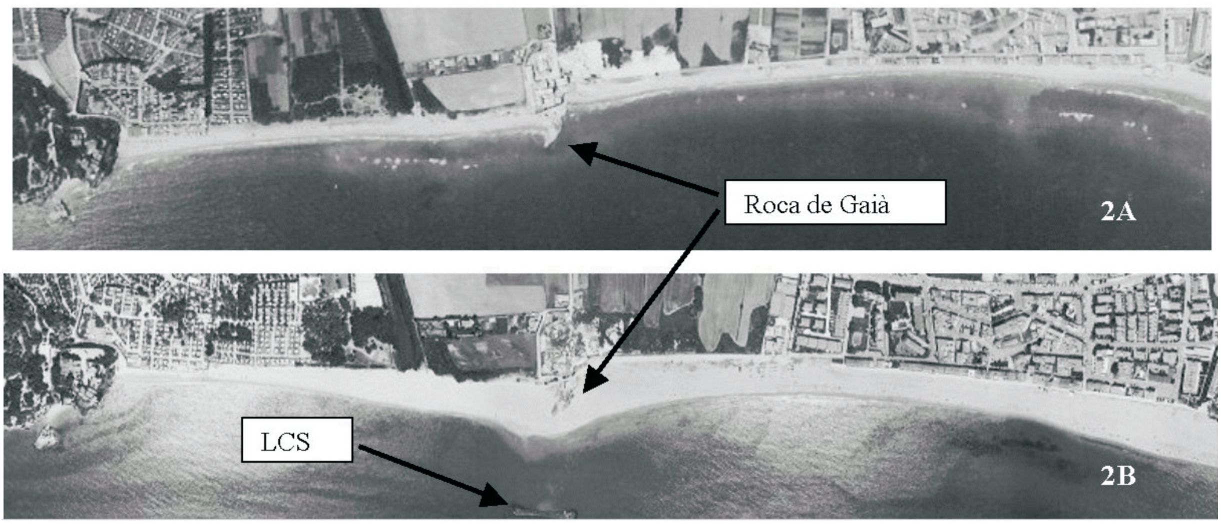

Figure 2. Aerial view of the Altafulla beach in 1983 (above) and 2001 (below).

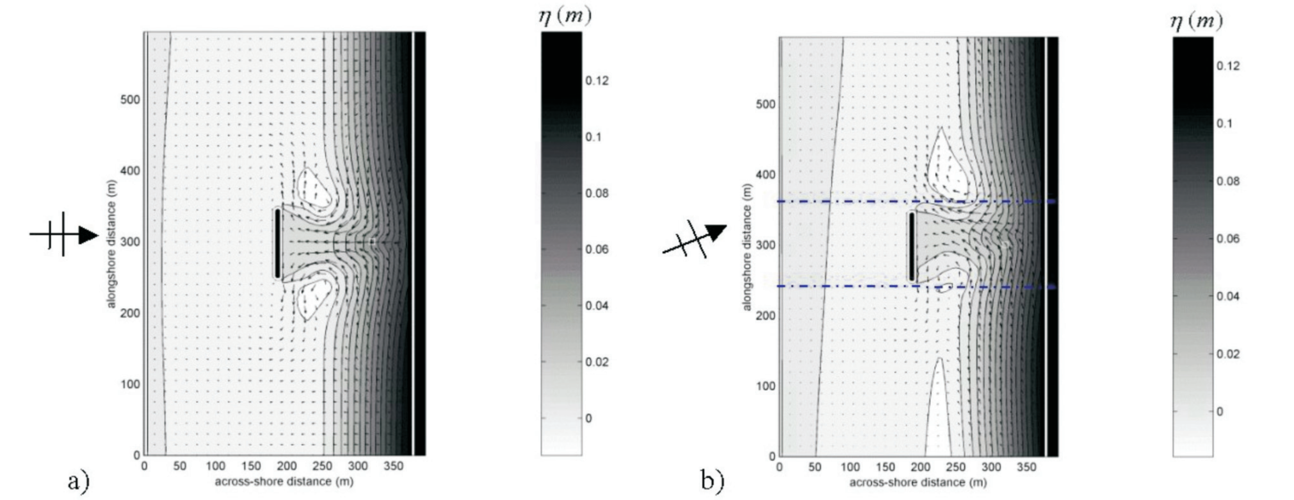

Figure 3. Circulation pattern induced by normal (a) and oblique (b) wave incidence for a LCS structure placed at 190 m from the shoreline. The simulated conditions correspond to a sea-state with Hs = 1m and Tp = 4s.

1991 a Low Crested Structure (LCS) together with a sand nourishment of 160,000 m3 were built to increase the width of the emerged beach. The LCS was placed in the middle of the coastal cell, in front of the "Roca de Gaià" which splits the beach (figure 2) in two parts. The structure was located between 3.5 and 4.5 m water depth and it is 100 m long, 5 m wide and the stillwater freeboard is less than 1 m. The nourishment took place at the East of the coastal cell (right part of figure 2) where there was a lower amount of sand due to the E-W (right to left in figure 2) net sediment transport pattern. Due to the lack of precise knowledge on the actual oceanographic conditions, the nourishment did not behave as expected and two years latter, in 1994, another recharge was required to maintain the sub-aerial beach surface. This time 250,000 m^3 of sand were nourished at the East side of the beach.

In the original bathymetry of 1989, obtained during a survey previous to the construction of the LCS, there was a rectilinear beach with isobaths reasonably parallel to the shoreline. The rocky outcrop "Roca de Gaià" placed near the middle of the beach interrupted this shoreline. The LCS was constructed at 180 m from the head of the "Roca de Gaià", and the distance from the LCS to the initial shoreline was about 230 m.

In July 1991 (3 months after the first nourishment) significant bathymetric changes and a fast redistribution of sediment near the structure were observed. The LCS modified the sheltered shoreline (and corresponding bathymetry), decreasing water depths and acting as a sediment trap. The distance between the LCS and the shoreline reached a mean value of 162 m. The outcrop had been by then completely buried.

In February 1999 the shoreline was located at 130 m from the LCS, while the beach and bathymetry changes were smoothly shaped behind the structure. The depth at the lee side of the LCS had dramatically reduced from 3 m in 1991 to less than 1 m in 1999.

The local wave climate has been derived from forecasted data (1996 to 2003) supplied by the Spanish Ministry of Public Works ("Puertos del Estado"), obtaining the distribution of significant wave heights and directions.

The analysis of these wave data shows a typical Mediterranean wave climate, with mild conditions most of the time. The significant wave height is lower than 1 m about 91% of the time and more than 99% of the time is lower than 2 m (including the calm periods). The prevailing wave conditions are those between E and S (more than 62% of the time).

Wave periods also show typical Mediterranean values, with peak periods ranging between 3 and 7 s about 73% of the time.

These data have been used to define the numerical simulations described below.

MATERIAL AND METHODS

The morphodynamic evolution, including the impact of the LCS has been analyzed by means of a suite of numerical models developed at the Laboratori d'Enginyeria Marítima (LIM-UPC). These models are well suited for the observed drivers and associated coastal responses (ALSINA *et al*., 2002).

The suite of models is composed by a wave model (LIMWAVE) (CÁCERES *et al*., 2002), a Q3D nearshore circulation model (LIMCIR) (CÁCERES *et al*., 2003) and an area morphodynamic model (LIMOS) (ALSINA *et al*., 2003). These models have been specifically adapted for the study of hydro-morphodynamics around a LCS and have been validated with the existing observations.

The LIMWAVE model is a phase-averaged model based on the conservation of the wave action equation (for the wave height), the eikonal equation (for the phase information) and the irrotationality of the wave number vector (for the wave angle) as presented in LIU (1990). This model incorporates depth-induced breaking dissipation according to DALLY *et al*. (1984), since it is the formulation more suitable for non-monotonically decreasing beach profiles (which is the case for this area of the Spanish Mediterranean).

The Q3D circulation model (LIMCIR) is based on the depth and time averaged mass and momentum conservation equations. It includes the driving effect of waves via the corresponding radiation stresses (Sanchez-arcilla et al, 1990 and RIVERO and SÁNCHEZ-ARCILLA, 1995), roller effects (DALLY and BROWN, 1995) and wave induced mass fluxes (DE VRIEND and STIVE, 1987). The turbulence closure is calculated in this paper using the OSIECKI and DALLY (1996) algebraic formulation. The rest of the closure terms include a state-of-art wind friction factor and MADSEN (1994) formulation to estimate bed shear stresses (considering the co-existence of waves and currents).

The morphodynamic model (LIMOS) features a sediment module which allows the use of some of the most advanced formulations in the state-of-art. For this paper the formulation of WATANABE *et al*. (1986) has been selected since it includes in a combined and robust manner the co-existing waves and currents to compute the local sediment transport.

The critical bed shear stress for the inception of sediment motion, calculated in terms of the threshold Shields parameter, is evaluated following SOULSBY (1997).

Finally the morphodynamic model computes bottom changes based on the sediment "continuity" equation, which includes the effects of gravitational (down-slope) transport (ALSINA *et al*., 2003).

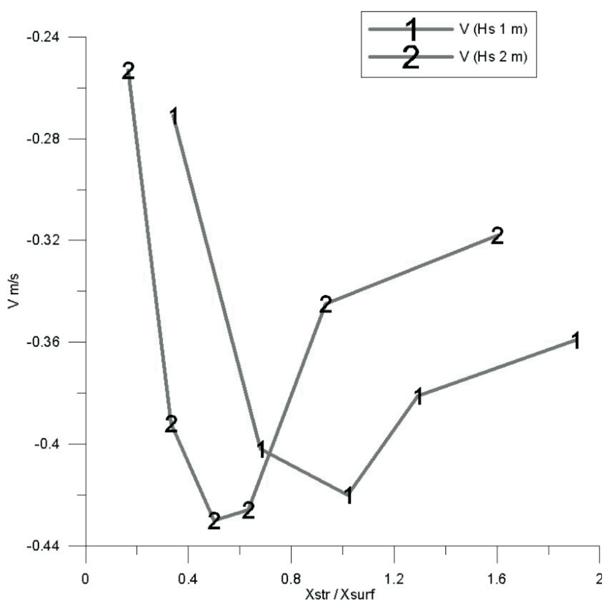

Figure 4. Peak velocity (as a characteristic velocity) in a transect from the structure to the coast. Wave conditions are Hs = 1m or 2m (as indicated in the graphs) and normal incidence. The LCS is placed at 150 m from the shore.

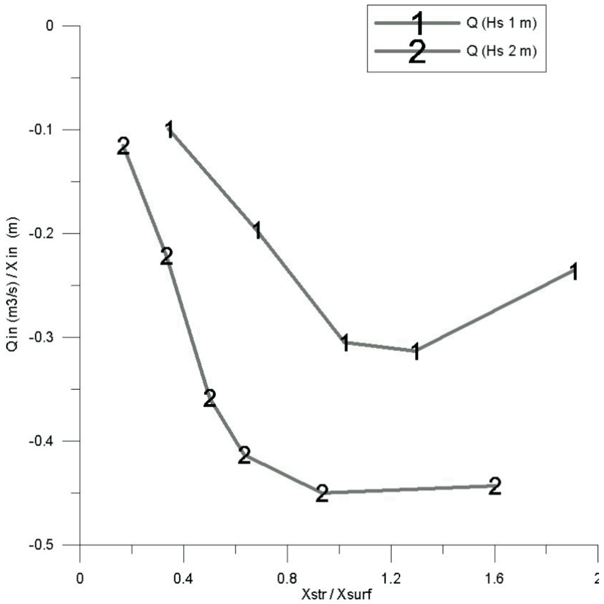

Figure 5. Alongshore water flux entering the area sheltered by the LCS. Wave conditions are, as, in figure 4, Hs = 1m or 2m (as indicated in the graphs) and normal incidence. The LCS is placed at 190 m from the shore.

DISCUSSIONS AND CONCLUSIONS

After observing the importance of different forcing terms in the obtained circulation, a number of test cases have been designed to determine the relative weight of these forcing terms in circulation and sediment transport simulations.

Various parameters conditioning the functional design of the structure have been taken into account in previous works as well as in the performed computations. One of these parameters is the distance from structure to shoreline (X_{str}), which has been widely employed (GOURLAY, 1980; DALLY and POPE, 1986; SUH and DALRYMPLE, 1987) during the last years to assess the morphodynamic response (tombolo, salient or minimal response). Different sea states have also been considered (see e.g. ZYSERMAN *et al*., 1999), including variables such as wave height and direction. The analyzed intervals of variation have been derived from the existing observations. This has provided a wide range of circulation and sediment transport results. This numerically simulated data set will serve to gain understanding on the water and sediment fluxes encountered in the functional design of LCS.

More specifically 22 model runs have been carried out, combining the following parameter values:

-2 values of wave height (H): 1 and 2 m, representing yearly average and mild storm conditions.

-2 values of wave direction (è): 0º (normal to the structure) and 15º (oblique incidence), representing the prevailing wave climates.

-6 values of structure distance to the shoreline (X_{str}): 50, 100, 150, 190, 280 and 480 m, so as to characterize feasible "construction" layouts.

Figure 3-a) shows the circulation obtained with $\theta = 0º$, H = 1 m and X_{str} = 190 m. Due to the presence of the structure there is a clear diffraction pattern giving rise to wave height gradients in the structure leeside. These wave gradients are the main circulation driving factor in this case. Although the pressure gradients associated to the varying set-up are conservative forces and cannot generate a vortical circulation (DINGEMANS, 1997), the obtained vortices display a "closed" pattern and do not, therefore, violate Kelvin's circulation conservation theorem. The resulting gradients in radiation stresses generate close to the shore water fluxes which converge towards the centre of the sheltered area. These converging fluxes also show (associated to the obtained "closed" vortices) a component directed towards the structure (i.e. flowing towards the offshore) and the required diverging flux (flowing parallel to the lee side of the LCS). The resulting two eddies, at both sides of the structure, control for this case the water circulation and, as it will be seen below, the associated sediment transport. It should be remarked that these results correspond to an emerged LCS since for a submerged one the circulation pattern is different (ALSINA *et al*., 2002), and will not be analyzed here Figure 3-b) shows the circulation pattern corresponding to the same H and X_{str} values but for oblique wave incidence (θ = 15º). The two aforementioned eddies appear to be "swept" by the longshore current associated to oblique wave incidence. This effect is more pronounced for the upstream vortex. The resulting mean-water-level pattern is also modified and a clear alongshore flow appears close to the coast. The inclusion of wave mass fluxes produces an enhancement of the longshore current component close to the coast. The undertow pattern in the lee of the LCS also appears to be "pushed" towards the shore by the wave mass fluxes. When this current comes close to the structure it contributes to enhance the two aforementioned eddies, but with some modifications. They consist in an intensification of the current in the downdrift part of the structure while currents flowing upstream are weakened.

The two cross-shore transects depicted in figure 3-b) have been studied in more detail. The magnitude of water flowing into the lee of the structure decreased from 71 m^3/s for normal incidence to 56 m^3/s with oblique incidence. This is due to the smaller water input in the upstream side (referred to the longshore current) in the case of oblique wave incidence. The maximum "output" (diverging from the structure area) velocity also decreases, due to the widening of the corresponding "flux" (from 75 m for normal incidence to 105 m for oblique waves). This change in behaviour clearly illustrates the multiple processes underlying the hydro-morphodynamics of a LCS and the corresponding difficulties for a correct functional design (as described in figure 1).

Figure 4 shows the maximum water velocity in the sheltered area, as a "measure" of the sediment stirring (together with the wave field) and transporting capacity. It shows that for both tested wave heights (1 m and 2 m) and for different X_{str} values (and, thus, for different X_{str}/X_{sz} ratios, where X_{sz} is the surf-zone width), there is a maximum in velocity. This peak would

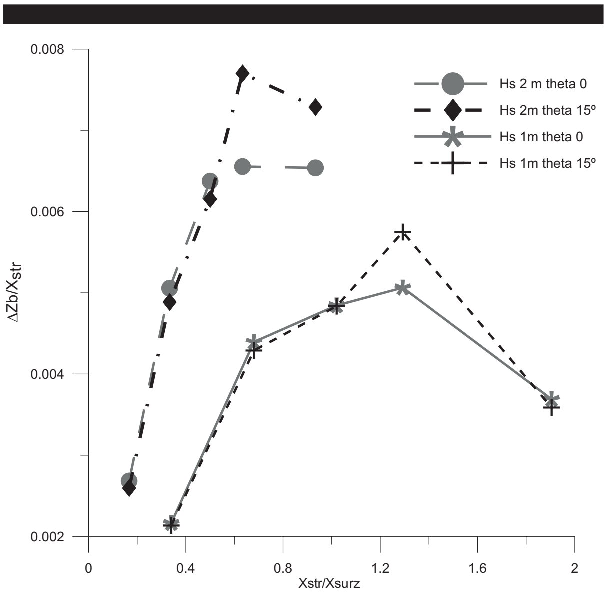

Figure 6. Averaged bottom evolution (estimated as an average of "disturbed" and "initial" bed levels, ΔZ_b) in the area sheltered by the LCS. Wave conditions are (as indicated by the various lines in the figure) Hs = 1m or 2m and normal or oblique (θ = 15º) wave incidence. The distance between the LCS and the coast (X_{str}) is made dimensionless using the surf-zone width (X_{sz}).

thus be a "point" (region) to be avoided in the X_{str}/X_{sz} axis to maximize the LCS depositional effects.

Figure 5 shows the water fluxes converging into the sheltered area for the cases of figure 4. A maximum "point" (region) is clearly apparent. This should be the "targeted" value for a correct functional design since it would maximize the sedimentary input into the lee of a LCS.

The main hydrodynamic effect of the LCS appears in the wave and mean-water-level fields for structures not far from the surf zone. This results, in turn, in a modification of the resulting circulation. As the structure gets closer to the coast (Xstr decreases) the current field is also directly modified (constrained) by the presence of the LCS.

Observing the maximum water velocities (figure 4), they are similar for both wave heights. This could be related to the obtained similar wave height (and radiation stresses) gradients for both tests. The differences found should, thus, be attributed to the varying wave mass fluxes particularly near the shoreline.

However, the input velocities (fluxes divided by the width of the input "zone") in the structure leeside increase 44% for a wave height of 2 m (with respect to the 1 m case). The breaking line for waves of 1 m is at 147 m from the shoreline, so the maximum water flux (and wave height gradients) will be close to this point. For wave heights of 2 m the maximum wave height and radiation stress gradients will be close to the breaking line, located at 300 m from the shoreline. This is where the maximum difference in input velocities (between both test cases) should be expected. In fact, it is where the maximum ratio between input water flux (Q_{in}) and width of input flux (X_{in}) is found.

It must be stressed that the right-most points (for H = 2 m) in figures 4 and 5 correspond to a structure located at a distance of 480 m from the shoreline. This "great" distance (compared to X_{sz}) is associated with a very wide zone in the lee of the LCS (of about 330 m), which in turn leads to a decrease of velocities but not of water fluxes.

Finally, figure 6 shows the dimensionless rate of sediment deposition ($\Delta z/X_{str}$, where Δz is the averaged variation of bottom level in the lee area of the LCS). The increase of sediment deposition (as a function of X_{str}/X_{sz}) for H = 2 m, with respect to H = 1 m, is clearly apparent. This should be attributed to the higher transport capacity associated to more energetic wave conditions. For normal incidence the maximum sediment deposit for both wave heights coincides with the maximum water flux input into the leeside of the structure. This confirms the clear relationship between the maximum deposit and the increase of input water fluxes.

On the other hand the oblique wave incidence enhances the sediment deposition between 8 and 18 % for H = 1 and 2 m respectively. Although in this case, the maximum sediment deposition peak occurs at the same X_{str}/X_{sz} ratio for normal and oblique (θ = 15º) wave incidence, it is not evident that these peaks will be obtained at a constant Xstr/Xsz ratio regardless of wave angle.

Conclusions

The hydrodynamics around a LCS are very complex due to the coexistance of a high number of wave-driven mechanisms. These lead to circulation and sediment transport patterns that are hardly considered in the functional design of such structures.

Most of the models usually employed in functional design of LCS only consider geometric parameters such as X_{str} and L_{str} (structure distance to the coast and structure length). More evolutioned models such as 3D morphodynamic modelling suites partially consider the circulation dynamics, but seldom take into account the quantitative relation with the incident wave parameters. In this paper, several simulations have been performed to evaluate the effect of different wave conditions (H and θ) on the resulting water/sediment fluxes. The importance of both parameters in the observed fluxes and deposition patterns at the leeside of a LCS has been verified, as well as the need to consider them in the functional design of such structures.

It has been observed that there is a value of the ratio X_{str}/X_{sz} which optimizes the sediment depositional trend. The simulations carried out showed that this value is not constant and varies depending on wave conditions (H and θ).

Finally, during the preliminary simulations, significant changes in the circulation induced by different bathymetries have been observed. This means that changing bathymetric conditions during the "life" of the structure should be explicitely considered. This subject requires further research including additional observations.

ACKNOWLEDGEMENTS

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