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Hybrid modelling of scouring - deposition in front of a coastal structure

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ABSTRACT

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Wave-structure interactions in the presence of a sand bottom constitute a complex problem, which is not yet satisfactorily solved. The process of erosion/deposition at the front toe of the structure, in particular, is only crudely defined up to the point that its quantitative dependence on wave conditions, structural permeability or sediment characteristics is poorly known. This paper analyses the scouring/deposition at the toe of detached breakwaters using large scale data from the CIEM wave flume in Barcelona and the simulations from a numerical wave-current-sediment transport model. The LIMORPH code has been developed and tested in a number of European Union research projects. The large scale wave flume data come from past (SCARCOST) and present (HYDRALAB III) European Union research projects. The paper discusses the relative merits of numerical/physical models and the gain in understanding for the underlying hydro/morphodynamic processes when a combination of both types of models is used. This is illustrated by the influence of wave characteristics and freeboard in erosion/deposition patterns.

ADDITIONAL INDEX WORDS: *Morphodynamics, Bottom evolution, Wave flume*

INTRODUCTION

Detached breakwaters are often employed to protect beaches against erosion. Most of these structures are frequently overtopped, being then named Low-Crested Structures (LCS). These LCS's offer a number of potential advantages with respect to more conventional structures but their morphodynamic functional design is extremely difficult due to the large number of different processes contributing to the resulting water/sediment fluxes. SÁNCHEZ-ARCILLA *et al.* (2006) identified four main driving mechanisms for alongshore sediment fluxes and three for cross-shore fluxes. This richness of mechanisms is not normally considered in the present state-of-art. Detached breakwater design is based on functional relationships (e.g. DALLY and POPE, 1986; SUH and DALRYMPLE, 1987; AHRENS and COX, 1990; HANSON and KRAUSS, 1990), 1-line models (e.g. HANSON and KRAUSS, 1989) and 3D morphodynamic models (e.g. WATANABE *et al.*, 1986; NICHOLSON *et al.*, 1997; ZYSERMAN *et al.*, 1999; ALSINA *et al.*, 2003). Only this last approach allows the modelling of complex hydrodynamic patterns around a detached breakwater considering the effect of a number of environmental and design variables.

Nevertheless the study of beach-structure interactions is very complex since the beach response is governed by, at least 14 different geometric, wave and sediment variables which are still difficult to include in a single model (HSU and SILVESTER, 1990; ILIC *et al.*, 1997). It is currently impossible to include all hydrodynamic and sediment processes in a single physical or numerical model. In particular, wave-structure interactions in the presence of a sand bottom constitute a tough problem, which is not yet satisfactorily solved. Scouring/deposition at the front toe of the structure is an illustration of this problem with immediate practical applications..

Although the use of numerical or physical models can help to get an idea about the beach response, a number of uncertainties persist, indicating that a single tool cannot adequately reproduce all processes involved in such coastal problems. Composite modelling (KAMPHUIS, 1996) integrates the benefits of both numerical and physical models, using them together in a balanced approach.

This paper addresses scouring/deposition at the toe of detached breakwaters using large scale data (from the CIEM wave flume in Barcelona) and the simulations from a numerical wave-current-sediment transport model. Some results from both types of models are presented. The paper discusses the relative merits (advantages and drawbacks) of numerical/physical models and the gain in understanding for the underlying hydro/morphodynamic processes when a combination of both types of models is used. In this way, a conceptual scheme for the hybrid (or composite) modelling of this problem is presented. The potential improvements in reproducing the bottom evolution are also considered in a preliminary manner.

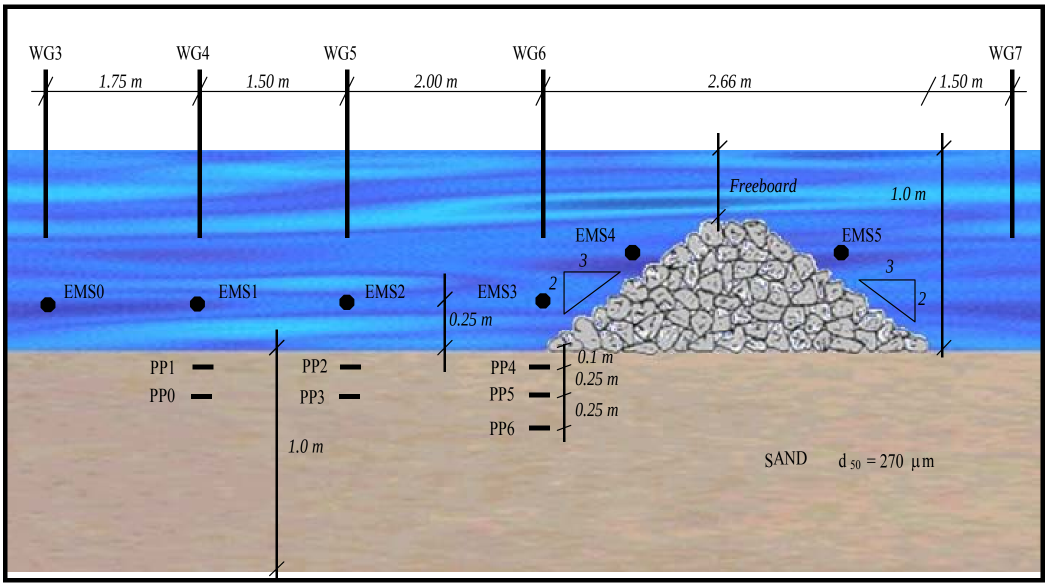

Figure 1. Sketch of the flume layout (including observational deployment) for mobile bed experiments. EMS stands for electromagnetic sensor, WG stands for wave gauge and PP for pore pressure sensor.

METHODS

Physical modelling

The experiments were carried out at the CIEM flume of LIM/UPC in Barcelona. This is an experimental facility of 100 m length, 3 m width and 5 m depth, equipped with a wedge type paddle to generate waves up to 1.6 m (significant wave heights of 0.9m).

In this case, the scale was designed to be 1/6, with a water depth at the structural toe equal to 1.0 m in all cases. In the physical model the rubble mound had a mean weight of W_{50} = 6.6 Kg and the sediment had a mean diameter of 270 microns.

The main experimental features are summarised in Figure 1, which corresponds to the case of submerged and permeable breakwater. Five geometries were tested with this same observational deployment (Sánchez-Arcilla *et al.*, 2000). These geometries include a submerged and permeable breakwater with a structure with a freeboard of 0.25 m. Additional low crested breakwater sections with a freeboard of 0.0 m (both permeable and impermeable cores) and an emerged structure with a freeboard of 0.75 m (also permeable and impermeable) have also been tested. The impermeability was obtained by means of a geotextile covered core. Beach profile changes were recorded by means of an automated mechanical bottom profiler.

Table 1: Characteristics of the different tests.

Test	*Hs* (m)	*F* (m)	T_p (s)	*s*	*d/L*	*waves*
B1	0.25	0.25	2.45	0.037	0.147	13,000
D1	0.33	0.25	2.86	0.040	0.122	9,000
P1	0.33	0.25	3.26	0.035	0.105	12,000
B0	0.25	0.0	2.45	0.037	0.147	12,000
D0	0.33	0.0	2.86	0.040	0.122	15,000
P0	0.33	0.0	3.26	0.035	0.105	12,000
Q0	0.33	0.0	2.04	0.062	0.186	12,000
R0	0.41	0.0	3.26	0.043	0.105	12,000
D2	0.33	-0.75	2.86	0.040	0.122	9,000
X2	0.33	-0.75	4.50	0.024	0.070	8,000
XR2	0.25	-0.75	4.50	0.018	0.070	2,000
X3	0.33	-0.75	4.50	0.024	0.070	6,000

Different waves were employed for the experiments. Table 1 summarises the characteristics of the different experiments, where H_s is the significant wave height, *F* is the freeboard, T_p is the peak period, *s* is the wave slope and *d/L* is the relative depth.

Numerical modelling

The morphodynamic evolution, including the impact of the LCS has been analysed 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 (Sánchez-Arcilla *et al.*, 2006).

The suite of models (LIMORPH) is composed by a wave model (González-Marco, 2005), a Q3D nearshore circulation model (Cáceres, 2004) and an area morphodynamic model (Alsina, 2005). These models have been specifically adapted for analysing hydro-morphodynamics around a LCS and have been validated with existing observations (Johnson *et al.*, 2005).

The wave model is a phase-averaged model based on the conservation of 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). The Q3D circulation model is based on the depth and time averaged mass and momentum conservation equations. It includes the driving effect of waves (radiation stresses), turbulence and wind as well as roller effects. Bed shear stresses and wave induced mass fluxes are also considered. The morphodynamic model, which solves the sediment conservation equation, features a sediment module which allows the use of some of the most advanced formulations in the state-of-art.

This suite of numerical models was validated against a number of field observations from two European beaches (Egmond in The Nederlands and Teignmouth in The United Kingdom) recorded in the frame of the EU project COAST3D. After the validation process (VAN RIJN *et al.*, 2003), it was applied to a beach profile with a submerged breakwater.

RESULTS

Experimental results

Experimental results for tests B1 and D1 (Table 1) show small beach profile variations at the toe of the structure, alternating scouring and deposition areas with amplitudes lower than 2 cm. The test with a submerged structure with freeboard of 0.25 m (case P1) presents a more dynamic bottom evolution. As it can be observed in Figure 2, there is a clear deposition at the front toe of the structure, followed by an area with less marked erosion where ripples appear.

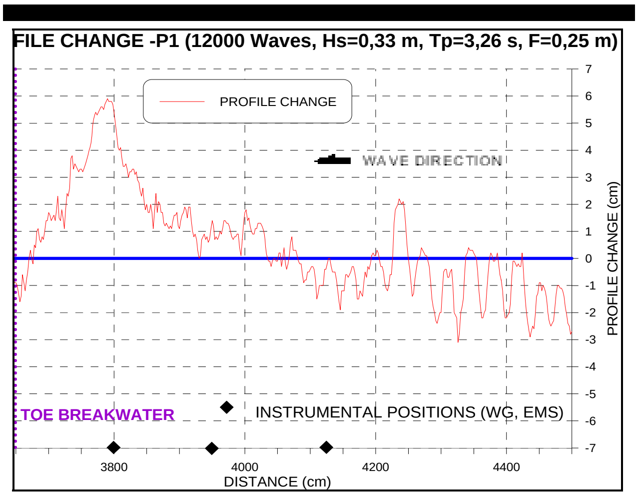

Figure 2. Bottom evolution at the front toe of a submerged breakwater for test P1.

This deposition pattern can be explained by considering that for submerged breakwaters, the reflection coefficient is lower than for emerged structures. Therefore the expected scouring at the front toe of the structure is also lower.

In the lee side of the structure there are small bottom variations for tests B1 and D1 while for test P1 a general erosive behaviour is observed, although at the structure toe there is deposition.

In all tests in which the breakwater freeboard is zero, there was continuous deposition at the front toe of the structure (e.g. see Figure 3), while in the lee side both deposition (tests D0 and P0) and slight erosion (tests B0, Q0 and R0) were observed. This can be explained by the significant breaking existing over the structure crest which produced a certain degree of structural sinkage and enhanced the deposition at the toe of the structure.

Finally, for emerged structures the general pattern shows scouring at the front toe of the breakwater followed by a deposition area (e.g. see Figure 4). Ripples frequently appear in erosion areas due to limited wave intensities.

Whenever the reflection coefficient increased (by making the structure emerged or by increasing the wave period) the conventional scour/deposition pattern appeared in front of the structure. It is worthwhile mentioning that deposition is always larger than erosion due to the barrier effect of the structure for bed sediment transport. It is also important to notice that the toe deposit decreases when the structure has an impermeable core. This is due to the constraining effect of the impermeable core which enhances the jet over the geotextile and this tends to wash the deposit toe away (SÁNCHEZ-ARCILLA *et al.*, 2000).

Numerical results

A number of numerical simulations were carried out changing the structural geometry (mainly the freeboard), the initial bottom configuration and incident wave features. Numerical results show that the position of the shoreline and the associated beach profile dynamics clearly depend on these factors. To illustrate this point, Figure 5 shows the numerical beach profile evolution in the vicinity of a submerged breakwater (with a freeboard of 1.5 m). This simulation was carried out with the LIMORPH code whose parameters were tuned with field observations from the two field cases mentioned above.

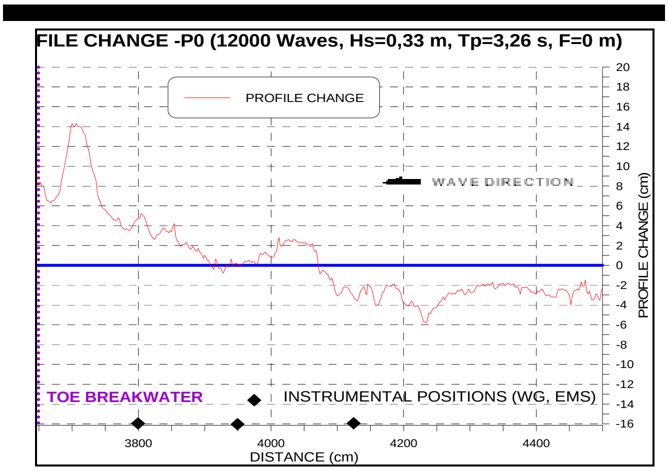

Figure 3. Bottom evolution at the front toe of a low crested (freeboard zero) breakwater for test P0.

The numerical results indicate deposition at the front and back toes of the structure. This is in accordance with the experimental results for submerged breakwaters presented above.

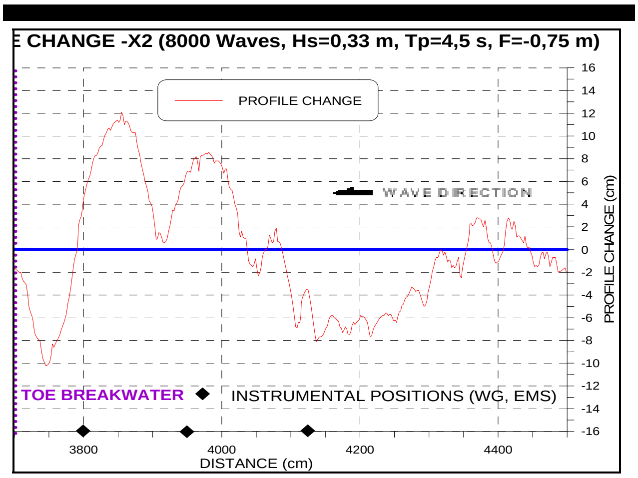

Figure 4. Bottom evolution at the front toe of an emerged breakwater for test X2.

The spatial scale employed in the discretisation ($\Delta x = 3$ m) does not allow reproducing bottom microfeatures such as ripples but is enough to reproduce the general pattern of the beach profile evolution.

Although both experimental tests and numerical simulations showed their ability to qualitatively reproduce beach-structure interactions under wave attack, they present a number of advantages and drawbacks which are presented in the next section.

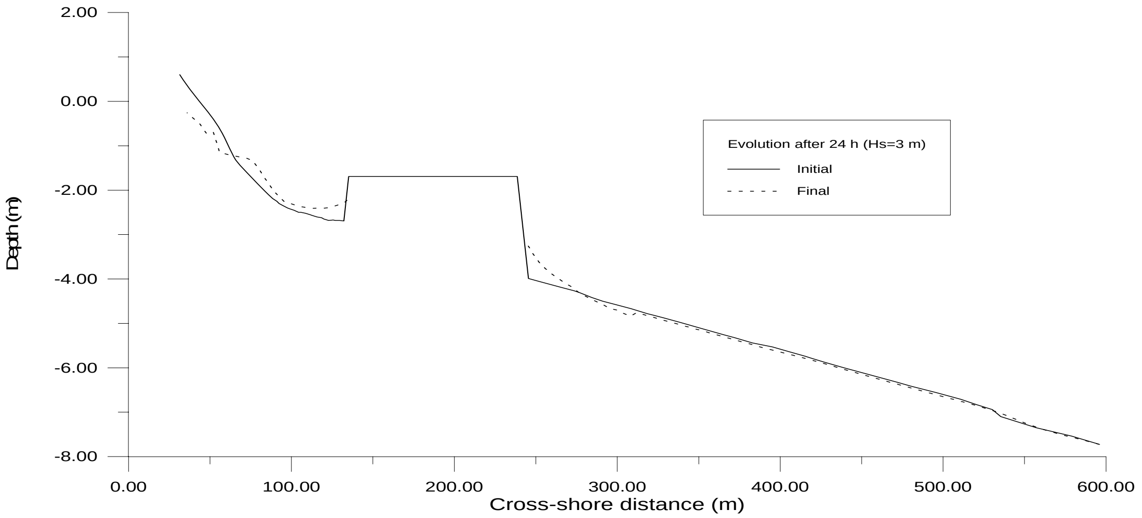

Figure 5. Numerical simulation of a beach profile in the vicinity of a submerged breakwater.

DISCUSSION

As it was shown in the previous section both physical and numerical models can reproduce relatively well the evolution of a beach profile in the vicinities of a LCS. Nevertheless, each of these approaches has its own specific strengths and weaknesses and no single tool is good enough to make the others redundant (VAN OS *et al.*, 2004).

The main strengths of laboratory experiments are repeatability and the controlled conditions of the tests. The weaknesses of this type of experiments are scale effects and model effects, which may distort the results. Other weaknesses are associated to the need of great investments in infrastructure and equipments.

Concerning numerical models, their main strengths are flexibility, versatility and low costs. On the contrary they are only approximations to Nature and as a consequence they present an inherent inaccuracy and miss some of the involved processes. Moreover explicit parameter (closure) values must be specified, introducing an additional uncertainty since many times the suitable values for these parameters are unknown. Finally, most numerical models employ deterministic approaches when in the "real world" many processes have random features.

Therefore, the combination of tools produces added value (VAN OS *et al.*, 2004) since it reduces the risk of methodological inbreeding and may lead to new understanding and methods. The integration of these different tools is the so called "hybrid modelling" or "composite modelling". As an illustration, numerical models can be used to assess scale and model distortions in lab (reduced-scale) experiments.

In Figure 6, there is a sketch of a possible "hybrid modelling" scheme to study bottom evolution around an LCS, combining the capabilities from both physical and numerical modelling. This combination takes into account the advantages of each type of modelling in order to partially cover the limitations of the other type. The physical wave flume model does not consider wave diffraction and, on the other hand, the water dynamics are constrained by the lateral walls which prevent longshore circulation. This constraining imposed by lateral walls has another undesirable effect which is the accumulation of water in the lee side of the structure. This piling up effect gives rise to unrealistic set-up values behind the structure, exceeding the ones actually expected in Nature.

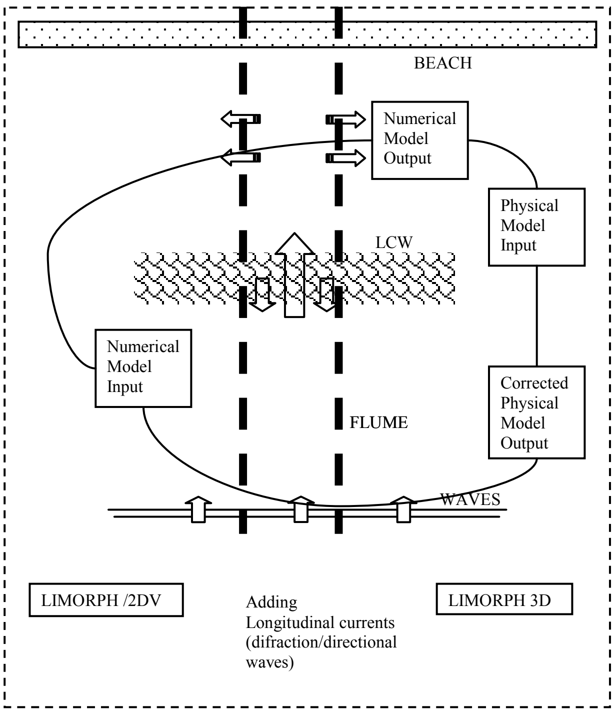

Figure 6. Sketch of the hybrid modelling scheme combining physical and numerical models.

To overcome these physical modelling limitations, the numerical model will be employed to compute longshore fluxes and the set-up in the lee side of the structure. These computed values could be introduced as an input in the physical model in such a way that the longshore flux could be generated by pumping water in a suitable manner within the flume. This pumped water (which should be recirculated towards the head of the model, close to the wave generator) would incorporate some of the longshore current effects and reduce the piling-up behind the LCS. However, such an arrangement requires a careful design of the pumping/absorbing system so that the generated currents are realistic and do not distort the 2DV frame reproduced in a wave flume. Such a design is being now considered for the Barcelona CIEM flume but has not yet been implemented.

Nevertheless, the results of such a "corrected" physical model could be then employed to partially circumvent some numerical model limitations. In particular, the numerical model cannot reproduce accurately the flux through and over the structure. These fluxes can be measured in the physical model and these recorded values introduced as an input for the numerical model. Numerical results would serve to determine the longshore flux and set-up behind the structure and the process could be carried out iteratively. After two or three cycles, the obtained results should be more representative of the actual beach evolution around a LCS.

CONCLUSIONS

Numerical and movable bed physical models have been employed to study beach evolution around low crested structures. Results provided by both tools appeared to be qualitatively similar, showing the capability of both model types to reproduce similar erosion and deposition patterns in the vicinity of such structures.

Nevertheless, both approaches present some restrictions due to their inherent limitations to simulate all involved processes without distortions. The wave flume cannot simulate wave diffraction and longshore currents, besides generating a piling up effect behind the structure, which gives rise to unrealistic set-up values.

On the other hand, the numerical model cannot simulate accurately the fluxes through and over the structure, so its results behind the LCS will also be distorted.

To partially overcome these problems a hybrid modelling scheme has been proposed. This scheme, only considered at a conceptual level in this paper, takes advantage of each modelling type capabilities to obtain results which are employed as an input in the other model. Using each tool to complement the other, more realistic results can be expected. This hybrid scheme will be developed and tested in the frame of the EU project HYDRALAB III.

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