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Mechanics of the scouring and sinking of submerged structures in a mobile bed: A physical model study

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ABSTRACT

Wave-induced flow velocity and turbulence may cause scouring in the seabed around coastal structures depending on the wave climate and tidal water depth. A 3-D physical modelling study was conducted to investigate the possible causes of the sinking of two submerged coastal structures on the Santa Maria del Mar (SMM) beach, Spain. The experimental investigation was conducted by employing a Froude similarity law with a geometric scale of 1:20, and the submerged modular structure was subjected to different wave climates and tidal water levels. The combinations of the significant wave height and peak period were chosen from in-situ real wave conditions that were monitored during the sinking of the prototype structures. Linking and unlinking conditions for the modules in the structure were investigated in this study. The results show that the modules sank to approximately 48% of their height at the end of the tests with storm waves and semi-linking conditions of low water depth. Most of the experimental results were compatible with the prototype monitoring results. Tests with proper linking among the modules and tests with an appropriate gravel foundation resulted in a sustainable solution because they presented much less or almost no scouring and sinking.

1. Introduction

Scouring of the sandy foundations of marine structures must be considered to be one of the causes of their sinking and consequent structural failure. Wave-induced scouring around marine structures, which is one of the most important threats to foundational stability, has become a research problem of considerable interest in recent years (Whitehouse, 1998; Sumer and Fredsøe, 2002; Bricker et al., 2012; Matutano et al., 2013; Abreu et al., 2013; Negro et al., 2014; Khan-Mozahedy, 2015; Nielsen et al., 2015, Manes and Brocchini, 2015).

Although there are numerous studies of scouring mechanisms in pipelines (e.g.,: Teh et al., 2003; Damgaard et al., 2006; Sumer et al., 2010; Cheng et al., 2011; Mattioli et al., 2013) and around emerged coastal structures such as vertical wall breakwaters and rubble mound breakwaters (for example Sumer and Fredsøe, 1997; Fredsøe and Sumer, 1997; Sutherland et al., 1999; Sumer and Fredsøe, 2000; Sanchez-Arcilla et al., 2000, Sumer et al., 2001a), there has been relatively little research on scouring around low crested breakwaters, especially on sandy seabeds near the coast. Stimulating investigations carried out in wave flumes using scour data obtained at roundheads and the trunks of low crested breakwaters (Sumer et al., 2005; Kramer et al., 2005) and scouring around spherical bodies and self-burial (Truelsen et al., 2005) are interesting exceptions. Nevertheless, field studies have been rare (Olsson and Pattiaratchi, 2008), and only a few real case results have been presented, including, for example, the subsidence of Accropodes due to scouring at the toe of a breakwater (Bartels et al., 2000). For a more detailed review, see Muñoz-Perez et al. (2015).

Unlike scour, neither settlement nor sinking is typically measured; these data cannot be found even in the exhaustive data for low crested structures compiled by Lamberti et al. (2005). Therefore, laboratory experiments have become one of the relatively least expensive ways to study scouring and sinking phenomena. Nevertheless, inevitable problems related to scaling effects (Dalrymple, 1988; Dean and Dalrymple, 1991; Hughes, 1993) are encountered when modelling the physics of sandy bottoms.

A case study of the settlement and sinking of a submerged structure composed of precast concrete modules was conducted and monitored in 2005 on the sandy coast of the Santa Maria del Mar beach (SMM), Spain (Medina et al., 2006; Muñoz-Perez and Medina, 2010; Muñoz-Perez et al., 2014). Moreover, a new methodology using pressure sensors attached to the modules was implemented to monitor the sinking. Unexpectedly, the average sinking speed was extremely rapid (approximately 3–6 cm/day), and the structure submerged to 50% of its height in 3 to 6 weeks (Muñoz-Perez et al., 2015). However, the actual causes of the structural failures and sinking were unknown. Therefore, to gain insights into the origin of these problems, a three-dimensional physical modelling study was conducted in 2014 at the Laboratorio Nacional Engenharia Civil (LNEC), Lisbon (Portugal).

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The aim of this paper is to present the results of the physical modelling and compare them with the prototype monitoring results to develop possible explanations of the sinking of submerged concrete modules into a sandy bottom. Furthermore, the validity of laboratory tests for this type of case and further improvements in the design and construction of submerged modular breakwaters will be discussed.

2. Physical model tests

2.1. Model setup

The experimental investigation was conducted in a 15 m long wave basin with an operating width of 3.0 m at the Laboratorio Nacional de Engenharia Civil (LNEC) in Lisbon, Portugal. The model was built and operated according to Froude's similarity law, with a geometrical scale of 1:20.

To simulate the real wave conditions surveyed during the first 24 days of the monitoring period in 2005, a sequence of eight representative field wave climates (WCs 1 to 8) was chosen from the wave conditions (Nov. 12–Dec. 5, 2005; Fig. 1). Each representative WC was obtained as the time-averaged values of Hs and Tp. Because WC7 was found to produce breaking waves during the experiment, a new wave condition (WC9) was subsequently introduced to check the influence of highest non-breaking wave on the bed morphology. The duration of each WC simulation test represented a single day in the prototype (Table 1).

The sequence of WCs was simulated for two selected water depths (WDs) to check the effects of different tidal levels. The WD was 3.0 m and 6.5 m at the position of the structure at the lower low water level (LLWL) and higher high water level (HHWL), respectively (Khan-Mozahedy et al., 2015). Therefore, the corresponding chosen WDs were 15 cm and 32.5 cm, respectively, in the model scale (1:20) at the position of the structure in the wave basin. Each WC had sequences of 24 min duration in the model, with each one assuring a series length with at least 500 irregular waves simulated by a Jonswap spectrum with a peak enhancement factor of 2.0, according to the actual sea state measurements from the Cadiz buoy located in front of the SMM Beach (data from www.puertos.es). Applying the morphological timescale suggested by Van Rijn et al. (2011) (see their equation 4.2), considering that the model sediments are lightweight crushed pumice stone (with density equal to 1.43 kg/m^3) and that the vertical to horizontal model scale distortion was also calculated according to their equation 4.3, the morphological time scale equals 1:60, and the 24 min series duration corresponds to 1 day in nature.

Table 1
Wave parameters of the chosen WCs at the prototype and model scales.

WCs	Dates of monitoring (2005)	No. of days/tests	Chosen WCs in prototype		WCs in model scale	
			Significant height, Hs (m)	Peak period, Tp (s)	Significant height, Hs (cm)	Peak period, Tp (s)
WC1	Nov. 12–17	6	1.0	6	5.0	1.3
WC2	Nov. 18–23	6	1.5	10	7.5	2.2
WC3	Nov. 24–25	2	0.5	6	2.5	1.3
WC4	Nov. 26–27	2	1.0	6	5.0	1.3
WC5	Nov. 28–29	2	0.5	12	2.5	2.7
WC6	Nov. 30–Dec.1	2	1.0	12	5.0	2.7
WC7	Dec. 2–3	2	3.0	8	15.0	1.8
WC8	Dec. 4–5	2	1.0	10	5.0	2.2
WC9	–	–	2.5	8	12.5	1.8

The beach was reproduced in the wave basin with a constant slope of 1:34, corresponding to the medium slope of the SMM beach (Fig. 2). The bed was reproduced at the beginning of each sequence of the WCs in this modelling study. The median size (D_{50}) of the SMM beach sand (specific gravity of 2.6) close to the deployed submerged breakwater was 0.23 mm (Muñoz-Perez et al., 2015). Because scaling the beach sand size using a sediment of equal density would entail the use of fine silt, which could no longer be considered a non-cohesive sediment, pumice stone, which has a specific gravity of 1.43 and $D_{50} = 1.6$ mm, was selected for the tests. The characteristics of this light weight sediment (LWS) under the laboratory hydrodynamic conditions were determined and compared with the prototype sand to check its suitability for this modelling study. Fig. 3 shows the most relevant non-dimensional parameters for the present study, namely the particle Reynolds number ($Re^* = u_b D_{50}/\nu$) and the Shields parameter ($\theta = u_b^2/g(s-1)D_{50}$), where u_b is the wave maximum oscillatory velocity at the bed, ν is the fluid viscosity, and s is the relative density of the sediment.

The Shields parameter, which is related to the densimetric Froude number and the mobility parameter by the friction coefficient and a constant (e.g., Nielsen, 1992), was used to scale the sediment characteristics because this parameter is commonly used to scale the initiation of motion and suspended sediment transport (e.g., Sumer and Fredsøe,

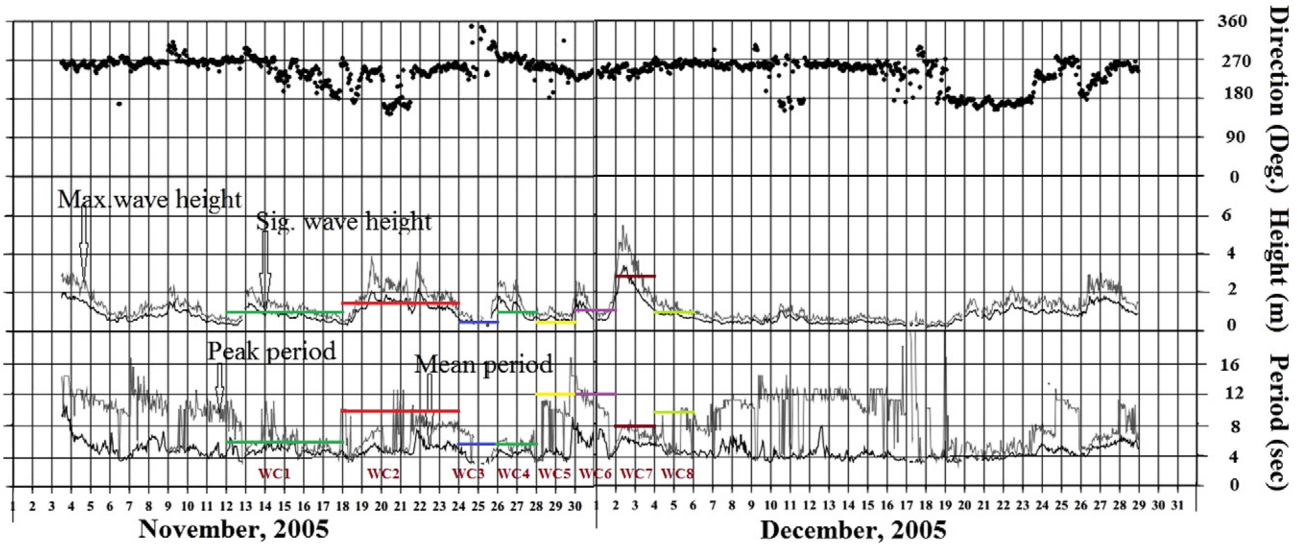

Fig. 1. Field-site wave parameters during the monitoring period and the sequence of wave conditions (WC) chosen for the modelling study: Top panel — wave direction (dotted line); Middle panel — maximum (grey line) and significant (black line) wave heights; Bottom panel — peak (grey line) and mean (black line) wave periods. The bottom panel also shows representative Hs and Tp for each of the WC (in different colours).