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Effects of gradation on the long-shore transport processes and reshaping of rubble mound breakwaters under construction exposed to head-on and oblique waves

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ABSTRACT

Breakwaters under construction are prone to undesired reshaping because their core is not designed to withstand severe or moderate wave loads. While the reshaping of a finished breakwater was subject of comprehensive research, few studies dealt specifically with the reshaping mechanisms of a breakwater under construction, i.e. of the breakwater core. This paper presents a set of experimental tests focused on the reshaping of rubble mound breakwater trunks and roundheads undergone during the construction phase. The study accounts for oblique wave attacks and grading of the construction material. Better insights on how and how far such reshaping takes place are derived in the perspective of providing coastal designers and constructors with valuable information for optimising the selection of the fractions and volumes of the construction materials and for taking into account potential damages within the construction schedule and therefore additional costs.

1. Introduction

In the breakwater design phase little attention is often paid to hydraulic loads during the construction phase, when the core material and other under-layers can be exposed to storm conditions for long periods of time before the upper protective layers are applied. Breakwater damage — in the form of reshaping — and material losses are serious concerns for contractors since they requires additional materials and lead to increased construction time.

An extensive number of previous studies analysed the stability of rock slopes and berm breakwaters via the stability number (a. o. Van Hijum and Pilarczyk, 1982; Van der Meer, 1988, 1992; Lamberti and Tomasicchio, 1997; Merli, 2009; Merli et al., 2013; Sigurdarson and Van der Meer, 2011, 2013; Thomsen et al., 2014). This research examined in details the breakwater reshaping for the trunk section under 2D waves. Since then, a set of parameters has been used to describe the deformed equilibrium profile: local origin (intersection of the profile and still water level), crest point (upper point of the beach crest), and step point (gentle to steep sloping transition). Research into the 3-dimensional stability of reshaping breakwaters was presented by Burcharth and Frigaard (1988) and Alikhani et al. (1996); a systematic experimental analysis of berm breakwaters under 3D wave attacks was performed by Lykke Andersen (2006).

Some research was also performed on roundheads for rock armour by Vidal et al. (1991) and Matsumi et al. (1994, 1996, 1998, 2000), for concrete armour units by Jensen (1984) and Maciñeira and Burcharth (2008), and for low crested rubble mound breakwaters by Burcharth et al. (2006).

Few specific studies were carried out considering breakwaters under construction. Hendry (1983) presented basin model studies undertaken to assess the optimum sequence of construction for breakwater extensions and new breakwaters, with reference to the Gansbaai Harbour in South Africa, East of Cape Town. Gillman (1987) presented the results of the damage to the North Breakwater roundhead when half constructed for the St. George Breakwater in Alaska.

More recent works analysed the temporary stability of the submerged portion of a breakwater roundhead (Van Gent and Van der Werf, 2011) and the damage to breakwater cores and roundheads (Curto, 2014; Mulders, 2010; Mulders and Verhagen, 2012) with

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varying stone grading in 3D conditions. An in-depth analysis to quantify the erosion volumes along a breakwater under construction was performed by Todd and Schepis (2013). Comola et al. (2014) performed an experimental investigation of the damage pattern and progression on a rock armoured breakwater roundhead subjected to multidirectional waves, with specific focus on the effects of wave loads (heights, periods), wave obliquity and wave spectrum characteristics. They developed also a probabilistic approach to predict for a typical roundhead geometry the damage distribution depending on the incoming waves and structural characteristics and derived a formula for the distribution of damage over the roundhead.

The tests by Van Gent and Van der Werf (2011) investigated the effects of different water levels, wave angles (long-crested waves) and structure slopes for a completed and a temporary roundhead. The results showed that

- the distribution of damage is similar for both structure slopes (1:1.5, 1:2); for the temporary roundhead the more damaged segment is the one adjacent to the trunk;
- the amount of damage in terms of percentage of displaced stones is also similar for the two slopes; for the temporary roundheads it is generally lower with a 1:1.5 slope than with a 1:2 slope (e.g. about a factor of 3); and
- differently from the completed roundhead, for the temporary roundhead the damage increases with increasing water level.

The tests by Todd and Schepis (2013) examined the patterns and volumes of the transported material at the trunk, roundhead and causeway of a breakwater under construction in 3D conditions under different wave attacks with a single wave direction. Their main outcomes — that are presented in terms of qualitative damage evolution only — can be synthesized as follows:

- the loss of core material occurs at the exposed construction face, with a distinct wash away line that cuts across the breakwater in the direction of wave propagation and is close to the trunk/roundhead conjunction, similarly to the results by Van Gent and Van der Werf (2011);
- the filter and armour stones, once displaced from the seaward face of the breakwater, mix with the core material and are transported across the breakwater to the lee side without providing any significant effect on the stability of the top core.

The aim of this paper is to analyse the influence of wide stone grading on rubble mound breakwaters under construction, considering also the effects of wave obliquity and wave loads. The reshaping of both trunk and roundheads and the long-shore sediment transport processes are examined in order to derive best practices for the selection of the mixture combining costs and stability. This paper synthesizes and discusses the 3D experimental results on the stability of trunks and roundheads by Mulders (2010), Mulders and Verhagen (2012), Curto (2014).

The paper therefore aims at answering the following main research question: How and how far does the exposed core of a breakwater under construction reshape to wave attack?

The following more specific research sub-questions are also examined at once:

- Do different material gradings (narrow vs. wide) cause different reshaping patterns?
- Does the material suffer any changes of its packing density during reshaping?
- Do different wave loads (low vs. high wave height) and angles of wave attack (head-on vs. oblique waves) have different impacts on reshaping and long-shore transport?
- Is there a dominant reshaping mechanism such as cross-shore or long-shore transport?

The paper first describes the experimental facility, the models and the measurements in Section 2. In Section 3 the stone transport mechanisms, including material sorting and packing, are described; the long-shore transport at the trunk and the total volume change of the breakwater are also quantified. The reshaping of the trunk and of the roundhead sections are presented respectively in Sections 4 and 5. The results for the trunk section are compared with the literature available for reshaping berm breakwaters: the deformation of the trunk is synthesized through the parameters for the crest and the step height and length, and the related stone long-shore transport is compared with available existing formulae. The results for the roundheads are presented through a sensitivity analysis of the percentage volume changes to the wave load, the wave obliquity and the gradation. The relevance of the results for the construction phase is shortly discussed in Section 6. Some conclusions and recommendations are finally drawn in Section 7.

2. Description of the experimental set-up

This section describes the facility (Section 2.1), the physical model of the breakwater including the material type and the two gradings (Section 2.2), the tested wave conditions (Section 2.3), the measurements and the methodology of analysis (Section 2.4).

2.1. The facility

Tests were carried out in the wave basin at the Water Lab of Delft University of Technology. The basin is 28.6 m long, 15.0 m wide and 0.60 m deep. The concrete bed is horizontal until halfway a transition takes place into a 1:30 sloping beach. Upwards the beach a layer of coarse rubble was placed in order to dampen the waves and minimize the reflection back to the breakwater. For the same reason the side walls of the basin were covered with a sloping layer of coarse rubble.

The wave generator consists of three hydraulic piston-type paddles whose length is 5 m each and maximum stroke is 0.26 m. They are used to generate all kinds of waves, regular and irregular, and they are synchronized to produce long crested waves, resulting in perpendicular wave generation. As the wave generators are not equipped with an active absorption system, the waves reflected by the model are re-reflected inside the basin and towards the structure again, and may result in higher incident wave energies and prematurely breaking of higher waves. However the formation of standing waves can be avoided by testing structures whose length is significantly smaller than the basin width and in this case, to minimize the occurrence of standing waves even further, the signal sent to the generator was set at 90% capacity.

2.2. Experimental set-up

The breakwater model in 1:20 scale was characterised by a 0.55 m wide and high trunk crest, 2:3 slopes, footprint length and width respectively of 6.7 m and 2.2 m (see the cross sections and the plan view respectively in Figs. 1 and 2). The radii of respectively the crest and the base of the roundhead were 0.275 m and 1.1 m. In the schemes reported in Fig. 1 the trunk test section is represented by the hatched part. Two 0.10 m wide stripes filled with dyed stones were designed for visual measurements of the long-shore transport.

The scale of the model was mainly determined by the available size of the basin. With the used 1:20 scale it was possible to measure wave height with sufficient accuracy as well as determine the transport of the model stones. Because dealing with stones, even on a scale 1:20, no laminar porous flow occurs in the model.

The structure was realized by combining four sections: two middle (i.e. half-trunk) parts with a length of 1.75 m each and two end (i.e.