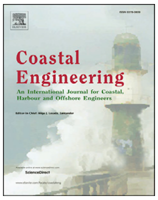
Coastal Engineering 135 (2018) 39–54

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng



Stability of rubble-mound breakwaters under tsunami first impact and overflow based on laboratory experiments

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ARTICLE INFO

Keywords:
Tsunami
Laboratory experiments
Stability
Breakwater
Solitary wave

ABSTRACT

Recent tragic tsunami events, like those that occurred in the Indian Ocean in 2004, and in Japan in 2011, have revealed the need of further work to reduce tsunami risk in coastal areas. An important aspect towards risk reduction is the study of the interaction between tsunami waves and coastal structures as these are the first to receive the tsunami's energy. Dikes and breakwaters must have an adequate structural behavior and maintain some functionality and operability under tsunami attacks to be able to contribute to the reduction of its consequences. Within this scope, laboratory experiments on scaled models of two typical Mediterranean rubble-mound breakwater typologies under tsunami waves were conducted for the first time. The tsunami's action was split into 2 parts: (1) the first impact of solitons was tested by means of large solitary waves and, (2) the subsequent overflow was approached by applying a pump-driven wave maker. The damage on the breakwaters due to these actions was measured and assessed. The result is an in-deep analysis of the relationships among Stability Number, Damage Level and Number of tsunami waves. The outcome of this analysis includes the development of a set of formulae that provide, in the range of the conducted tests, the value of the Damage Parameter, so that tsunami actions can be taken into account in the design of rubble mound structures. Finally, based on the results of these experiments, the threshold values of the Damage Parameter used to characterize damage in armors (Initiation of damage, initiation of destruction, destruction) was particularized for tsunami actions.

1. Introduction

Tsunamis are relatively infrequent but very destructive phenomena that can have devastating consequences in coastal areas. The magnitude of these consequences has been observed during the last decade, with events as the ones which occurred in the Indian Ocean in 2004 and in Japan in 2011. In view of these tragic episodes, the scientific community is strengthening its efforts to develop strategies to mitigate the risk of tsunami.

One possible mitigation strategy focuses on improving coastal structures, as they play an important role in diminishing tsunami wave impacts (Takagi et al., 2014) since they stand as the first defense barrier at the coastline. As an example, Tomita et al. (2012) presented a work developed after the 2011 tsunami event in Japan, in which the presence of harbor structures at Kamaishi port played an active role in decreasing the destructive effect of the tsunami wave. Although breakwaters at Kamaishi port were partially destroyed, they delayed the arrival of the wave to land by six minutes, reducing the inundation area considerably.

Field surveys have already revealed the different hydraulic performance of vertical and rubble-mound breakwaters during tsunami events. Indeed, the response of vertical concrete structures has already been addressed by several authors, e.g. Asakura et al. (2002), Kato et al. (2006), Mizutani and Imamura (2001). However, the effectiveness and stability of rubble-mound breakwaters (RMBs) during tsunami events have not been sufficiently studied. RMBs are usually designed to resist the wave loads generated by wind waves, but tsunami wave loads are rarely considered in their design.

Stability analyses of RMBs have been traditionally performed for storm waves through scaled laboratory models resulting in empirical formulae. The limitations of initial works such as those of Iribarren (1938) and Hudson (1959), were overcome by Losada and Giménez Curto (1979) and Van der Meer (1987) who introduced the role of wave parameters, such as wave period, number of waves, or water depth in the determination of armor units weight. More recent works focused on presenting improvements to Van der Meer's (1987) formulation (i.e.: Vidal et al., 2006; Etemad-Shahidi and Bali, 2012) or introducing new

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https://doi.org/10.1016/j.coastaleng.2018.01.004
Received 11 August 2017; Received in revised form 28 December 2017; Accepted 13 January 2018

physics, such as the incident wave direction (i.e.: van Gent, 2014).

However, knowledge on armor unit stability design for storm wave loads, cannot be extended to tsunami waves, mainly because the hydraulic loads are applied differently. Tsunamis can produce violent impulsive forces Nistor et al. (2009), when the wave crest impacts the breakwater. Apart from the wave loads exerted upon the monolithic parts of the RMBs, such as the crown-walls, large wave drag loads are developed at the armor units. Although gravitational forces are opposed to the action of drag forces at the seaward slope during wave rush up, some armor units can be eventually extracted. The tsunami wave crest is then followed by a continuous wave overflow, acting at the leeside slope for several minutes. It can induce breakwater structural failure leeward, mainly by scour at the crown-wall foundation and especially due to the extraction of units (Kato et al., 2012). The latter is produced by the combined effect of flow-induced drag forces on the units and gravitational forces. This process can be repeated several times during a tsunami event, due to the arrival of all the waves that form it (Royer and Reid, 1971). Other features, such as the flow established across the breakwater's core due to the large hydraulic gradient developed by the different water level at both sides of the breakwater during wave overflow, are also relevant to determine armor unit stability, especially at the leeside slope.

One of the first studies presenting formulations to quantify the weight to design stable armor units in RMBs for tsunami waves was the one presented by Esteban et al. (2012). They proposed using the tsunami's wave height in Hudson’s (1959) formulation, as a first approach to calculate armor unit size to design tsunami resilient structures. The formulation was derived from laboratory experiments and observations from field surveys, after the 2011 event in Japan.

Field surveys conducted during the last decade after each tsunami event have provided very valuable information about the behavior of coastal structures (Synolakis and Kong, 2006; Okal et al., 2006; Mori and Takahashi, 2012; Mikami et al., 2012; Arikawa et al., 2012). However, several features, such as the low frequency of tsunami occurrence, the singularity of the localities where they occur, or the uncertainty regarding the real state of coastal structures before they take place, among others, result in data from field surveys being insufficient. As a conclusion, they cannot be used to derive a general hydraulic response of coastal structures under tsunami wave loading. In addition, several works, such as Esteban et al. (2014), highlighted the necessity of further work to better understand breakwater behavior. Specifically, the necessity of new laboratory experiments with a realistic generation of tsunami waves was pointed out as a valuable approach to complement field surveys. Some approaches have been presented in the last years to analyze tsunami wave interaction with RMBs, such as Hanzawa et al., in 2012 on detached rubble-mound breakwaters, Harbitz et al., 2016 and Guler et al., 2015, on a scaled model of the Haydarpasa port in Istanbul, Turkey. These works were a step forward in the study of the interaction between RMB and tsunami waves, but new studies are needed to extend the results to other typologies, configurations and flow behaviors, focused on covering not only the hydrodynamics but also the stability analysis of the armor units at an adequate scale.

Solitary waves have been frequently used in laboratory experiments to simulate tsunami waves, (Synolakis, 1987; Borthwick et al., 2006; Esteban et al., 2014). However, tsunami wave hydrodynamics are somehow incomplete using solitary waves (Madsen et al., 2008) since the “tail” of the tsunami, which propagates after the wave crest, is not included in the solitary wave shape. Recent studies have proposed more sophisticated approaches based on the use of different wave profiles, as discussed by Kanoglu et al. (2015). Accordingly, Rossetto et al. (2011) and Goseberg et al. (2013) used a pneumatic and a pump-driven wave maker, respectively, to get a better representation of not only the wave crest, but also the tail, to reproduce tsunami wave profiles measured in the field. More recently, Schimmels et al. (2016) generated more realistic wave profiles using real tsunami records generated with a piston type wavemaker, improving tsunami wave representation, especially at the crest. Although important improvements have been made in the last years, none of them can provide a complete representation of the whole tsunami wave, especially at a large scale. Existing methods are only feasible at small scales, which are not applicable to the scenario demanded by the analysis of armor unit stability. Large laboratory scale analyses are needed to avoid scale effects in order to preserve turbulent flow conditions inside the RMBs ((Hughes, 1993; Frostick et al., 2011).

The work presented in this paper is focused on gaining a better understanding on the interaction between tsunami waves and RMBs, with the aim of improving the existing knowledge about armor unit stability. The work analyzes not only the damage produced by the first tsunami wave on the armored layers but also presents new formulations to design stable armor ones. Laboratory experiments on scaled models were conducted on rubble mound breakwaters. Due to the unfeasibility of reproducing the full tsunami length, the tsunami wave was reproduced simulating first wave impacts and the wave overflow separately. Armor damage caused by the first leading waves in a tsunami event was simulated by means of solitary waves. Next, tsunami overflow was simulated by creating an overflow current. Two RBMs, with and without a crown-wall on the breakwater crest were tested. Sections reproduce two breakwaters representative of marinas and fishing ports in the Spanish Mediterranean coast at a 1:20 scale.

The 1:20 scale used allows to conduct the stability assessment appropriately, while the dual modeling of the tsunami wave (solitary waves and steady currents) allows to analyze the structure's behavior accurately. Even though the number of experiments was limited, their robustness and the results obtained allow them to be used as a first step in the elaboration of a database to calculate the stability of structures against tsunamis. In addition, based on the results of these experiments, the threshold values of the Parameter of Damage used to characterize damage in armors (Initiation of damage, initiation of destruction, destruction) was particularized for tsunami actions.

The paper is structured as follows: Section 2 describes the experimental set-up; section 3 presents the experimental results; section 4 analyses the results and presents some empirical formulas for stability including an example of their application, and finally, section 5 presents the conclusions drawn from the study.

2. Experimental set up

Two different RMB cross-sections were tested. They were defined to represent the classical design and dimensions of a breakwater in a marina in the Mediterranean Spanish coast (MOPU, 1988). Although destructive tsunamis have been recorded historically in this region, (Papadopoulos, 2016), their hydraulic loading is not considered in conventional structural designs. Marina breakwaters are mainly built in shallow areas using quarry stones. The slopes are usually 1/3 to ensure quarry stone stability. They are designed with a low crest, sometimes with a crown-wall on top, with most of them being overtopped during large storm events. This aspect makes these structures highly vulnerable in a potential tsunami event.

Experiments were performed at the University of Cantabria (Spain) facilities. The COCOTsu (Wave-Current-Tsunami) flume located at the Environmental Hydraulics Institute (IHCantabria) laboratory was used. The flume is 52 m long, 2 m wide and 2.5 m high. Model structures were built inside the 24-m long testing area with transparent side walls and bottom. The flume is equipped with a 2 m-stroke piston wavemaker capable of generating long waves as the ones used in the present tests. At the same time, this facility is also capable of generating currents due to a pumping system that can work under wave action. The flume's bottom is not horizontal. It is 0.35 m deeper at the wavemaker location than at the test area. A 1/13.5 sloped ramp connects both sections, as shown in Fig. 1. Tests were performed using a water depth of 0.4 m on the testing section (0.75 m at the wavemaker).