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Deformation of rubble-mound breakwaters under cyclic loads

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ABSTRACT

Rubble-mound breakwaters usually consist of a core of small quarry-run rock protected by one or more intermediate layers or underlayers that separate the core from the cover layers, which are composed of large armor units. Failure of rubble-mound breakwaters may be due to effects such as removal or damage of the armor units, overtopping leading to scouring, toe erosion, loss of the core material, or foundation problems under waves. However, whether rubble mounds fail under seismic loads is unknown. High seismic activity can lead to large settlements and even to failure of the breakwaters. The design of coastal structures should take into account the most relevant factors in each case, including seismic loading. The objective of this study is to understanding the failure mechanisms of conventional breakwater structures under seismic loads on rigid foundations. Hence, an experimental study was carried out on conventional breakwater structures with and without toes, subjected to different dynamic loadings of variable frequencies and amplitudes, in a shaking tank. A shaking tank with a single degree of freedom was developed to study the simple responses of conventional rubble-mound breakwaters under cyclic loads. For each test, an automatic raining crane system was used to achieve the same relative density and porosity of the core material. The input motion induced horizontal accelerations of different magnitudes during the tests. The accelerations and the deformation phases of the model were measured by a data acquisition system and an image processing system. The experiments on the conventional rubble-mound type breakwater model were performed under rigid-bottom conditions. The model's scale was 1:50. Cyclic responses of breakwaters with toes and without toes were examined separately, and their behaviors were compared. The results were compared with a numerical study, and the material properties and failure modes were thus defined.

1. Introduction

In the past 20 years, many port structures have failed due to earthquakes, including events in Los Angeles, USA, in 1994; Kobe, Japan, in 1995; Kocaeli, Turkey, in 1999; Athens, Greece, in 1999; Taiwan in 1999; and Southeast Asia in 2003. However, these earthquakes provided valuable information about the seismic response of port structures. The occurrence of an earthquake near a port is a rare event, compared to the frequency of storms, but its economic impact can be so devastating that it is a matter of international and national interest. For example, the settlement of a breakwater can allow wave transmission into a port basin and impede operations.

Breakwaters are generally designed to limit wave penetration and wave overtopping during specific design storms. They are also designed to resist the related wave actions. It is unlikely that a major earthquake would occur simultaneously with a design sea state, because the two events are not typically related. Consequently, designed-storm wave action and an earthquake can be treated as two independent load situations. Only wave actions from a moderate sea state should be considered together with design earthquakes. Decisions on this sea state must be made based on the site-specific, long-term statistics of the storm. The responses of rubble-mound breakwaters to seismic actions have received little attention thus far. However, PIANC (2001) did give a very short discussion about the performance of rubble-mound breakwaters under earthquake loading. It defined several types of earthquake-induced failure modes:

- Crest lowering due to shake down of rubble material, causing differential settlement of superstructure elements (Fig. 1a).
- Crest lowering and lateral spreading due to settlement or liquefaction of subsoil, causing differential settlement of superstructure elements (Fig. 1b).
- Failures due to liquefaction of subsoil. Subsequent lowering of crest leading to possible tilt and displacement of superstructure elements (Fig. 1c).

Failures of rubble-mound breakwaters due to seismic loading have been reported in the past, especially for cases where the structures were built on poor soil (Memos et al., 2000, Yuksel et al., 2003, 2004, Sumer et al., 2007). A limited number of publications deal with the modeling of the seismic responses of rubble-mound breakwaters. Most studies address the estimation of hydrodynamic pressure on the

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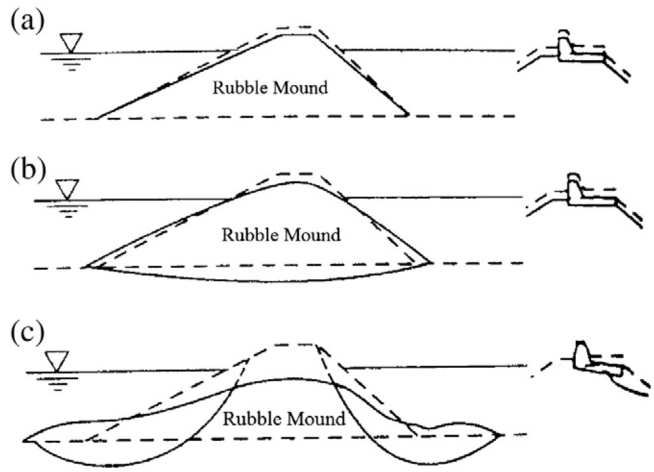

Fig. 1. Typical failure modes for rubble-mound breakwaters (PIANC, 2001).

slopes of earth embankments. However, dams are structures that are very similar to rubble-mound breakwaters, although there are differences between the two types of structures. The main differences are that dams are designed as very firm and impermeable structures, in contrast to rubble-mound breakwaters. Dams retain water on one side only, whereas breakwaters are wet on both sides. Dams also sit on firm foundations, whereas in many cases breakwaters are located on soft foundations. Embankment structures of breakwaters, such as granular core materials, are also different from dams. In some cases, heavy cranes also operate on the superstructural elements over the breakwaters. In most situations, only limited overtopping is tolerated, so most transmission occurs internally, whereas dams never allow transmission. Dams are constructed under dry conditions on solid foundations, whereas breakwaters are constructed in wet conditions. The bulk of the breakwater cross-section is composed of a relatively dense rockfill core armored with one or two layers of rock or one of the numerous types of precast-concrete armor units. The outer layer is referred to as the primary cover layer.

Experimental and numerical studies are very limited in terms of the response of rubble-mound breakwaters under seismic loading; these include Wang et al. (1978), Memos and Protonotarios (1992), Memos et al. (2000), Memos et al. (2003), and Yuksel et al.(2004). In one of the interesting research works on rubble-mound breakwaters under seismic loads, Memos et al. (2000) investigated the stability of rubble-mound breakwaters under earthquake action. They found that the failure of rubble-mound breakwaters became more severe when liquefaction of the base occurred. Additionally, amplification developed within the loose foundation soil underlying the structure.

Memos et al. (2003) also performed shaking-table experiments on rubble-mound breakwaters and developed a numerical code to predict the hydrodynamic pressures on the faces of the breakwater. Their models were subjected to horizontal shaking ranging from 0.063 g to 1.553 g on breakwaters with soft foundations. They concluded that the weak foundation soils induced large deformations of the structure even under moderate seismic intensity. However, they did not consider slope erosion or volumetric deformations of the breakwater bodies under seismic loads.

Yuksel et al. (2004) analyzed the seismic response of a breakwater placed at a fishery port after the Kocaeli earthquake in 1999 (Fig. 2). The damage to the rubble-mound breakwater is shown in Fig. 3. Large settlements, on the order of 1.5 m, were observed at the seaside of the breakwater. The damage was mostly in the form of flattening of the cross section and sliding of the slope. Numerical results agreed with measurements of cross-sections of the liquefied foundation.

Sumer et al. (2007) also reviewed earthquake-induced liquefaction around marine structures. They summarized the impact of earthquakes on marine structures (such as rubble-mound breakwaters) based on field observations.

Yuksel et al. (2007) studied the seismic responses of rubble-mound breakwater and presented preliminary results from physical models of a rubble mound sitting on a rigid foundation. They compared the failures for homogenous and conventional mounds seated on a rigid bottom. A homogenous model was found to be more rigid than the conventional breakwater under their experimental conditions, but they drew their primary conclusions about the seismic response of the rubble-mound breakwaters.

This paper reports an experimental and numerical study on two types of rubble-mound breakwaters on a rigid foundation to understand the simple physical behavior of the rubble mound bodies under different cyclic loadings. The experiments were performed with two types of model breakwaters, with toe (Type I) and without toe (Type II), in 1-g shaking table tests.

2. Experimental study

The experiments were performed in a shaking tank. A schematic representation of the shaking tank is given in Fig. 4. The shaking tank was 4.5 m long, 1.0 m wide and 1.0 m deep. The tank was steel, with one side of glass. Wave absorbers were located at both ends of the tank to eliminate water reflections due to the cyclic response of the tank and allowed only one degree of freedom in the longitudinal direction.

Physical models for the breakwaters were constructed to be geometrically similar to the full-size structure. It was assumed that, because gravitational forces dominate, models should be scaled with the Froude model law. Therefore, viscous forces were made negligible by selecting linear scales of sufficient size and by careful selection of the core material for the model.

Physical models are mostly conducted at scales much smaller than full scale. Using small-scale models enables more-rapid gathering of

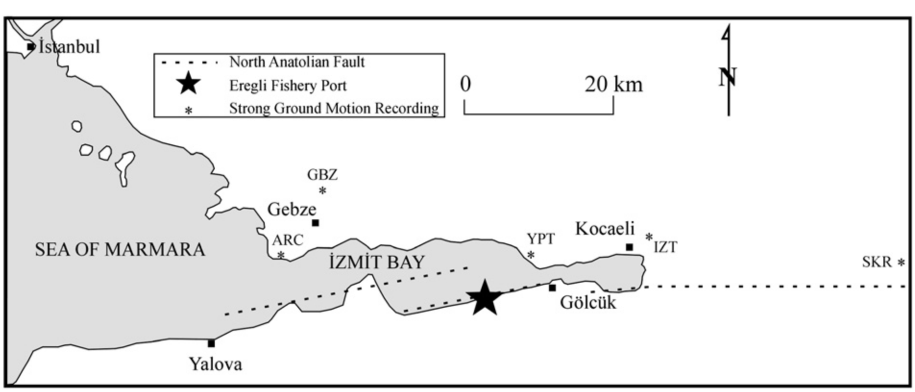

Fig. 2. Case history site map and the location of the Eregli Fishery Port Breakwater (Yuksel et al., 2004).