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Centrifuge model tests and large deformation analyses of a breakwater subject to combined effects of tsunami

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ABSTRACT

In this study, centrifuge model tests and effective stress analyses are performed on a tsunami-affected breakwater similar to those that were seriously damaged during the magnitude-9.0 East Japan Earthquake in 2011. The centrifuge model tests are performed at a scale of 1/200 to simulate the failure of the breakwater. This study is a significant improvement on a previous one [1] by the same authors. The centrifuge model tests now allow the seepage flow to be blocked as well as admitted, and the effective stress analyses are now performed based on the finite strain formulation in order to take large deformations into account instead of just the infinitesimal strain formulation that is applicable only to small displacements. Both the centrifuge model tests and the effective stress analyses demonstrate the important part played by the seepage of pore water in the failure of the rubble mound, in addition to the wave force of the tsunami action. In particular, it is shown that the breakwater damage of 2011 could have been prevented or at least mitigated by preventing seepage flow in the rubble mound.

1. Introduction

An earthquake of magnitude 9.0, as measured by the Japan Meteorological Agency (JMA), occurred off the northeastern coast of Japan at 14:46 JST on March 11, 2011. The JMA named it “The 2011 off the Pacific coast of Tohoku Earthquake” (hereafter, the 2011 East Japan Earthquake). This is the greatest earthquake in magnitude to affect Japan since modern earthquake monitoring systems were established there.

The recorded heights of the tsunamis triggered by the earthquake were higher than 7.3 m at Soma, higher than 4.2 m at Oarai, and higher than 4.1 m at Kamaishi. Moreover, the impact of the tsunamis was the strongest since the existing design methodology was adopted for breakwaters. The existing design methodology of a breakwater is based on the limit equilibrium by considering the wave force acting on the lateral side and the additional pressure acting underneath the caisson [2], as shown in Fig. 1. The wave pressure on the lateral side is given as a linear distribution using the following values: the effective height above the still-water level, η^*; the intensities p_1, p_2, and p_3 of the wave pressure at the still-water level, the sea bottom, and the toe of the caisson, respectively; and the water depths h, d, and h' in front of the caisson, the crest of the mound, and the toe of the caisson, respectively. The uplift pressure acting at the bottom of the caisson is described by a triangular distribution with the pressure intensity p_u at the front toe.

The most typical example of damage to a breakwater was the damage at the Kamaishi Harbor [3,4]. The breakwater there was designed specifically to protect against the impact of a tsunami. It was constructed at the mouth of Kamaishi Harbor at a depth of 63 m or less and over a length of 990 m in the northern part and 670 m in the southern part with an opening of 300 m in between. However, the breakwater was devastated by the tsunami. This may have partially resulted from the inadequacies in the design procedure used at the time, but it was nevertheless characteristic of the serious damage that can be caused by a tsunami.

Fig. 2 shows a typical cross section of the breakwater, which comprises a caisson and a rubble mound. Based on video data recorded from the coastline, the first arrival of the tsunami was at 15:24 (about 40 min after the earthquake occurred), and did not damage the breakwater.

However, there was a continuous overtopping of water at the top of the breakwater. The video data for 15:32, when the height of the tsunami had decreased, shows the breakwater to be seriously damaged. By 15:59, the damage had progressed further and many of the caissons fell into the harbor side from the rubble mound. The mound itself was seriously damaged to such an extent that about half of it was lost.

In order to investigate the primary mechanism for this type of breakwater failure due to a tsunami, we have performed a series of

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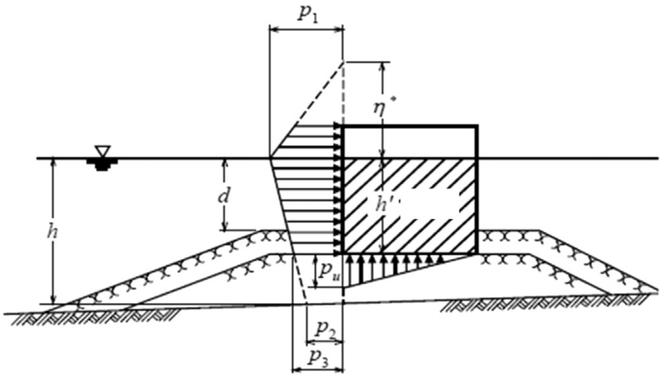

Fig. 1. Current breakwater design [2].

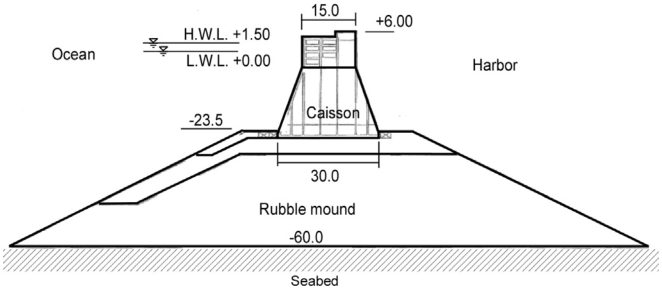

Fig. 2. Cross section of a composite breakwater at Kamaishi Harbor (units in m).

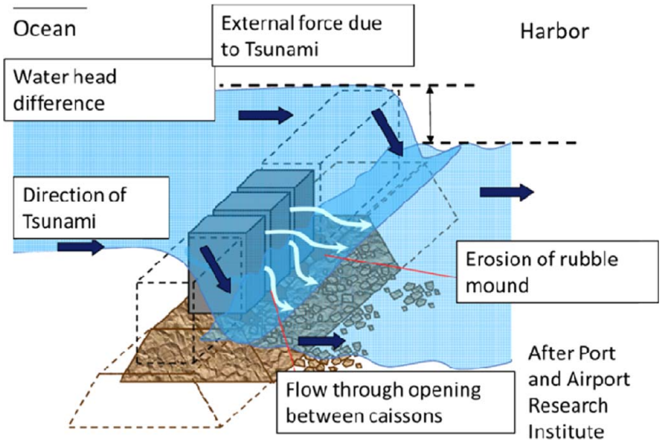

Fig. 3. Primary failure mechanism hypothesized by hydrodynamics experts (modified after [5]).

centrifuge model tests and effective stress analyses. As a straightforward extension of the existing design procedure shown in Fig. 1, a group of experts in hydrodynamics considered the primary mechanism of failure to have been erosion of the rubble mound by water flowing through the openings between the caissons [3–5], as shown in Fig. 3. In parallel to the efforts of that group, this study was performed with the aim of evaluating the effect of seepage flow through the rubble mound due to the water head difference caused by the tsunami in combination with the wave force action.

We previously reported preliminary results on the combined failure mechanism of a model breakwater subject to a simulated tsunami [1]. In that study, Silica No. 4 sand was used as the material for the rubble mound, in addition to Silica No. 1 sand, to reduce the effect of seepage flow into the rubble mound. Even so, seepage still existed and it was difficult to evaluate its effects or otherwise. In the previous study, both cases with Silica No. 1 and No. 4 sands resulted in the failure of the breakwater due to the seepage flow. The present study significantly improves the limitations of the previous one: (1) centrifuge model tests are newly performed with and without allowing seepage into the rubble mound by introducing artificial impermeable layer using a rubber membrane covering the surface of the rubble mound on the bay side for achieving no seepage flow condition, (2) effective stress analyses are performed based on the finite strain formulation in order to take large deformations into account. The previous study was based on the infinitesimal strain formulation that is applicable only to small displacements, even though the deformation observed in 2011 (particularly the movement of the caisson) was significant.

2. Centrifuge model tests of a breakwater subject to a tsunami

2.1. Tsunami generator in centrifuge and model test conditions

We used the geotechnical beam centrifuge at the Disaster Prevention Research Institute, Kyoto University (effective radius 2.5 m) for the centrifuge model tests in this study. The equipment for simulating a tsunami in the centrifuge is shown in Fig. 4. Tsunami-like flow toward the caisson is generated by opening a valve at the bottom of a water tank. A BF diaphragm-type cylinder placed at the bottom of the right hand side of the box is utilized to remotely open the valve. The operation is done using compressed air from a portable air tank (about a mass of 10 kg) that is attached to the centrifuge arm. Initially, an air pressure of 200 kPa is applied to the BF cylinder to close the valve. Then, by applying an air pressure of 300 kPa at the start of each experiment, a differential air pressure of 100 kPa quickly opens the valve to generate tsunami-like flow. The levels of the air pressure were determined by trial and error basis under a given centrifugal acceleration. Overflowing water at the other end of the model (left in Fig. 4) is absorbed in a provisional storage pit to reduce the effect of wave reflection from the (left-hand) wall of the container.

The centrifuge model tests are performed in a 25g centrifugal acceleration field using a 1/200-scale model of a 21-m-high caisson. We adopt a generalized scaling relation [6] that resolves the restriction of conventional scaling laws on the scale ratio due to the performance of the centrifuge. This makes it possible to carry out centrifuge model tests for large prototypes by setting a virtual 1g field between the prototype and the centrifugal field even when the centrifuge capacity is limited. Table 1 lists the generalized scaling factors, combinations of the scaling factors for 1g model

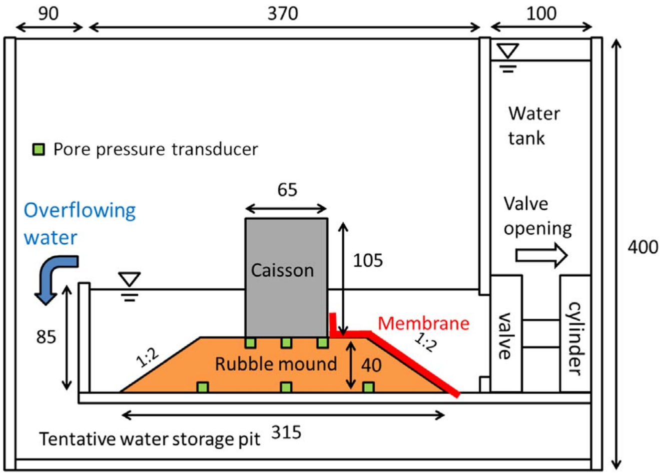

Fig. 4. Apparatus for simulating tsunami in centrifuge model tests (units in mm in model scale).

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