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Centrifuge modelling for stability evaluation of a breakwater foundation subjected to an earthquake and a tsunami

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A B S T R A C T

Many breakwaters were failed due to the geo-disaster caused by the 2011 off the Pacific Coast of Tohoku Earthquake and Tsunami. Investigations were carried out, and it was found that the breakwater failed mainly due to the failure of its foundation. However, mechanism of the failure of the breakwater has not yet been completely explained. This paper focuses on the stability evaluation of a breakwater foundation subjected to an earthquake and a tsunami. The main feature of the study is application of centrifuge technique for a geo-disaster caused by an earthquake and a tsunami. Results of the study show that in the case of a geo-disaster brought by an earthquake and a tsunami, excessive pore water pressure generated in the sandy ground, and consequently liquefaction occurred during the earthquake. That resulted in deformation of the foundation ground and settlement of the breakwater. During the tsunami, scouring could occur around the harbor side mound, and seepage took place beneath the breakwater. These were the main reasons of decrease in bearing capacity of the foundation ground and failure of the breakwater. Numerical simulations were also performed to make clear the mechanism and behavior of the breakwater under an earthquake and a tsunami. Overall, this study can be useful to understand the failure process of a breakwater under an earthquake and a tsunami, and it can be helpful to develop countermeasures in order to reduce the earthquake and tsunami induced damage of a breakwater in the future.

1. Introduction

The 2011 off the Pacific Coast of Tohoku Earthquake struck the coast of Japan on 11th March 2011 at 14:46 JST. The main shock of the earthquake was preceded by several foreshocks and followed by hundreds of aftershocks. One of the foreshocks was with moment magnitude (M_W) of 7.3. The tsunami waves of height up to 40.5 m (Miyako, Iwate Prefecture, Japan) were triggered by the earthquake (Dong et al., 2012). The tsunami led to the catastrophic losses for the population and structures near the coastlines (Hazarika et al., 2012, 2013; Hara et al., 2012; Sugano et al., 2014; Kazama and Noda, 2012; Takahashi et al., 2011). Lots of breakwaters were severely damaged by the earthquake and tsunami across the affected areas. The world's deepest breakwater at Kamaishi port (Iwate Prefecture, Japan) also collapsed, and failed to stop the tsunami. The caissons slid down (from the mound), toppled and sank into the seawater. Investigations (Arikawa et al., 2012, 2013) were carried out, and it was found that the breakwater failed mainly due to the failure of its mound. Damage of the mound was the main reason of the failure of the breakwater rather than its main body.

Countermeasures against geo-disasters brought by an earthquake and a tsunami are very important for the construction of earthquake and tsunami resistant breakwaters, which can reduce the damage brought by an earthquake and a tsunami in the future. In order to develop countermeasures against such geo-disaster, it is extremely important to determine the failure mechanism of a breakwater subjected to an earthquake and a tsunami. In the case of a geo-disaster caused by a strong earthquake and a tsunami, several factors (e.g. seismic inertia forces on a breakwater, excess pore water pressure in foundation, tsunami wave forces on a breakwater, seepage force in foundation, scouring of mound and piping of seabed soils) affect the stability of a breakwater and its foundation. If a strong earthquake strikes the breakwater for a long period, excess pore water pressure generates in the foundation ground, and it may lead to liquefaction, which causes reduction in bearing capacity of its foundation. The foundation may deform severely, and that results in settlement, sliding and overturning of the breakwater. During a tsunami, scouring of harbor side mound occurs due to overflowing tsunami. Tsunami creates water level difference between the seaside and harbor side of the breakwater for a long duration. This difference in the

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seawater level generates seepage of seawater beneath the breakwater, and the seepage simultaneously generates seepage forces in the direction of flow. It may cause piping and boiling of the foundation soils. In addition, tsunami waves impose tsunami forces on the breakwater. These factors ultimately decrease the confining pressure, stiffness and bearing capacity of the foundation.

The failure mechanism of a breakwater under tsunami overflow has not yet been completely known. Some research have been performed relating to the stability of a breakwater subjected to tsunami forces. But all the forces which can act on a breakwater during a tsunami to destabilize it have not been considered in these studies. Only few destabilizing forces were considered in their studies. For example, Takahashi et al. (2014) investigated the effects of tsunami induced seepage on the stability of a breakwater, and it was found that the seepage force decreased the bearing capacity of rubble foundation significantly. But, the effects of overflowing tsunami waves such as scouring of mound were not considered in the study. Kasama et al. (2015) conducted a physical model test under 1 *g* gravitation field, and described the stability of a breakwater subjected to tsunami induced seepage, and it was observed that there was significant reduction in the bearing capacity of mound due to seepage of seawater beneath a caisson during the tsunami. Scouring of mound due to the overflowing tsunami is not considered in the study. In addition, seabed soils were also not considered beneath the mound, which has significant impacts on the stability of a breakwater during tsunami (e.g. seepage and piping of seabed soils). Imase et al. (2012) and Matsuda et al. (2016) evaluated the stability of a breakwater during earthquake and tsunami. But, tsunami induced scouring of mound was not considered in their studies. Therefore, physical processes of instability of a breakwater due to a tsunami (e.g. combined effects of scouring of mound, seepage and piping beneath breakwater) could not explained by their studies. Dong et al. (2012), Chen et al. (2013) and Zen et al. (2013) discussed both the pop-out failure of armoured blocks and reduction of bearing capacity due to tsunami induced seepage by conducting model tests under 1 *g* gravitational field. Scouring of mound and seabed soils were not allowed during their physical model tests. Chaudhary et al. (2017c) described the stability of a breakwater under combined actions of an earthquake and tsunami. But it is an analytical study, and some important factors such as scouring of mound and pore water pressures in foundation were not considered in the study.

Main factors for instability of a breakwater foundation during a tsunami are: (i) Tsunami wave forces on a caisson, (ii) Seepage of seawater beneath a caisson (through mound and seabed soils), (iii) Piping of seabed soils and (iv) Scouring of mound (and seabed soils). But, all those studies considered either one or two of these factors such as tsunami induced seepage or tsunami induced scouring. All the possible factors (e.g. seepage, scouring, and piping) which are responsible for the instability of a breakwater during a tsunami did not consider in their studies. In fact, most of the studies did not consider seabed soils (as their mound rests on base of a soil box), therefore effects of some important parameters such as scouring and piping of the seabed soils during a tsunami could not be understood. Thus, instability of a breakwater during a tsunami could not be explained completely by these studies. To the end, the authors conducted a series of centrifuge model tests to evaluate the instability of a breakwater and its foundation subjected to a tsunami, and all the possible factors are considered in this study which can affect the stability of a breakwater foundation during a tsunami. The main novelty of this study is that all constraints are made free, and tsunami overflow test was conducted under centrifuge gravitational field in such a way that it could represent the actual failure process of a breakwater during a tsunami which may occur in the real ground. In addition, stability evaluation of breakwater under earthquake loadings is also included in the study.

Generally, a tsunami is followed by an undersea earthquake ($M_L \geq 6.5$). The foundation of a breakwater may damage severely during the earthquake due to high excess pore water pressure (or liquefaction), and a breakwater may settle heavily during the earthquake. During a tsunami, the tsunami induced seepage (beneath a breakwater) and scouring (of mound) impose instability to the breakwater. In the present study, the stability of a breakwater is determined under an earthquake and a tsunami. To determine the effects of foundation soils on the performance of the breakwater, two soil layers were used in the foundation (beneath mound) during the tests. A series of centrifuge model tests were performed to determine the stability of the breakwater subjected to an earthquake and a tsunami. Numerical simulations were also conducted to make clear the mechanism. However, due to limitation of centrifuge devices, effects of an earthquake on tsunami overflow could not be considered in the present study.

2. Centrifuge model tests

The centrifuge technique has been often used to investigate various geotechnical problems since 1960s. The main advantage of the technique is that high stress can be generated corresponding to a prototype which is necessary to simulate the non-linear behavior of soil.

2.1. Experimental setup and procedures

Centrifuge model tests were conducted at DPRI (Disaster Prevention Research Institute), Kyoto University, Japan using a beam type geotechnical centrifuge machine. The centrifuge machine has an effective radius of 2.5 m, and it can be operated up to acceleration of 200 g for static tests, and 50 g for dynamic tests.

Soil box was made of steel, and its front face was made of acrylic plates (see Fig. 1). A water tank and movable gate were installed in the soil box to generate tsunami. The moveable gate could be closed over water inlet hole (located at the bottom of the water tank). It can be opened by sending a signal from a remote computer, and allow the water to release from the water tank. Once the water is released from the tank, it flows across the soil box where the model is placed. It is then captured in a drainage tank which is attached at the bottom of the soil box to avoid reflection of water waves generated due to the presence of the wall on opposite side (see Fig. 1).

2.2. Model description

The future earthquakes such as Tokai earthquake, Nankai Earthquake and Tonankai Earthquake are matters of great concern for the politicians, policy makers and researchers of Japan. These are predicted to occur any time in the near future. According to the report of the central disaster management council of the ministry of Japan (Central Disaster Management Council, 2003), about 2 m seismic subsidence is expected due to the Nankai earthquake in the Kochi area (Shikoku Island, Japan). The Miyazaki prefecture is predicted as one of the most affected areas by the Nankai earthquake. Tsunami waves of height more than 15 m are

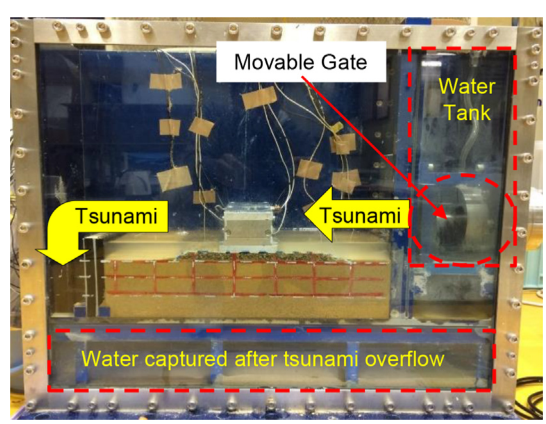

Fig. 1. Soil box used for the centrifuge model tests.