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Geosynthetic-sheet pile reinforced foundation for mitigation of earthquake and tsunami induced damage of breakwater

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ABSTRACT

Earthquake and tsunami impose great threats on the stability of a breakwater. Foundation of the breakwater is weakened by these forces, and it may result in collapse of the breakwater. Lateral flow of seabed soils take place beneath the breakwater, and excess pore water pressure is generated in the foundation by an earthquake that precedes tsunami. These factors may lead to excessive settlement and horizontal displacement of the breakwater. Tsunami introduces additional instability to the deformed breakwater. Due to water level difference between seaside and harborside of the breakwater during a tsunami, seepage occurs through its foundation, and it may cause pipping of seabed soils. Tsunami induced scouring of mound is also a big problem for the stability of the breakwater foundation. Finally, these result in failure of the breakwater foundation. Due to failure of its foundation, the breakwater may collapse and cannot block the tsunami. It results in entering of the tsunami in coastal areas. In order to make a breakwater resilient against earthquake and tsunami induced damage, reinforcing countermeasures were developed for foundation of a breakwater. Geogrid, gabions and sheet piles were used for reinforcing a foundation model. The effectiveness of the model is evaluated through physical modeling for mitigating the earthquake and tsunami induced damage. Shaking table tests were performed to determine the effectiveness of the reinforced model under different earthquake loadings. Tsunami overflow test was conducted on the same deformed model in order to see the effects of tsunami on the model. Comparisons were made between the unreinforced and reinforced foundations, and it was observed during the tests that the reinforced foundation performed well in reducing the damage of the breakwater brought by the earthquake and tsunami. Overall, this study is useful for practice engineering, and the reinforced foundation model can be adopted for designing a breakwater foundation to reduce damage triggered by an earthquake and tsunami in the future.

1. Introduction

Composite breakwater is widely used as a coastal protective structure due to its stability and ease of construction. Different components of a breakwater and its foundation are shown in Fig. 1. In the past few years, lots of coastal structures (e.g. breakwaters, seawalls) were damaged by the past earthquakes and tsunamis (e.g. the 2004 Indian Ocean Earthquake and the 2011 Tohoku Earthquake and tsunamis). Many breakwaters failed during the 2011 Tohoku Earthquake and subsequent tsunami (Kazama and Noda, 2012; Takahashi et al., 2011; Arikawa et al., 2013). Japan suffered devastating damage due to the earthquake which triggered high tsunami (Hazarika et al., 2012, 2013; Sugano et al., 2014; Arikawa et al., 2012). The breakwaters at almost all major ports of the affected areas damaged due to the earthquake and tsunami (Kazama and Noda, 2012). Due to the damage of the breakwaters, they could not barricade the tsunami, and the tsunami entered the coastal plain areas. Investigation were carried out, and it was found that several breakwaters were collapsed mainly due to the failure of their foundations (Takahashi et al., 2011, 2014b; Arikawa et al., 2012, 2013). Mound scouring and sliding of caisson on the mound were the major reasons of the failure. The breakwater at several ports (e.g. Kamishi, Kuji, Hachinohe, Miyako and Ofunato) in Japan were damaged mainly due to their foundation failures during the earthquake and tsunami. Therefore, it is utmost important to develop countermeasures for foundation of a breakwater in order to make it resilient against earthquake and tsunami.

The devastating damage caused by the past earthquakes and tsunamis compel researchers to develop earthquake and tsunami resistant

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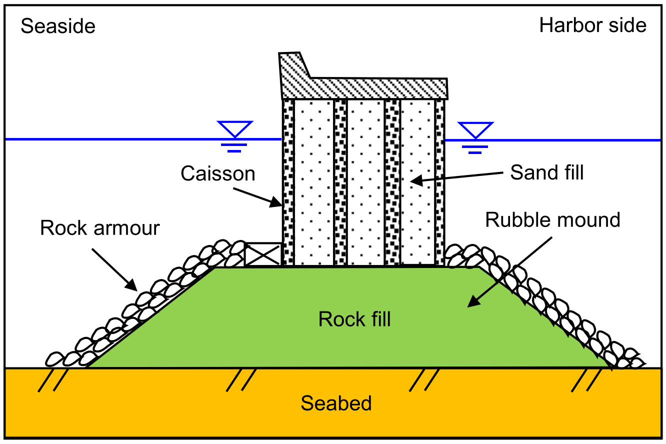

Fig. 1. Different components of a breakwater and its foundation.

breakwater in order to mitigate damage in the future. Therefore, reinforcing countermeasures for foundation of a breakwater are utmost important for construction of earthquake and tsunami resistant breakwater, which can reduce its damage in the future brought by an earthquake and tsunami. Recently, some research works have been undertaken for reinforcing the foundation of a breakwater against a tsunami. Kikuchi et al. (2015) used steel walls into foundation behind a breakwater in order to mitigate tsunami-induced damage of the breakwater. Ueda et al. (2016) blanketed a mound by membrane to reduce seepage of water through the mound during a tsunami. Tsujio et al. (2013) increased width of a mound to reduce displacement of a breakwater due to abnormal tsunami. Mitsui et al. (2013) suggested to use filter units for covering a rubble mound to increase stability of a breakwater. Sassa et al. (2016) discussed the stability of a breakwater under effects of overflow and seepage caused by a tsunami. Mitsui et al. (2012) discussed the stability of a rubble mound covered by armor units during tsunami. Takahashi et al. (2014a) put concrete blocks behind breakwater for stability of a mound against tsunami. Kishida et al. (2013) suggested to use friction increasing asphalt mat for a mound to reduce lateral move of a breakwater produce by tsunami forces. However, all these research deal with reinforcing countermeasures to enhance the stability of a breakwater foundation against only tsunami. These were not aimed to reduce the effects of an earthquake (that precedes tsunami), and hence did not take into account earthquake induced damage to a breakwater foundation such as liquefaction generated settlement of the breakwater and deformation of the ground. Earthquake generated excess pore water pressure (EPWP) may cause for deformation of foundation ground which may lead to excessive settlement of the breakwater. In this way the earthquake (that precedes tsunami) can reduce effective height of the breakwater, and the breakwater may not barricade the tsunami. On the other hand, Chaudhary et al. (2016, 2017a,c) developed remedial measures for foundation of a breakwater, and discussed their effectiveness against only earthquakes. Tsunami was not considered in the research. Chaudhary et al. (2017b) discussed the stability of a breakwater under combined actions of an earthquake and tsunami. But, it was an analytical study, and some important parameters such as scouring, seepage and pore water pressures in the foundation ground were not considered in his study. Towards this end, the authors developed countermeasures for a breakwater foundation to mitigate breakwater damage caused by both earthquakes (precede a tsunami) and tsunami.

Generally, an earthquake precedes a tsunami, and the tsunami strikes within a small time interval after the earthquake. It may be possible that EPWPs (produced by the earthquake in foundation) do not fully dissipate during the tsunami. Excessive seismic subsidence may decrease effective height of the breakwater. In this way, the tsunami can impose more damage to the breakwater (and its foundation), and the breakwater may not block the tsunami. This phenomena makes it a complex disaster caused by both the earthquake and tsunami (caused not by only tsunami or by only earthquake). Both the earthquake and tsunami impose instability to a breakwater foundation. Hazarika et al. (2015a) performed centrifuge model test to observe the behavior of a breakwater foundation under actions of an earthquake and tsunami. Excessive settlement of the breakwater took place due to the earthquake. Hence, to develop an effective and sustainable countermeasures against a tsunami to mitigate such damage in the future, these countermeasures should be effective against both the strong earthquake motion (that precedes the tsunami) and the tsunami. For this purpose, countermeasures are proposed for foundation of a breakwater to mitigate the earthquake and tsunami induced damage of the breakwater foundation. A pair of physical models, an unreinforced and a reinforced, were produced and shaking table tests were carried out to judge its effectiveness against earthquake. A tsunami test was done on the same model.

2. Reinforced breakwater

In order to make a breakwater resilient against both earthquake and tsunami induced damage, a new reinforcing foundation model has been developed by the authors for a breakwater. As reinforcing countermeasures, geogrid, sheet piles and gabions are used in the foundation to mitigate damage of the breakwater created by an earthquake and tsunami. Geogrid is provided between seabed and rubble mound. The geogrid is chosen in such a way that its mess aperture size is less than size of rubble of the mound. In addition, the geogrid should be strong enough to bear overcoming loads from the breakwater, seawater and mound. Purpose of using the geogrid is to resist deformation of the mound during an earthquake, and hence it can reduce seismic subsidence of the breakwater. Tsunami induced seepage beneath a breakwater is a great threat for the stability of the breakwater. Rubble can move and sink in the seabed soils due to seepage force. Due to less mess aperture size of the geogrid (compared to size of rubble), it can resist downward movement of the rubble, and thus can reduce damage of the mound; and enhance the breakwater stability during the tsunami. In addition to the geogrid, two rows of sheet piles are embedded on both sides of the mound as shown in Fig. 2. Lateral deformation of foundation soils is one of the major reasons for subsidence and horizontal displacement of a breakwater during an earthquake. The sheet piles can restrict the lateral deformation of the foundation soils, and thus can mitigate such deformation caused by EPWP (or liquefaction) generated by the earthquake. Thus, settlement and lateral move of a breakwater can be diminished during an earthquake.

During a tsunami, seepage beneath the breakwater is one of the causes of its failure. The sheet piles work as cut off walls, and can cease the seepage of seawater beneath the mound during the tsunami. Hence, they can reduce damage of the foundation ground due to seepage during the tsunami. A number of gabions are used beside the caisson to

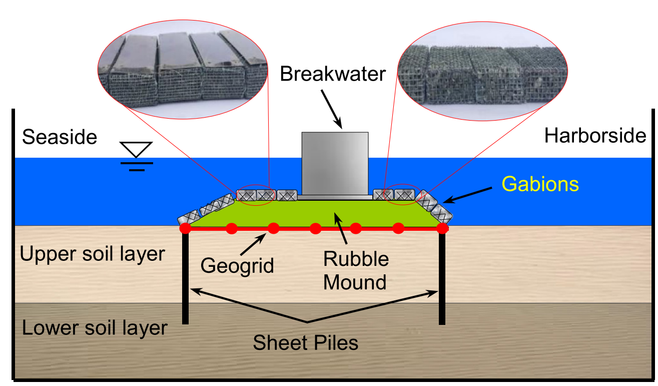

Fig. 2. Reinforced foundation for a resilient breakwater.