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# Effects of duration and acceleration level of earthquake ground motion on the behavior of unreinforced and reinforced breakwater foundation

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ABSTRACT

This paper describes an effective reinforcement technique for foundation of breakwater in order to provide resiliency to the breakwater against earthquake and tsunami related compound geo-disaster. As reinforcing measures, the technique uses gabions and sheet piles in the foundation of the breakwater. A series of shaking table tests were performed to evaluate the effectiveness of the technique under different earthquake loadings, and comparisons were made between conventional and reinforced foundation. The results of these tests reveal the advantages of the reinforcing foundation technique in terms of reduction in settlement and horizontal displacement of the breakwater during the earthquake loadings. Duration and level of acceleration of earthquake loadings had significant impacts on the settlement and horizontal displacement of the breakwater. It was found that one of the reasons of settlement of the breakwater is lateral flow of foundation soils during earthquake, and the sheet piles could reduce the lateral flow. The excess pore water pressures could be reduced significantly during earthquake due to the reinforcing technique. Numerical analyses were also performed to confirm the effectiveness of the technique, and to determine behavior of the reinforcement-soil-breakwater system during the earthquakes.

## 1. Introduction

Breakwater is an artificial offshore structure, which is built to protect port and harbor from destructive effects of sea waves, currents, typhoons and tsunamis by reflecting and dissipating their energies. It creates sufficiently calm water for safe navigation, anchorage of vessels, loading and unloading of cargoes and other harbor activities. In the recent few decades, more and more marine infrastructures, such as breakwater, are either constructed or extended due to increase in global economic activities. The breakwaters are built on seabed, and are vulnerable to earthquake and tsunami. During the 2011 off the Pacific Coast of Tohoku Earthquake and subsequent tsunami, many coastal structures including breakwaters were damaged [1–4]. The main shock ($M_w = 9.0$) was preceded by a number of large foreshocks and followed by hundreds of aftershocks. One of the major foreshocks had a moment magnitude of 7.2. The world's deepest breakwater at Kamaishi port (Iwate Prefecture, Japan) collapsed during the 2011 earthquake and tsunami. It was reported [5–9] that the breakwater collapsed mainly due to failure of its foundation. Mound was scoured by the tsunami. Caissons slid down from the mound and sank in sea. There are some other breakwaters (e.g. Hattaro Breakwater in Hachinohe Port, Aomori Prefecture; Ryujin-zaki Breakwater at Miyako Port, Iwate Prefecture and breakwater at Onagawa Port, Miyagi Prefecture) which also collapsed due to failure of their foundations during the 2011 earthquake and tsunami. Due to failure of the breakwaters, the tsunami could easily enter into coastal areas, and led to catastrophic losses for structures and population there. Therefore, safe performance of breakwater is very important for smooth operation of costal activities during such compound geo-disaster caused by earthquake and tsunami.

Countermeasures against such geo-disasters are essential for construction of earthquake and tsunami resistant breakwater. The 2011 earthquake and tsunami once again reminded the researchers the importance of developing new techniques for foundation of breakwater that can provide resiliency to the breakwater against earthquakes and tsunamis. Many researchers suggested countermeasures for foundations of breakwaters only against tsunami. But, no research is available for resiliency of breakwater against both earthquake and tsunami. Kikuchi et al. [10] suggested use of steel walls on harbor side mound of breakwater for protection against tsunami. Arikawa et al. [6] discussed effects of widening of rubble mound to reduce the damage caused by tsunami. Oikawa et al. [11] suggested use of a row of steel piles in harbor side in order to reduce the damage to breakwater mound during

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tsunami. Maruyama et al. [12] put armor units (concrete blocks) on harbor side of rubble mound to enhance its stability against tsunami. However, all those countermeasures were suggested to decrease the effect of tsunami on the performance of breakwater during tsunami. But, they are not aimed at mitigating the effects of earthquake on the performance of the breakwater. Since, tsunami is triggered by earthquake, and the earthquake strikes before the tsunami, it produces a compound disaster (caused by both earthquake and tsunami). Therefore, for stability of breakwater, consideration of tsunami alone would not be a practical solution. Effects of earthquake should also be considered before tsunami. In case of a compound geo-disaster caused by earthquake and tsunami, there are several factors which affect the stability of breakwater. The excess pore water pressure (or liquefaction) is generated by the earthquake, and it causes decrease in bearing capacity of the foundation soil. It may result in high deformation of mound, and heavy settlement of the breakwater. In addition, seismic inertia forces act on the breakwater. All these phenomena take place before the tsunami attack. If the tsunami strikes the breakwater under this condition (after earthquake), it may create much damage. Due to excessive settlement of the breakwater during earthquake, tsunami may easily overflow the breakwater, and may create devastation on seacoast. Hence, these factors cannot be ignored for stability of breakwater subjected to tsunami. These are the reasons that a new reinforcement technique has been developed against both earthquake and tsunami for foundation of breakwater, which provides resiliency to the breakwater against earthquake and tsunami. The technique uses gabion mound and protective gabions, and reinforcing the foundation soils with sheet piles to reduce the damage to the breakwater caused by the earthquake and tsunami.

To determine the effect of earthquake on the performance of breakwater, Hazarika et al. [14] conducted a series of centrifuge model tests for stability of breakwater against earthquake and tsunami, and found that earthquake had significant impacts on the stability of the breakwater which hit the breakwater before tsunami. It may also be possible that tsunami hit the breakwater after earthquake, and excess pore water pressure could not dissipate completely before tsunami. The soil was still in unstable condition. Therefore, to evaluate effectiveness of the technique against tsunami, it is very important to confirm its efficiency against earthquake first, and then apply the technique for protection of breakwater against tsunami waves. A series of shaking table tests were performed to evaluate the effectiveness of the technique against earthquakes. The effectiveness of the technique was determined based on the results of shaking table tests, which are described in the paper. In addition, effects of amplitude of acceleration and duration of earthquake ground motion are also discussed. Numerical simulation was performed to determine the mechanism. Model flume tests are ongoing to determine the effectiveness of the technique against tsunami, and it may be addressed in a paper in the future.

## 2. Reinforcing foundation technique for a resilient breakwater

A new reinforcing technique has been developed for foundation of breakwater, which provides resiliency to the breakwater against earthquake and tsunami induced forces. As reinforcing materials, gabions and sheet piles are used in the foundation of breakwater as shown in

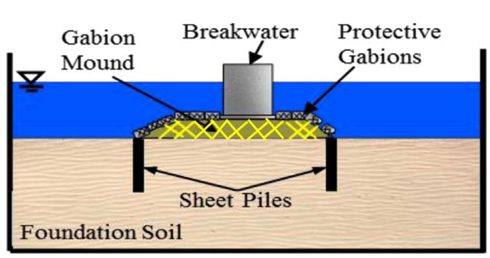


**Fig. 1.** Reinforcing foundation model to make breakwater resilient.

Fig. 1. The rubble mound is wrapped by gabion, and protective gabions are used to cover the entire mound. The gabion mound can prevent the deformation of rubble mound and reduce settlement and horizontal displacement of the breakwater during earthquake. Protective gabions are placed over the gabion mound on both the seaside and harbor side besides the breakwater. Due to friction between protective gabions and gabion mound, they can resist the lateral movement of the breakwater during earthquake, and thus they can reduce horizontal displacement of breakwater. These properties can reduce subsidence and lateral displacement of the breakwater. In addition to gabion mound and protective gabions, sheet piles are also used in the foundation at the both ends of the mound. The sheet pile is expected to resist lateral deformation of foundation soils due to their bending characteristics. Thus, it can reduce deformation of foundation soils due to liquefaction (or, high excess pore water pressure) during earthquake ground motion. Hence, these countermeasures can reduce settlement and horizontal displacement of breakwater during earthquake ground motion. Authors have developed more than 10 different models for reinforcing foundation of breakwater. This paper discusses effectiveness of one of these models against earthquake loading. However, few of them are described in Hazarika et al. [13–16].

## 3. Shaking table tests

A series of shaking table tests were conducted under 1*g* gravitational field for different earthquake loadings. The settlement, horizontal displacement, pore water pressure, water pressure and acceleration were measured during the tests. The effect of reinforcement on the performance of the breakwater was evaluated based on reduction in settlement and horizontal displacement of caisson (breakwater).

### 3.1. Model description

The earthquakes, such as Tokai Earthquake, Nankai Earthquake and Tonankai Earthquake, are predicted to occur in Japan in near future. According to the central disaster management council of the ministry of Japan [17], high seismic subsidence (about 2 m) is expected due to the Nankai earthquake in the Kochi area (Shikoku Island, Japan). The Nankai earthquake will generate high tsunami waves. It is predicted that Miyazaki prefecture in Kyushu Island will be one of the tsunami affected areas by the Nankai earthquake. This is the reason that breakwater at Miyazaki port (Miyazaki Prefecture, Japan) was used as a prototype for this research. The prototype to model ratio (N) was adopted as 64. The scaling law proposed by Iai [18] was used to determine various parameters for the tests, and are shown in Table 1. Soil box was made with steel frames and acrylic plates. The foundation soils (seabed) of the breakwater was made with Toyoura sand of relative density, $D_r = 60\%$. The thickness of foundation soil was 450 mm (28.8 m in prototype scale). The mean grain size ($D_{50}$) of Toyoura sand was 0.16 mm. The foundation soil was prepared by pouring of sand using hopper system, and by controlling height and

**Table 1**
Similitude for 1*g* shaking table test.

| Properties | Prototype/model | Scale factor |
|---|---|---|
| Length | N | 64 |
| Density | 1 | 1 |
| Time | $N^{0.75}$ | 22.63 |
| Stress | N | 64 |
| Pore water pressure | N | 64 |
| Acceleration | 1 | 1 |
| Displacement | $N^{1.5}$ | 512 |
| Frequency | $N^{-0.75}$ | 0.04 |
| Permeability | $N^{0.75}$ | 22.63 |
| Axial stiffness | $N^{1.5}$ | 512 |
| Bending stiffness | $N^{3.5}$ | $2.1 \times 10^6$ |