SEISMIC RESISTANCE OF BREAKWATER FOUNDATION REINFORCED BY STEEL SHEET PILE AND GABION - EVALUATION THROUGH MODEL SHAKING TABLE TEST

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Abstract

Many breakwaters were damaged during past gigantic earthquakes and tsunamis. It was reported that breakwaters were failed mainly due to failure of their foundations. Mounds were scoured by the tsunamis. Caissons were slid down from the mound, and sank in sea. Due to failure of the breakwater, the tsunami entered in coastal areas. The tsunami led to catastrophic losses for population and structures near coastlines. The extent of damage of breakwaters during past earthquakes and tsunamis exposed vulnerabilities of conventional breakwaters, and raised the importance of developing earthquake and tsunami resistant breakwater.

Countermeasures against compound disasters brought by earthquake and tsunami are essential for construction of earthquake and tsunami resistant breakwaters, which can reduce damage in the future. In order to provide resiliency to breakwater against earthquake and tsunami induce forces, new reinforcing techniques have been developed for foundation of breakwater. The techniques involve use of steel sheet piles and gabions in the foundation of breakwater as reinforcing materials. This paper evaluates newly developed reinforcing techniques for breakwater foundation that can render resiliency to breakwaters against earthquake and tsunami related compound disasters. The gabions improve bearing capacity due to confining effect. It can also protect mound against scouring and toe erosion during tsunami. In this way, subsidence and lateral displacement of the breakwater can be reduced or prevented due to these properties. Sheet piles behave as boundaries, and can restrict lateral deformation of the foundation soils during earthquake due to their bending characteristics. Thus, deformation of the foundation soil can be prevented during liquefaction (high excess pore water pressure) caused by earthquake. Effectiveness of the proposed techniques in mitigating the earthquake induced damage is described through physical modelling. As a part of the physical modelling, a series of shaking table test were performed, and comparisons were made between conventional foundation and proposed reinforced foundation. Test results reveal that the reinforced foundation performs well in reducing the damage to breakwater brought by the earthquake. Settlement and horizontal displacement of the breakwater were reduced significantly by the reinforcing techniques. Installation of sheet piles around the mound could prevent breakwater tilting or overturning during earthquake. It was observed that in the case of earthquake with high intensity and longer duration, the proposed reinforcing techniques provide better mitigation effect. One of the major causes of breakwater settlement is the lateral flow of foundation soils. During earthquake, sheet piles could restrict the lateral flow, and thus could prevent any differential settlement.

Keywords: breakwater; earthquake; reinforcement; gabions; sheet piles

1. Introduction

Many coastal structures (such as breakwaters, seawalls and river dikes) were failed during the past gigantic earthquakes (such as the 2004 Indian Ocean Earthquake and the 2011 Off the Pacific Coast of Tohoku Earthquake) and subsequent tsunamis. The 2011 off the Pacific Coast of Tohoku Earthquake (M_w = 9.0) was the most powerful earthquake ever hit Japan since the modern recordkeeping started. The earthquake triggered powerful tsunami waves with run-up height up to 40.50 m (Miyako, Iwate prefecture, Japan). Lots of coastal protection facilities (breakwaters, sea walls, river dikes, etc.) were damaged due to the earthquake and subsequent tsunami [1-4].

Japan has many experiences of tsunami related disasters (such as 1896 Meiji Sanriku tsunami, 1983 Nihon-kai Chubu earthquake tsunami, 1993 Hokkaido Nansei-oki earthquake tsunami). Disaster prevention and mitigation research works in Japan have been energetically carried out since the 1960 Chilean tsunami attacked the coast of Japan. However, the 2011 tsunami was more devastating and beyond the imagination than the previous tsunamis.

Focusing on breakwaters in particular, the pattern of the damage due to the 2011 compound disaster is classified into four types: (1) scouring due to overflow; (2) force of tsunami wave; (3) scouring around breakwater foundation; and (4) difference in water level due to backrush [5, 6]. Scouring due to overflow is defined as the state where scouring of the mound on the back of the caissons (harbor side) or the ground surface is caused by tsunami overflow or whirlpool accompanied by tsunami overflow. The caissons slide from the mound owing to insufficient bearing capacity, although the tsunami force due to the difference in the water level between the harbor side and sea side of a port does not influence the stability of the caissons. A good example is the central part of Hattaro Breakwater in Hachinohe Port (Aomori Prefecture). Failure due to tsunami wave force is defined as the state, when a direct tsunami force acts on the caissons due to difference in the water level between the harbor side and sea side of breakwater making the caisson unstable, which causes sliding, overturning and bearing capacity failure. A classic example is the north part of breakwater in Kamaishi Port (Iwate Prefecture). Arikawa et al. [7] provided a detailed failure mechanism of this breakwater through experimental and numerical study. Failure due to scouring around breakwater is defined as the state, where scouring to the rubble mound is caused by flow around the breakwater head, which causes the caissons to slide, and make them unstable. A typical example is Ryujin-zaki Breakwater at Miyako Port (Iwate Prefecture). Finally, failure due to the difference in water level during backrush is defined as the state where the caissons become unstable not because of scouring accompanied by the tsunami force of a leading wave or overflow, but because of the difference in the water level between the harbor side and sea side of the breakwater during backrush, causing the caissons to slide, overturn, and experience bearing capacity failure. The breakwater at Onagawa Port (Miyagi Prefecture) is an example of this type of failure. Those examples show that damage to the mound is more significant than that to the main body of the breakwater during the earthquake and tsunami.

The extent of damage or collapse of geotechnical structures due to scouring and erosion by the 2011 tsunami exposed the vulnerabilities of conventional breakwater and reminded the importance of developing and building tsunami-resistant structures, and suggest practically applicable technology [8]. Countermeasures against scouring due to overflow and tsunami wave force are essential for the construction of earthquake and tsunami resistant breakwaters. Equally important are some countermeasures to prevent seepage failure due to water level difference. Hazarika [9] proposed new reinforcing techniques for foundation of breakwater using gabion mound (foundation rubbles covered with gabions) and protective gabion (rubbles and gabions), and reinforcing the foundation soils with steel sheet piles in order to reduce the damage of breakwater due to earthquake and tsunami. This paper deals with the effectiveness of the proposed techniques against earthquake. Physical models are developed for the proposed techniques, and shaking table tests were performed to evaluate their effectiveness against earthquake. However, tsunami overflow tests are ongoing to determine their performance during tsunami overflow tests, and it may be report in a paper in the future.

2. New Reinforcement Foundation Technique for Breakwater

Predicted future earthquakes such as the Tokai earthquake, the Nankai Earthquake and the Tonankai-Nankai Earthquake are matter of great concern for the policy makers, engineers and researchers in Japan. According to the central disaster mitigation council of the ministry of Japan [10], about 2 m seismic subsidence (ground sinking) is expected by the Nankai earthquake in the Kochi area of Shikoku Island, Japan. In order to mitigate the damage caused by such future earthquakes and tsunamis, it is necessary to take appropriate countermeasures that can protect the waterfront structures and human lives. Therefore, it is necessary to develop new reinforcing measures to make breakwater resilient against the future earthquakes and tsunamis.

Many efforts for reinforcing breakwater foundation against tsunami have been undertaken by researchers in Japan. For example, constructing the widening work on the rubble mound (Arikawa et al. [11], installing a row of steel pile in the harbor side of the breakwater mound [12], and putting armor units (concrete blocks) on harbor side rubble mound [13]. However, all those techniques were developed merely focusing on the tsunami resistant characteristics of breakwater. They do not consider the earthquake induced damage of breakwater foundation such as liquefaction induced settlement and deformation of the mound. Reducing the settlement and the deformation caused by earthquake that precedes tsunami is very significant because maintaining the crown is extremely important for reducing the run-up height.

In order to provide resiliency to breakwater due to both earthquake and tsunami induced damage, new reinforcing techniques were proposed by Hazarika [9]. In these techniques, in place of rubble mound, gabion mound was adopted, and protective gabions were used to cover entire mound as shown in Fig. 1. The purpose of using gabion mound is to protect the mound from scouring and toe erosion due to tsunami waves. It can also improve the bearing capacity of the foundation due to its confinement property. Owing to these properties, subsidence and lateral displacement of breakwater mound can be prevented or reduced to a certain extent. In addition to the gabion and protective gabion, steel sheet piles are installed in the foundation. These sheet piles behave like cut off walls, and can restrict lateral deformation of foundation soils due to their bending characteristics during liquefaction of foundation soils, and thus prevent deformation and settlement of breakwater. The sheet piles can also prevent scouring of the foundation soils due to tsunami (both leading wave and backrush). The sheet piles can also prevent seepage flow of water below the breakwater during tsunami, and reduce uplifting force due to seepage. Such multifunctional measures can prevent any bearing capacity failure of the foundation during earthquake and tsunami. In the following sections, the evaluation of the technique through 1g shaking table test are described.

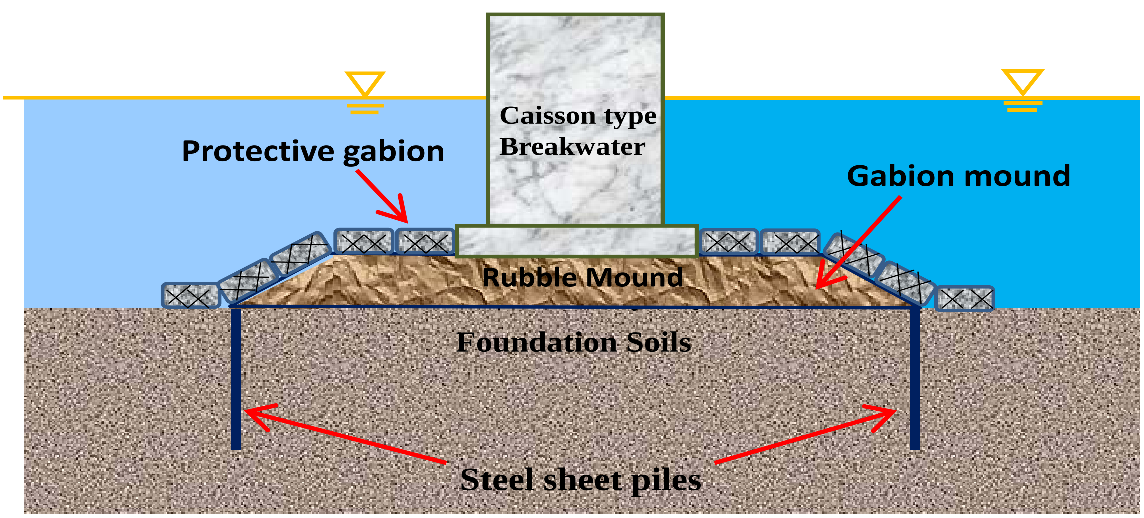


Fig. 1 New reinforcing foundation technique for a resilient breakwater (Hazarika, 2013)

3. 1g Shaking Table Test

Shaking table tests were performed under 1g gravitational field for caisson type breakwater under different earthquake loadings. The acceleration, pore water pressure, water pressure, horizontal displacement and settlement were measured during the experiments. Through the tests, the reinforcing effects of the sheet piles and gabion under earthquake loadings were made clear. The effect of reinforcement on breakwater performance was evaluated based on reduction in the horizontal displacement and settlement of breakwater.

3.1 Model Description

The breakwater at Miyazaki port was chosen as a prototype. The prototype to model ratio was 64, and the similitude relationship proposed by Iai [14] was used to determine the various parameters for the tests, which are shown in Table 1.

Table 1 Similitude for 1g shaking table test

Items	Prototype/ Model	Scale Factor
Length	N	64
Density	1	1
Time	$N^{0.75}$	22.63
Stress	N	64
Pore water pressure	N	64
Displacement	$N^{1.5}$	521
Acceleration	1	1
Frequency	$N^{-0.75}$	0.044
Permeability	$N^{0.75}$	22.63
Bending stiffness	$N^{3.5}$	2097152
Axial stiffness	$N^{1.5}$	521

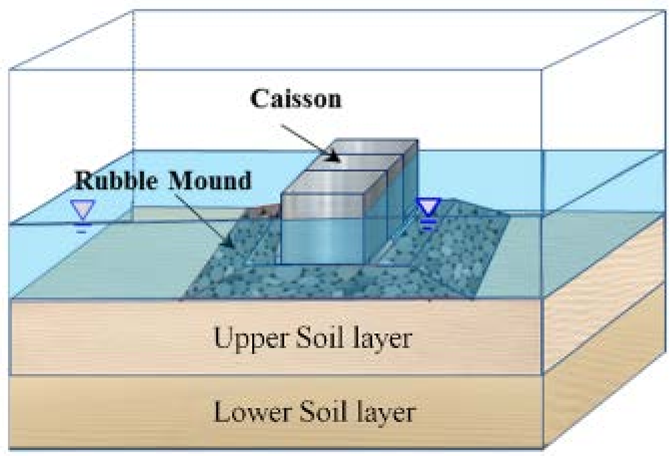
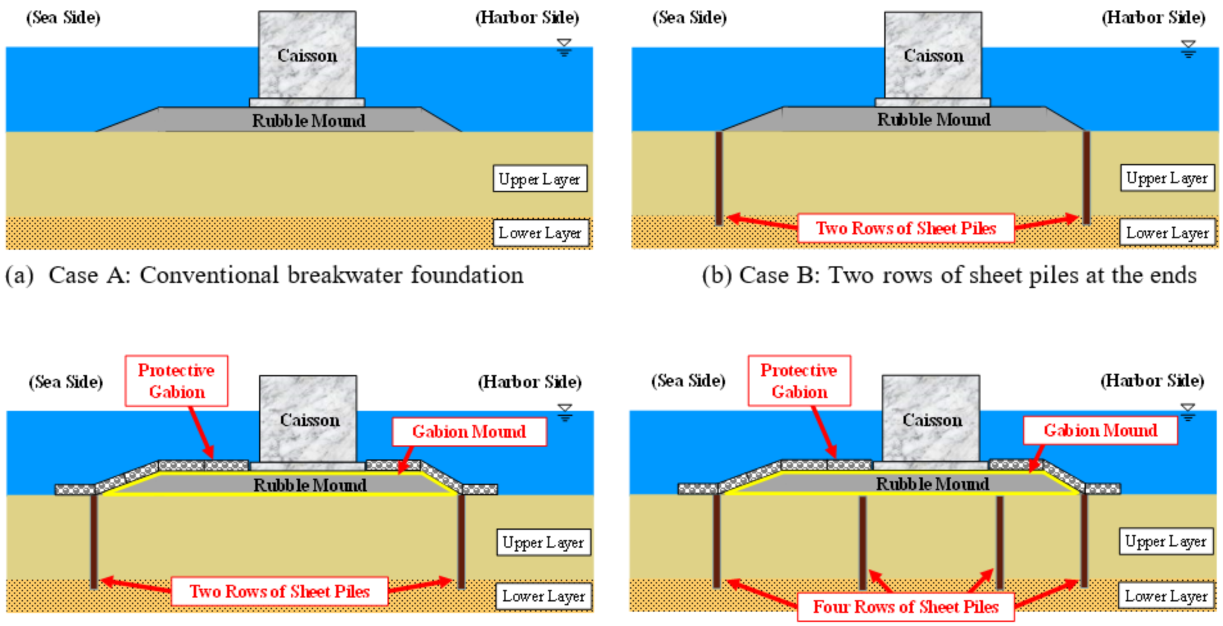


Fig. 2 Three dimensional view of Breakwater foundation model for shaking table test

Soil box was made of steel frames and acrylic plates. Box type model caissons (breakwaters) were made of aluminium and filled with lead balls and silica sand to adjust weight (specific gravity 2.3) and center of gravity. One main caisson at center and two dummy caissons (one dummy caisson on both sides of main caisson) were used in the tests. The dummy caissons were used to prevent effect of soil box (e.g. side friction between main caisson and soil box) on the performance of the breakwater. The three dimensional view of the shaking table model is shown in Fig. 2. All instrumentations were made at the central caisson. Steel sheet piles were made of steel plate (200 mm height, 400 mm width and 3.2 mm thickness). The thickness of the sheet pile was determined by adjusting stiffness to prototype. The foundation soils (Toyoura sand) of the breakwater were made of two layers: a lower layer of relative density, D_r = 90% and an upper layer of relative density, D_r = 60%. The lower layer of relative density 90% behaves as hard strata representing the bed rock. While No. 6 gravel (5 mm - 13 mm) was used for rubble mound, No. 7 gravel (2.5 mm - 5 mm) was used for protective gabion, which was wrapped with wire mesh of steel wire (diameter = 0.63 mm). The element tests were performed to determine dynamic characteristics of Toyoura sand and crushed stones against cyclic loadings, and have been discussed in Hara et al. (paper N° 0865 of the same conference) [14].

3.2 Test Setup

Four different models of breakwater foundation were used in the test as shown in Fig. 3: (a) Case A: Conventional breakwater foundation (unreinforced foundation), (b) Case B: Breakwater foundation reinforced with two rows of sheet piles, (c) Case C: Breakwater foundation reinforced with gabion and two rows of sheet piles (d) Case D: Breakwater foundation reinforced with gabion and four rows of sheet piles (two rows in the center).



(a) Case A: Conventional breakwater foundation
(b) Case B: Two rows of sheet piles at the ends
(c) Case C: Two rows of sheet piles and gabion
(d) Case D: Four rows of sheet piles and gabion

Fig. 3 Layouts of the models used in 1g shaking table tests

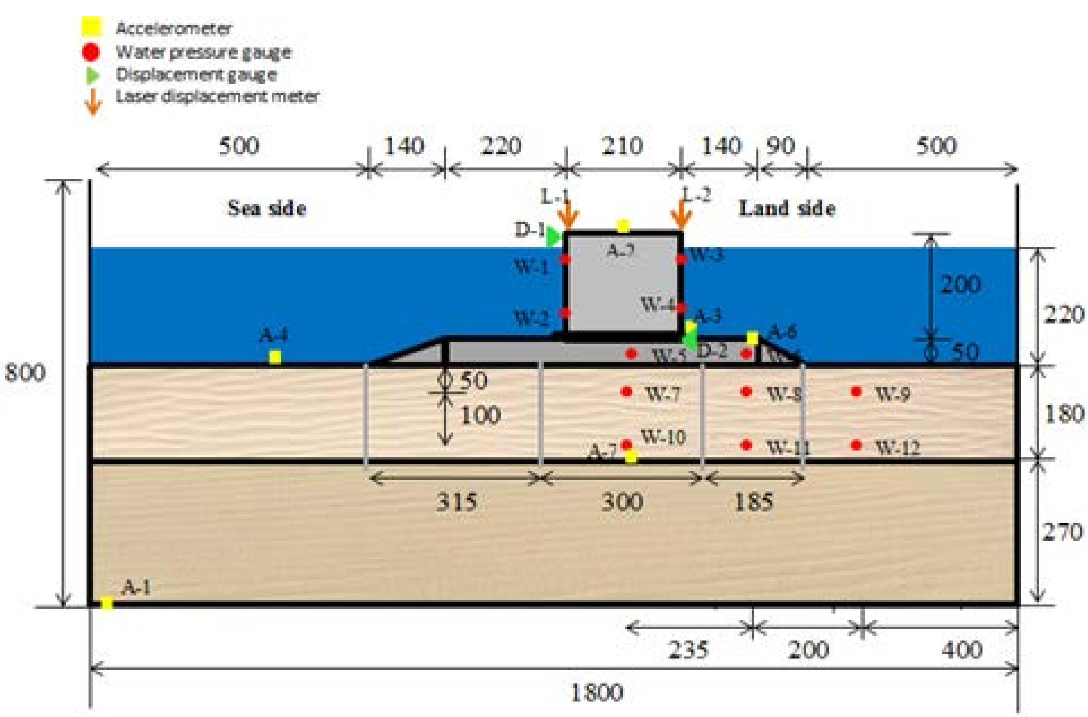


Fig. 4 Cross sectional view and instrumentation of the model for 1g Shaking table test (Units in mm)

Instrumentations for shaking table test are shown in Fig. 4. Two laser displacement gauges (L-1 and L-2) and two displacement gauges (D-1 and D-2) were installed to monitor the settlements and horizontal displacements of the caisson respectively. Seven accelerometers (A-1 to A-7) were used to record the accelerations. Four water pressure gauges (W-1 to W-4) were installed to measure water pressures on the breakwater, and eight pore water pressure gauges (W-5 to W-12) were installed to monitor pore water pressures inside the foundation soils.

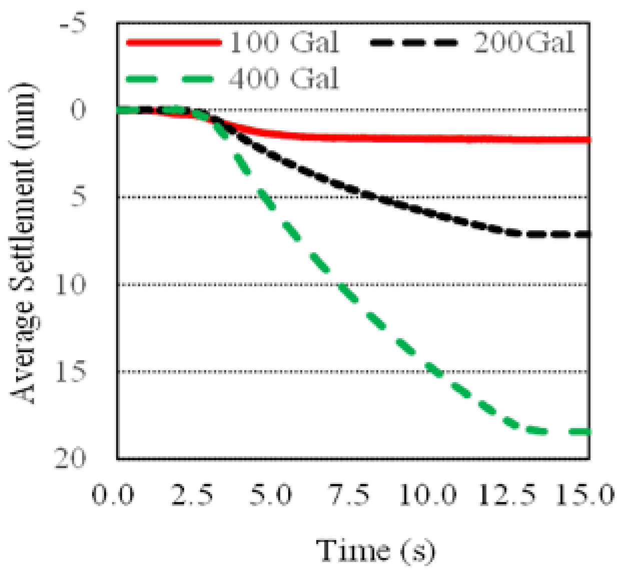
3.3 Test Results

Earthquake loadings in form of sinusoidal waves of frequency 15 Hz with two different continuation time (1 second representing short duration and 8 second representing long duration) and different accelerations magnitudes (100 Gal, 200 Gal and 400 Gal) were applied sequentially to the same model. In order to determine the effect of reinforcement, comparisons were made between unreinforced and reinforced breakwater foundation.

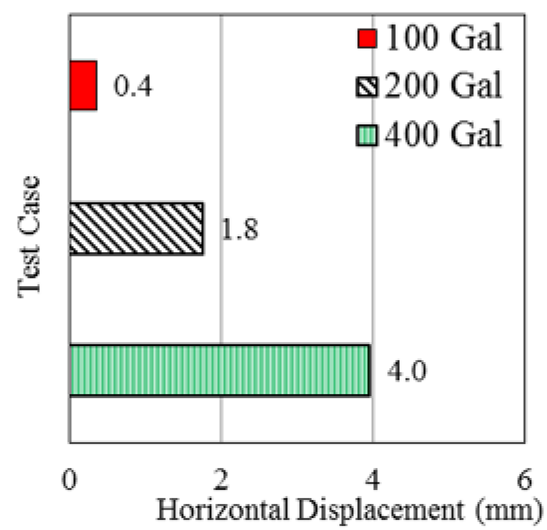
Effect of Acceleration Magnitudes of the Earthquake Loadings

In order to observe the effect of different acceleration magnitudes of earthquake loadings on the performance of the breakwater, average settlement (measured at L-1 and L-2) and horizontal displacement (measured at D-1) of the caisson were determined for different acceleration magnitudes (100 gal, 200 Gal and 400 Gal) and are shown in Fig. 5. It can be seen from Fig. 5(a) that the settlement increases with increase in acceleration magnitude. For 100 Gal, average settlement of the caisson is 1.7 mm and that increases to 18.4 mm for 400 Gal.

Fig. 5(b) shows horizontal displacement of the caisson measured at D-1. Horizontal displacement increases with increase in accelerations of earthquake loadings. It is 0.4 mm at 100 Gal, and increases to 4 mm at 400 Gal representing a tenfold increase in displacement.



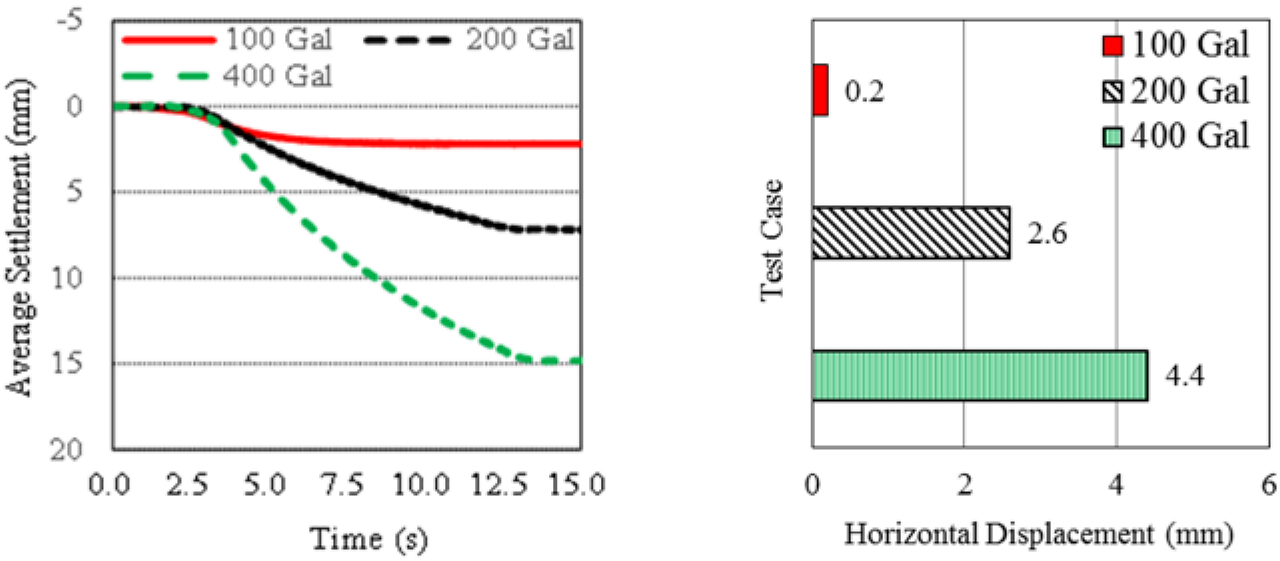
(a) Average settlement of the caisson



(b) Horizontal displacement of the caisson

Fig. 5 Deformation of the caisson for Case A (Conventional breakwater)

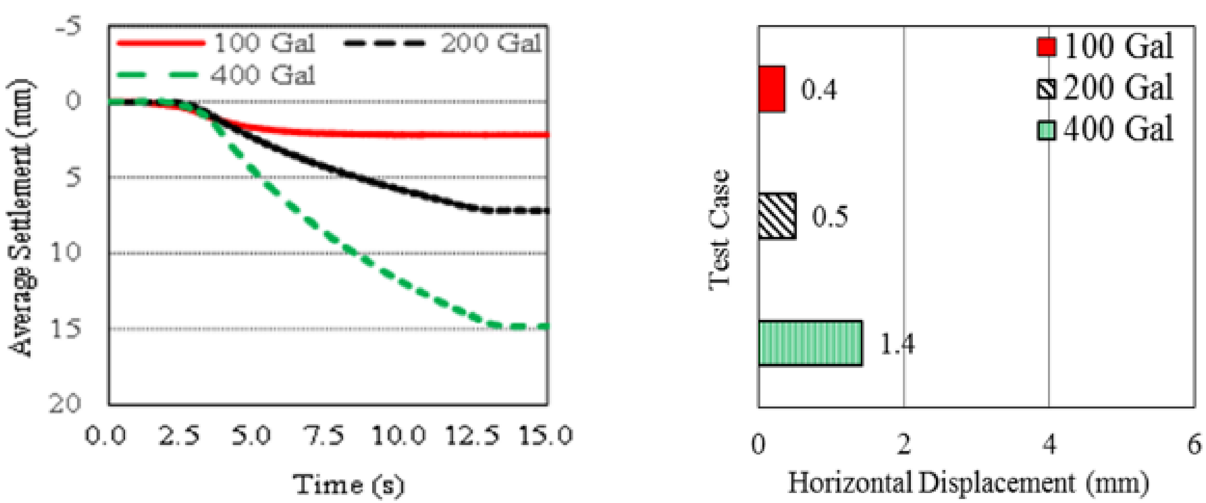
Deformation of the caisson for the breakwater foundation reinforced with two rows of sheet piles is shown in Fig. 6. Fig. 6(a) shows the time history of average settlement of the caisson. Settlement increases with the increase in accelerations of earthquake loadings. It is 2.2 mm at 100 Gal, and increases to 14.8 mm at 400 Gal. Horizontal displacement of the caisson measured at D-1 is shown in Fig. 6(b). It can be seen that horizontal displacement increases with increase in accelerations of earthquake loadings. It is 0.2 mm at 100 Gal, and increases to 4.4 mm at 400 Gal.



(a) Average settlement of the caisson (b) Horizontal displacement of the caisson

Fig. 6 Deformation of the caisson for Case B (Breakwater foundation reinforced with two rows of sheet piles)

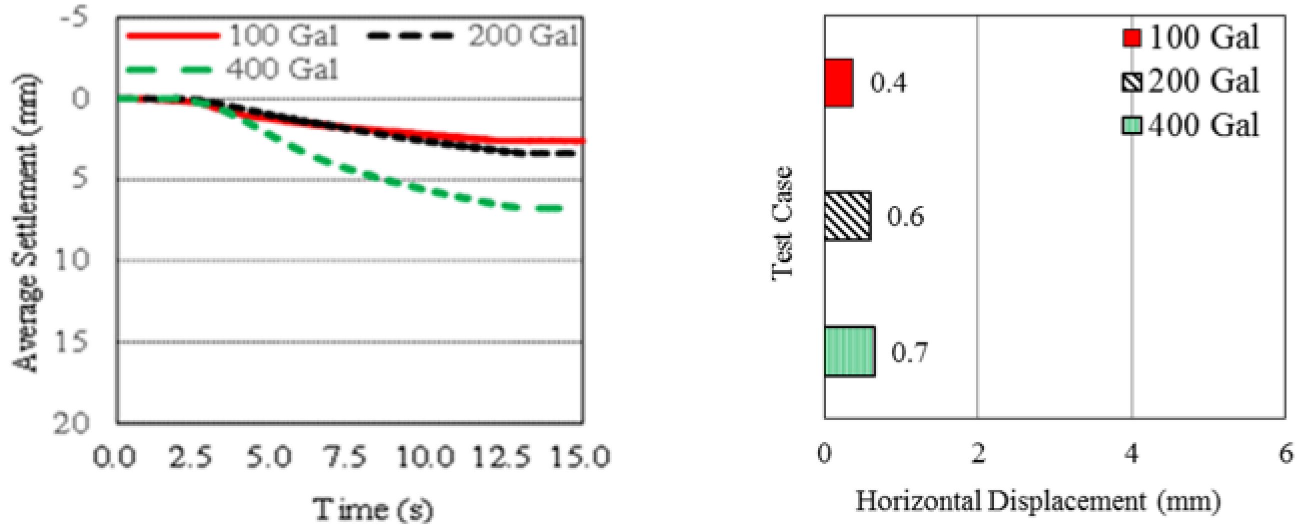
Fig. 7 shows the deformation for Case C: breakwater foundation reinforced with gabion and two rows of sheet piles. Fig. 7(a) shows the time history of average settlement of the caisson. It can be observed that settlement increases with increase in accelerations of earthquake loadings. The settlement is 1.3 mm at 100 Gal, and increases to 10.0 mm at 400 Gal. Fig. 7(b) shows the horizontal displacement of the caisson measured at D-1. It can be noticed that horizontal displacement is 0.4 mm at 100 Gal, which increases marginally to 0.5 mm at 200 Gal. At 400 Gal the displacement is 1.4 mm, representing threefold increase as compared to 100 Gal.



(a) Average settlement of the caisson (b) Horizontal displacement of the caisson

Fig. 7 Deformation of the caisson for Case C (breakwater foundation reinforced with gabion and two rows of sheet piles)

Average settlement of the caisson was calculated for Case D: breakwater foundation reinforced with gabion and four rows of sheet piles, and is shown in Fig. 8. It can be seen from Fig. 8(a) that the settlement is 2.6 mm at 100 Gal, and increases to 6.8 mm at 400 Gal. Fig. 8(b) shows the horizontal displacement of the caisson recorded at D-1. Horizontal displacement is 0.4 mm at 100 Gal, which increases marginally to 0.6 mm at 200. And, finally it increases to 0.7 mm at 400 Gal, representing only twofold increase, which is very less as compared to Case A.



(a) Average settlement of the caisson (b) Horizontal displacement of the caisson

Fig. 8 Deformation of the caisson for case D (Breakwater foundation reinforced with gabion and four rows of sheet piles)

Comparisons between Conventional and Reinforced Breakwater Foundation

Comparisons were made for the residual settlements between the conventional and all the three cases of reinforced breakwater foundation, and are shown in Fig. 9. It can be observed that the settlement is maximum for breakwater foundation without reinforcement, and is in decreasing order from case A to case D. At 400 Gal, the amount of settlement for Case D (reinforced with gabion and four rows of sheet piles) is less than one third of that for Case A (Without reinforcement). Case D shows maximum reduction in settlement at higher accelerations (200 Gal and 400 Gal), and, thus it provides the best solution towards a resilient breakwater.

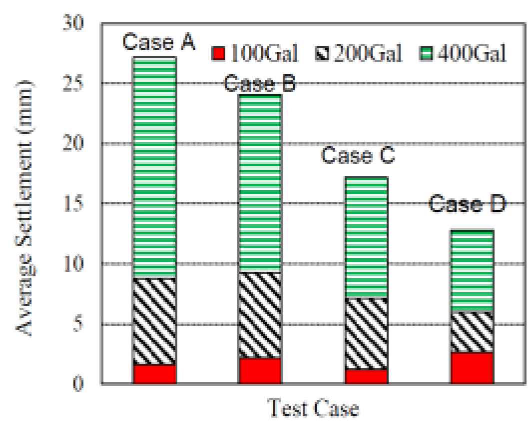


Fig. 9 Settlement of caisson for different test cases

4. Summary and Conclusions

In this research, effectiveness of a resilient technique for breakwater foundation against the earthquake and tsunami induced forces was evaluated through model testing. The following conclusions could be derived based on this research.

1. The horizontal and vertical displacement of breakwater are significantly reduced by reinforcing the foundation with steel sheet piles and gabions.

2. One of the major causes of breakwater settlement is the lateral flow of foundation soils. During earthquake, sheet piles could restrict the lateral flow, and thus could prevent any differential settlement.
3. Installation of sheet piles around the mound could prevent breakwater overturning during earthquake loadings.
4. In case of earthquake with longer duration, the proposed reinforcing technique provides better mitigation effect as the vertical settlement of breakwater could be reduced significantly.

To arrive at an economic and efficient reinforcement of breakwater foundation more detailed studies are needed. Further studies including centrifuge tests for making clear the mechanism of reinforced foundation of breakwater during earthquake and tsunami are in progress. Quantitative evaluation of the techniques by numerical simulations was discussed in Hazarika et al. [16].

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