16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 1539
Registration Code: S-W1462853669

STABILITY OF BREAKWATER FOUNDATION UNDER EARTHQUAKES AND TSUNAMIS: CENTRIFUGE TESTS

B. Chaudhary [(1)], H. Hazarika [(2)] and K. Nishimura [(3)]

[(1)] *Research Associate, Kyoto University, Japan, e-mail: babloomit@gmail.com*
[(2)] *Professor, Kyushu University, Japan, e-mail: hazarika@civil.kyushu-u.ac.jp*
[(3)]*Master Student, Kyushu University, Japan, e-mail: kazenotani.no.tarao@gmail.com*

Abstract

Breakwaters are designed to protect coastal areas and seaports from destructive effects of sea waves, currents and tsunamis by absorbing their wave energies and reducing overtopping effects. But, the extent of damage of breakwaters during the past earthquakes (e.g. the 2011 off the Pacific Coast of Tohoku Earthquake and 2004 Indian Ocean Earthquake) and tsunamis exposed the vulnerabilities of breakwaters. For example, large numbers of breakwaters were heavily damaged by the 2011 off the Pacific Coast of Tohoku Earthquake and subsequent tsunami. The world's deepest and Japan's 1st earthquake resistant breakwater at Kamaishi port was one of them. The breakwater at Kamaishi port failed to block the tsunami. The Kamaishi port suffered heavy casualties due to the tsunami. It was reported that the breakwater collapsed mainly due to failure of its foundation. The damage to the body of breakwater was not significant. However, exact mechanism of failure of the breakwater has not yet been completely known.

Countermeasures are very important to reduce damage caused by such compound geo-disaster caused by earthquakes and tsunamis in the future. In order to develop countermeasures, it is important to understand the failure mechanism. Therefore, to determine the failure mechanism, and to reproduce the failure process of breakwater subjected to earthquake and tsunami, this paper describes the stability of breakwater foundation subjected to earthquake and tsunami using centrifuge tests. The main feature of the study is application of the centrifuge technique for compound geo-disaster caused by earthquake and tsunami. A series of centrifuge model tests were performed to determine stability of breakwater foundation subjected to earthquake and tsunami. The Breakwater at Miyazaki port (Miyazaki Prefecture, Japan) is chosen as the prototype. In addition to mound, two layers of foundation soils (seabed) was considered in the test. Centrifuge model tests were performed under 25 g gravitational fields. Foreshocks and main shock were used as earthquake, and effects of foreshocks and main shock were evaluated in terms of horizontal displacement and settlement of the breakwater. After the main shock, tsunami overflow test was performed on the same model. In the case of compound geo-disaster brought by earthquake and tsunami, a number of forces act on breakwater. Excessive pore pressure increases with the increase of acceleration of earthquake loading, and leads to high deformation of the foundation soil. It increases shear strain of the foundation soil. These factors decrease effective stress and shear strength, and finally reduce bearing capacity of the foundation. That resulted in flow of foundation soil below the breakwater, and led to settlement and horizontal displacement of the breakwater. Seismic inertia forces, generated by the earthquake, also affected the stability of the breakwater during earthquake. Acceleration magnitude of earthquake affects stability of breakwater significantly. Settlement and horizontal displacement of the breakwater increased with the increase in acceleration of the earthquake loading. Very high settlement and horizontal displacement of the breakwater was observed during main shock. It was observed that in addition to tsunami, earthquake was one of the main reasons of failure of the breakwater. High scouring of mound occurred on harbor side during tsunami overflow. Seabed was also scoured by the tsunami waves. Scoured sand was piled up on harbor side by the tsunami waves. Seepage of water occurred below the breakwater, and was concentrated mostly through the mound. However, significant amount of seepage was also noticed through the upper soil layer. The seepage force reduced confining pressure and shear strength. Thus, bearing capacity of the foundation soil reduced significantly during tsunami. Finally, these factors made the breakwater unstable.

Keywords: breakwater; centrifuge; earthquake; stability; tsunami

1. Introduction

Tsunami is frequently generated by strong earthquake with $M_L \geq 6.5$ in open sea due to quick dislocation of a seismological fault. Tsunami carrying huge energy always could lead to great catastrophic losses for the structures and population living near to coastlines where tsunami waves could reach. Japan has many experiences of tsunami disasters such as the 1896 Meiji Sanriku tsunami that caused 22,000 dead and missing. Even after improvement of coastal defense systems which have been significantly implemented since the 1960s, the 1983 Nihon-kai Chubu earthquake tsunami (the Japan Sea tsunami) killed 100 persons, and 1993 Hokkaido Nansei-oki earthquake tsunami (the Okushiri tsunami) caused 230 dead and missing including casualties by the seismic damage. The 2011 off the Pacific Coast of Tohoku Earthquake (M_W=9.0) struck the east coast of Japan on 11th March 2011 at 14:46 (JST). The earthquake occurred in the subduction zone where the Pacific plate subducts beneath the North American plate. It was the most powerful earthquake ever hit Japan, and the 4th most powerful earthquake in the world since modern record keeping started in 1900. The earthquake triggered powerful tsunami waves that reached run-up heights of up to 40.50 meters in Miyako in Tohoku (Iwate Prefecture) and in the Sendai area, travelled up to 10 km inland. The maximum inundation height was 19.5 m, and inundation area was 400 km^2 (approximate). The 2011earthquake generated a higher tsunami than the tsunami level determined for tsunami disaster management in communities such as the 1896 Meiji Sanriku tsunami. It caused devastated damage in wide areas by not only inundation but also tsunami-debris [1-5]. More than 20000 people were killed and a large number of structures were collapsed. Many coastal protection facilities (e.g. breakwaters, seawalls, river dikes, groins and jetties) were severely damaged.

Breakwaters are frequently used to protect seacoast ports and harbors from destructive effects of sea waves, typhoons and tsunamis, and create calm water for smooth operation of ships and cargoes. In addition, they protect coastal structures and lives from the destructive forces. But, many breakwaters were damaged severely by the 2011 off the Pacific Coast of Tohoku Earthquake and subsequent tsunami. The world's deepest breakwater at Kamaishi port (Iwate Prefecture, Japan) was also collapsed due to the 2011 earthquake and tsunami. Due to the failure of the breakwaters, the tsunami entered in coastal areas, and led to catastrophic losses for structures and population in the coastal areas. The failure of its foundation was main reason of collapse of the breakwater. Caissons were slid and toppled by the tsunami. This happened due to large difference in water level between the front and back of the breakwater during tsunami, which creates high water pressure on the breakwater. The tsunami wave also imposed a huge horizontal force on the breakwater. The main reasons of failure of the breakwater were [16 and 17] (i) Scouring of foundation mound, (ii) Sliding and turning of breakwater, (iii) Toe erosion and joint failure, (iv) Decrease in bearing capacity due to increase in pore water pressure, (v) Dynamic water pressure as wave force (vi) Water level difference between the front and back of the breakwater. Some other breakwaters of Japan such as Hattaro Breakwater in Hachinohe Port, Aomori Prefecture; Ryujin-zaki Breakwater at Miyako Port, Iwate Prefecture and breakwater at Onagawa Port, Miyagi Prefecture were also damaged due to the 2011 earthquake and tsunami. The damage to the mound and foundation was main reasons of failure of these breakwaters during the earthquake and tsunami.

Looking at the extent of damage or collapse of breakwater due to scouring and erosion by tsunami, it is, therefore, of utmost importance to develop and build tsunami-resistant breakwater and suggest practically applicable technology [8]. After 2011 off the Pacific Coast of Tohoku Earthquake, it becomes more important to develop countermeasures for breakwater foundation in order to construction earthquake and tsunami resistant breakwater, which can reduce the damage caused by compound geo-disaster brought by earthquake and tsunami in the future. To develop countermeasures, it is very important to understand failure mechanism of breakwater subjected to earthquake and tsunami. The mechanism of failure of breakwater foundation under such compound geo-disaster has not yet been completely revealed. Therefore, to determine the failure mechanism, this paper describes the stability of breakwater foundation subjected earthquake and tsunami using centrifuge model tests. In the study, both the earthquake and tsunami were considered for the stability of breakwater foundation. In order to correlate the research to real ground problem, two foreshocks and one main shock were used in the test. A series of centrifuge model tests were performed to determine the stability of the breakwater foundation subjected to earthquake and tsunami.

2. Centrifuge Model Tests

Centrifuge model tests were conducted using beam type geotechnical centrifuge machine at Disaster Prevention Research Institute, Kyoto University, Japan. Centrifuge model tests were conducted under 25 g gravitational fields.

2.1 Model Description

The Breakwater at Miyazaki port (Miyazaki Prefecture, Japan), which is likely to be affected by the predicted Nankai trough earthquake, is chosen as prototype for this research. Soil box, made from acrylic plates and steel frames, was used in the centrifuge model test. A water tank and movable gate were installed in the soil box to generate tsunami. The moveable gate can be operated by a signal sent from a remote computer. Due to limitations of the tsunami generation devices used in the soil box, the maximum centrifugal acceleration was limited to 25 g. The prototype to model ratio (N) was 225. Model breakwater (caisson type), made of aluminum, was filled with lead balls to adjust the weight (specific gravity 2.3) and center of gravity. The foundation soil was constructed using two layers of Toyoura sand. Lower layer is the bearing layer with relative density 90%, and upper layer is the foundation layer with relative density 60%. The rubble mound was made of crushed stone (rock A) with a relative density D_r=60% which was achieved by tamping. A three-dimensional view of the centrifuge model is shown in Fig. 1. The cross sectional view and instrumentations of the test model are shown in Fig. 2. The generalized scaling law proposed by Iai et al. [9] was adopted to determine the various parameters for the tests, which are shown in Table 1. The generalized scaling law is a combination of the scaling laws for centrifuge test and the laws for 1 g dynamic model test. In order to observe deformation of foundation soils, membranes (red color) were fixed on front wall of the soil box, and they were fixed in such a way that they can deform with soils during tests. The dotted lines (white color) were drawn on the front face of the soil box to see scouring during tsunami (see Fig. 5). As per the similitude law (see Table 1), fluid of viscosity 1.3×10^{-4} m^2/s (130cSt) at 25°C was used in the test. Properties of foundation materials are shown in Table 2. The dynamic characteristics of sand and stone were determined against cyclic loading through element tests, and which have been reported in Hazarika et al. [10].

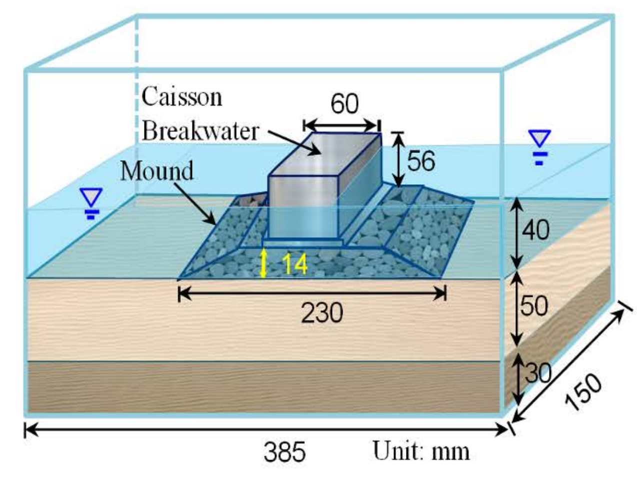

Fig. 1 Three dimensional view of the model

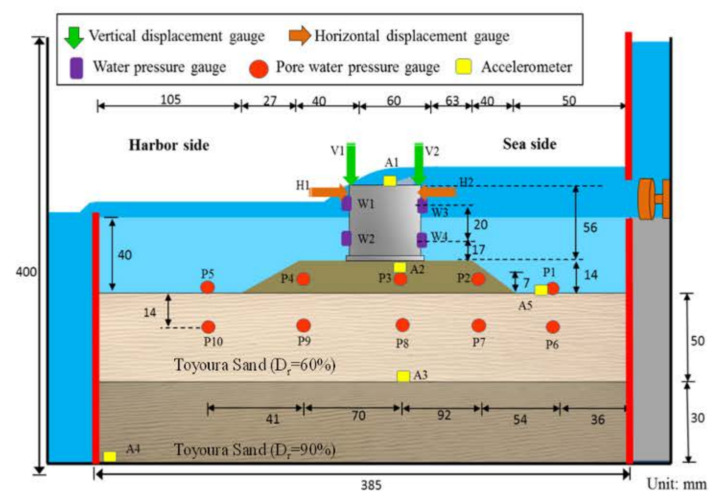

Fig. 2 Experimental setup and instrumentations for the test

2.2 Instrumentations and Procedures

Acceleration, water pressure, pore water pressure, settlements of the caisson, foundation soils and rubble mound were measured during the experiment. Accelerometers were installed to record acceleration at six locations (A1 to A6). Pore water pressure gauges were installed at ten locations (P1 to P10) to monitor the pore water pressures. Displacement gauges were installed at two locations (H1 and H2) to measure horizontal displacement of the caisson. Two displacement gauges were used at two locations (V1 and V2) to monitor the settlement of the caisson. Four water pressure gauges (W1 to W4) were installed to measure water pressures on the caisson.

Table1 Generalized similitude for centrifuge model test (25g)

Items	Partition		Generalized model (prototype/physical) (N=mn =225) (m=9 and n=25) (c)	
	Virtual 1g model (prototype /virtual model) (m) (a)	**Centrifuge model (virtual/ physical) (n) (b)**		
Length	m	n	mn	225
Density	1	1	1	1
Time	$m^{0.75}$	n	$mn^{0.75}$	130
Stress	m	1	n	9
Pore Water Pressure	m	1	n	9
Acceleration	1	1/n	1/m	0.04
Frequency	$1/m^{0.75}$	1/n	$1/(mn^{0.75})$	0.008
Permeability	$m^{0.75}$	n	$mn^{0.75}$	130
Bending Stiffness	$m^{3.5}$	n^4	$m^4\,n^{3.5}$	$8.54\text{x}10^8$
Axial Stiffness	$m^{1.5}$	n^2	$m^2\,n^{1.5}$	$1.69\ \text{x}10^4$

Table 2 Properties of foundation materials

Properties	Toyoura Sand	Rock-A
Specific Gravity, ρ_s	2.64	2.77
Dry Density ρ_d (g/cm^3)	1.5	1.6
Max. Dry Density (g/cm^3)	1.64	1.78
Min. Dry Density (g/cm^3)	1.34	1.42
Uniformity Coefficient, U_c	1.7	1.5
Mean Grain Size, D_{50} (mm)	0.16	4.7

2.3 Earthquake Loading and Tsunami Overflow

In the case of tsunami generating earthquake, the main shock of earthquake is preceded by several foreshocks. In order to correlate such real ground problem, two foreshocks and one main shock were used in the test. Earthquake loading was applied at the bottom of the soil box in the form of sinusoidal waves. The frequency and time of the loadings were kept same for foreshocks and main shock. However, magnitudes of acceleration were different for foreshocks and main shock. Time of earthquake loading was 1.4 sec (corresponds to 181 sec ≈ 3 min), and frequency was 83 Hz, which corresponds to 0.66 Hz (for prototype). The acceleration of 1st foreshock was 25 m/s^2 (corresponds to 1 m/s^2), and that for the 2nd foreshock was 50 m/s^2 (corresponds to 2 m/s^2). The acceleration of main shock was 100 m/s^2 (corresponds to 4 m/s^2). Sufficient time gap was provided between two loadings in order to dissipate pore water pressures completely inside the foundation soil and mound. Tsunami overflow test was performed after the main shock. Sufficient time gap was provided between the main shock and tsunami overflow.

3. Results and Discussions

Stability of the breakwater is discussed in terms of settlement and horizontal displacement of the caisson during earthquake loadings and tsunami overflow.

3.1 Effects of Earthquakes

Settlement of the caisson was measured under different acceleration magnitudes (foreshocks and main shock), and is shown in Fig. 3. It can be observed that the settlement increases with the acceleration. The excess pore water pressure increases with the increase in acceleration. It causes the decrease in shear strength and bearing capacity of the foundation, and leads to increase in settlement of the caisson. Settlement of the caisson, measured at V1, is shown in Fig 3. It can be seen that the settlement is 3.5 mm for the 1st foreshock (25 m/s^2), and increases to 7.2 mm during the 2nd foreshock (50 m/s^2). It finally increases to 22.4 mm at the end of the main shock (100 m/s^2). It can be noticed that the settlement increases to 2.2 times as acceleration increases from 25

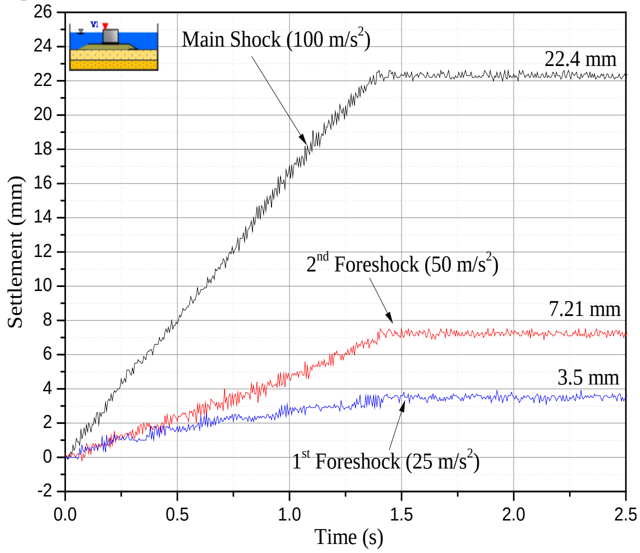

Fig. 3 Settlement of the caisson measure at V1 during earthquake loading

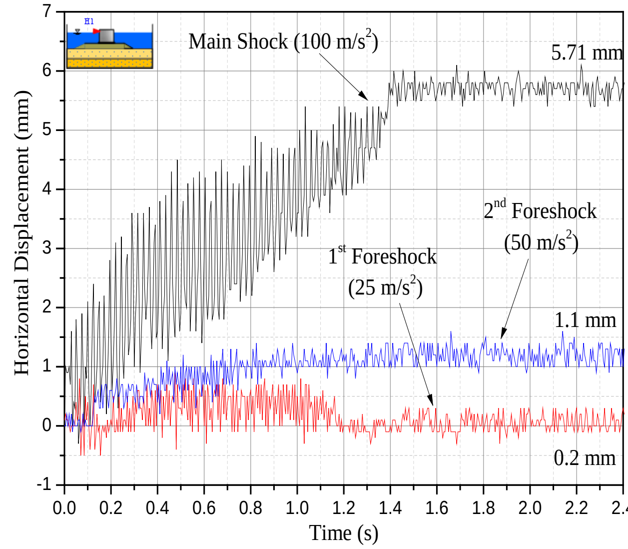

Fig. 4 Horizontal displacement of the caisson measure at H1 during earthquake loading

m/s^2 to 50 m/s^2, and increases to 6.4 times as acceleration increases from 25 m/s^2 to 100 m/s^2. The settlement increases very high during the main shock as compared to the foreshocks.

Horizontal displacements (measure at H1) of the caisson for different acceleration magnitudes are shown in Fig. 4. Horizontal displacement increases with the increase in acceleration. The pore water pressure increases with the increase in acceleration. It causes decrease in shear strength and bearing capacity of the foundation, and finally cause of increase in horizontal displacement of the caisson. It can be seen in Fig. 4 that the horizontal displacement is 0.2 mm for the 1st foreshock (25 m/s^2), and increases to 1.1 mm during the 2nd foreshock (50 m/s^2). Its value further increases to 5.7 mm at the end of the main shock (100 m/s^2). It can be noted that the horizontal displacement increases to 5.5 times as acceleration increases from 25 m/s^2 to 50 m/s^2, and increases to 28.5 times as acceleration increases from 25 m/s^2 to 100 m/s^2.

3.2 Effects of Tsunami Overflow

The tsunami overflow test was performed on the same deformed model after few minutes of the main shock. To observed effect of the tsunami, the photograph of the model before and after tsunami overflow is compared. Fig. 5 shows the breakwater before earthquake. Fig. 6 shows the breakwater after earthquake (main shock) and before tsunami overflow. It can be observed that the breakwater settled heavily inside the mound and the foundation. The mound and foundation soil were deformed severely (as the membraned deformed). Fig. 7 shows photograph of the model after tsunami overflow test. It can be observed that almost whole the mound (encircled) was scoured on harbor side of the caisson. All the stones of the mound were washed away by the tsunami. The seabed was also damaged by the tsunami due to seepage. The seabed was scoured, and sand was piled up on the harbor side by the tsunami waves. Seepage of water occurred below the caisson, and it was concentrated mostly through the mound. However, significant amount of seepage was also observed through the upper soil layer. No significant settlement and horizontal displacement of the caisson was observed during tsunami overflow test. There are two possible reasons for it. One is that the caisson had already settled heavily (almost 50% of its height) inside the foundation during the main shock, and tsunami struck it under this deformed condition. Due to very high settlement of the caisson during earthquake, further settlement was not possible during tsunami. Another reason is that due to limitation of soil box, maximum amount of water used for tsunami was limited to 6 liter only, and it might be possible that the tsunami generated by that amount of water did not able to impose sufficient force on the embedded caisson for further settlement.

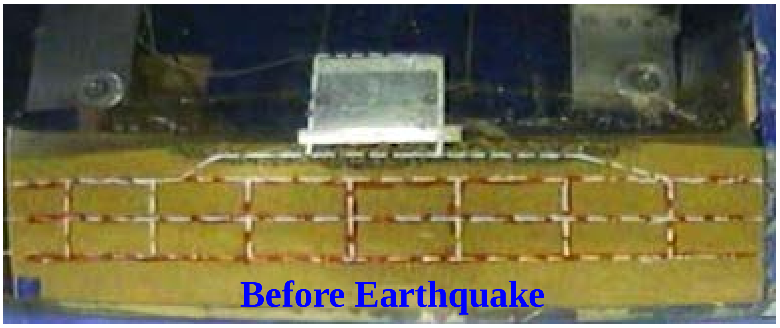

Fig. 5 Breakwater before earthquake

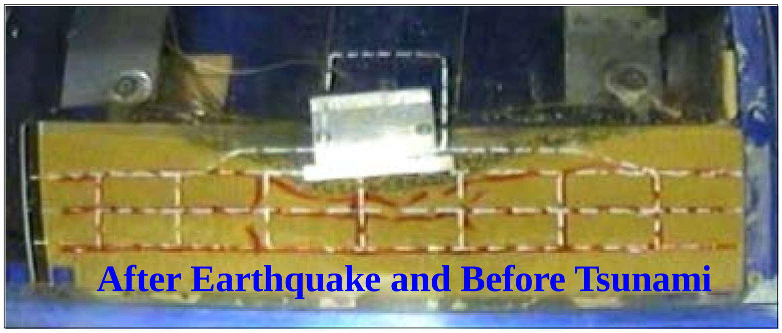

Fig. 6 Breakwater after erathquake (before tsunami overflow)

Fig. 7 Breakwater after tsunami overflow

4. Conclusions

The stability of breakwater has been discussed against earthquake and tsunami using centrifuge model tests. Two foreshocks and one main shock were used as earthquake in the study. In addition to mound, foundation soils were also used as seabed.

1) The settlement and horizontal displacement of the caisson increase with the increase in acceleration of the earthquake loading. It is due to the fact that pore pressure increases with acceleration, which leads to high deformation of the foundation soil and increase of shear strain. These factors reduce effective stress and shear strength, and finally became reasons for decrease in bearing capacity of the foundation.

2) The breakwater showed very high settlement and horizontal displacement during high intensity earthquake (e.g. 100 m/s^2).

3) In the case of tsunami, high scouring of the mound occurred on the harbor side. Seepage of water occurred below the caisson, and it was concentrated mostly through the mound. However, significant amount of seepage was also observed through the upper soil layer. Some scoured sand was piled up on harbor side by

tsunami waves. The seepage force reduced confining pressure and shear strength. Thus, bearing capacity of the foundation soil significantly reduced under tsunami.

The countermeasures for breakwater foundation against earthquake and tsunami have been developed to make the breakwater resilient, and can reduce the damage caused by earthquake and tsunami induces forces [11]. Experiments are ongoing to evaluate effectiveness of the techniques. Further studies include centrifuge model tests, hydraulic tests, shaking table tests and numerical simulations to clarify resiliency characteristics of the techniques.

5. Acknowledgements

This study was funded by the Japan Iron and Steel Federation under priority themes research grant. The authors express their deep gratitude for this financial support. A part of the financial support for conducting the tests was provided by Kyushu University under P & P research grant. The authors express his deep gratitude for that. Special thanks go to Dr. Tetsuo Tobita, Dr. Kyohei Ueda and Ms. Ayako Namigishi of Kyoto University for their support and cooperation during conducting the centrifuge model tests at Disaster Prevention Research Institute (DPRI), Kyoto University.

5. References

[1] Arikawa T, Sato M, Shimosako K, Hasegawa I, Yoem GS, Tomita T (2012): Failure Mechanism of Kamaishi breakwater due to the great east Japan earthquake tsunami. *Proceedings of 33rd Conference on Coastal Engineering*, Santander, Spain, 1-13.

[2] Hara T, Ohkawara M, Ohsumi T, Yamanaka M, Ishihara Y, Tsunekawa Y (2012): Damage of southern central part of coastal region of Iwate prefecture due to off the Pacific Coast of Tohoku Earthquake. *Geotechnical Engineering Magazine, Japanese Geotechnical Society*, 7, 25-36.

[3] Hazarika H, Kataoka S, Kasama K, Kaneko K, Suetsugu D (2012): Composite ground disasters caused by the earthquake and tsunami in Aomori, Iwate Prefecture, northern. *Geotechnical Engineering Journal, Special Issue on 2011 Great East Japan Earthquake*, 7(1), 13-23 (in Japanese).

[4] Hazarika H, Hara T, Furuichi H (2013a): Soil structure interaction during earthquake and tsunami- Two case studies from the latest disaster in Japan. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, France, 131-142.

[5] Hazarika H, Kasama K, Suetsugu D, Kataoka S, Yasufuku N (2013b): Damage to geotechnical structures in waterfront areas of northern Tohoku due to the march 11, 2011 tsunami disaster. *Indian Geotechnical Journal*, 43(2), 137-152.

[6] MLIT (2011): Earthquake and tsunami resistant measures against ports in Tohoku area. Technical Committee Report No. 3, *Ministry of Land, Infrastructure, Transport and Tourism, Government of Japan* (in Japanese).

[7] MLIT (2013): Guidelines for earthquake resistant design of breakwaters. *Reference Materials, Ministry of Land, Infrastructure, Transport and Tourism, Government of Japan* (in Japanese).

[8] JGS (2014): Report of the technical committee for tsunami resistant geotechnical structures. *Proceedings of the special symposium of Japanese Geotechnical Society on the Great East Japan Disaster*, 33-42 (in Japanese).

[9] Iai S, Tobita T, Nakahara T (2005): Generalized scaling relations for dynamic centrifuge tests. *Geotechnique* 55(5), 355–362.

[10] Hazarika H, Hara T, Nishimura K, Yamasaki N, Monji N, Chaudhary B, Ishikura R, Kasama K (2016): Fundamental study on seismic resistant behavior of caisson type breakwater foundation reinforced by steel sheet pile and gabion. *Journal of Japan Association for Earthquake Engineering*, 16(1), 184-204 (in Japanese).

[11] Hazarika H, Chaudhary B, Monji N, Ishikura R, Kasama K, Hara T, Yamazaki N, Noda T, Yamada S (2015): Resilient Breakwater Foundation against Level II Earthquake and Tsunami. *Proceedings of 6th International Geotechnical Symposium on Disaster Mitigation in Special Geoenvironmental Conditions*, Chennai, India, 35-46(Keynote).