Model testing on resilient solution for breakwater protection against tsunami

Hemanta Hazarika\textsuperscript{i)}, Kengo Nishimura\textsuperscript{ii)} and Babloo Chaudhary\textsuperscript{iii)}

\textsuperscript{i)} Professor, Graduate School of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan.
\textsuperscript{ii)} Master Student, Graduate School of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan.
\textsuperscript{iii)} Ph.D Student, Graduate School of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan.

ABSTRACT

Tsunami waves generated by the 2011 off the Pacific Coast of Tohoku Earthquake caused catastrophic damage to waterfront structures, such as breakwaters and sea walls. Countermeasures of compound disaster by future mega earthquake such as, Nankai megathrust earthquake and subsequent tsunami, are issues that should be resolved urgently. Therefore, the authors developed reinforcing technique of breakwater foundation using steel sheet piles and gabions that can minimize damage subjected to the tsunami higher than the design tsunami level. In this research, hydraulic model tests were performed to evaluate tsunami resistant characteristic of proposed reinforcing technique. Results of this research revealed that the settlement and the inclination of the caissons during tsunami could be significantly reduced by the proposed reinforced reinforcing technique.

Keywords: breakwater, resiliency, scouring, seepage, tsunami

1 INTRODUCTION

Tsunami waves generated by the 2011 off the Pacific Coast of Tohoku Earthquake caused catastrophic damage to waterfront structures, such as breakwaters and sea walls. Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan classified the damage pattern of breakwaters into four types: 1) scouring due to overflow, 2) force of tsunami wave, 3) scouring around both ends of breakwater, and 4) difference in water level due to backrush (MLIT, 2011; MLIT, 2013). For example, in the case of the caisson type breakwater at Hachinohe Port, Aomori Prefecture, overflowed water of tsunami generated strong water flow and whirlpools, resulting in scouring of the rubble mound and the foundation ground. This in turn, made the breakwater unstable and it ultimately collapsed. This means that scouring of the rubble mound and the foundation ground is connected to breakwater instability, and strong wave forces finally cause the tilting/overturning of the caisson type breakwater. Moreover, it was revealed that seepage flow in the rubble mound results in the decrease of bearing capacity of rubble mound (Kasama et al. 2014). Therefore, it is important to consider the combined effect of scouring, seepage, wave force, and resulting decrease of bearing capacity of breakwater foundation in a comprehensive way.

On the other hand, countermeasures of compound disaster by predicted Nankai megathrust earthquakes and subsequent tsunami are issues that need to be tackled urgently. Hazarika (2013) developed a resilient reinforcing technique of breakwater foundation (Fig. 1.) using steel sheet piles and gabions that can minimize damage subjected to the tsunami higher than the design tsunami level. Many other methods for reinforcing breakwater foundation against tsunami have been developed in Japan. For example, constructing the widening work on the rubble mound (Arikawa et al. 2013), installing a row of steel pile in the harbor side of the breakwater mound (Oikawa et al. 2014), and putting armor units (concrete blocks) on harbor-side rubble mound (Maruyama et al. 2012). However, all those techniques did 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 levee crown is very effective for reducing the run-up height. Therefore, it is necessary to

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{breakwater_design.png}
\caption{Reinforcing technique of breakwater foundation using steel sheet piles and gabions.}
\end{figure}
consider the various forces caused by both earthquake and tsunami. The technique developed by Hazarika et al. (2015b) is a step forward in this direction. To evaluate the effectiveness of the proposed technique shaking table tests, cyclic triaxial tests, and numerical simulation were conducted to evaluate characteristics of proposed reinforcing technique (Hazarika et al. 2015a).

The purpose of this research is confirming the effectiveness of the proposed technique against tsunami and developing the reinforcing technique of breakwater foundation. The authors developed the hydraulic experiment apparatus that can observe not only rubble mound of breakwater but also sea ground, and hydraulic model tests were performed to evaluate the tsunami resilient characteristic of proposed reinforcing technique. The authors reproduced tsunami overflow state during the tests to estimate the effect of steel sheet piles and gabions, and installed displacement gauges, acceleration gauges, water pressure gauges, pore water pressure gauges and cameras to make clear the state of the breakwater model. To that end, the authors compared two conditions: breakwater with no reinforcement and breakwater reinforced by four rows of steel sheet piles and gabions.

2 OUTLINE OF HYDRAULIC MODEL TEST

2.1 Methodology

The authors developed a hydraulic experiment apparatus. The apparatus has the provision of not only reproducing one-way water reflux but also has the provision to reproduce the foundation soils and the seabed. The picture of this apparatus and the breakwater model is shown in Fig. 2. The dimension of the apparatus is as follows: H 1.0 m × W 0.4 m × L 5.0 m. The schematic drawing of this apparatus is shown in Fig. 3. and Fig. 4.

![Fig. 2. The model and the apparatus](image)

![Fig. 3. The dimension of the apparatus (Sectional view)](image)

![Fig. 4. The dimension of the apparatus (Plain view)](image)

2.2 Setting up of the model

The authors simulated the caisson type breakwater at Miyazaki Port, Miyazaki Prefecture, which is likely to be affected by the predicted Nankai trough earthquake in the near future. A prototype to model ratio of 64 was adopted in the test. Relative density (Dr) of bearing ground was 90 %, and this layer was made by heavy compaction. Relative density of foundation ground was 60 %, and this layer was prepared by air pluviation. Both layers were made of Toyoura Sand. The model of rubble mound was made of crushed stones, and grain size was 5.0 ~ 9.5 mm. The model steel sheet pile was made of one steel sheet. The gabions were modeled by based on the prototype gabion (10 ton type) used in harbor. The caisson model was made of aluminum sheet, and specific gravity was set to 2.3. Three such caissons were used and they could move independently during this test. Measuring devices, such as four displacement gauges, two acceleration gauges, four water pressure gauges, and fourteen pore water pressure gauges were installed, as shown in Fig. 5. In addition, videos were recorded during the test from the side and top of apparatus.

![Fig. 5. Test model and locations of measuring devices](image)
2.3 Test Conditions

Experimental conditions in this test are shown in Table 1. Initial water level was set to 14.0 cm, this value was modeled on L.W.L. (low water level) of Miyazaki Port. When overflow of water became stable, water level of the sea side was 28.0 ~ 28.5 cm, and that of the harbor side was 15.5 cm, and the overflow height was 3.0 ~ 3.5 cm. Two cases were performed this time: Case 1 was for breakwaters with no reinforcement, Case 2 was for breakwaters with four rows of steel sheet piles and gabions, as shown in Fig. 6. Two steel sheet piles were installed in the toe of the mound and another two were installed at both ends of the caissons.

Table 1: Test conditions

| Cases          | Case 1                     | Case 2                     |
|----------------|----------------------------|----------------------------|
| Reinforcement  | Breakwaters with no reinforcement | Breakwaters with four rows of steel sheet piles and gabions |
| Spacing between caissons (cm) | 0.2                         | 0.2                         |
| Initial water level (cm)       | 14.0                        | 14.0                        |
| Overflow height (cm)           | 3.0                         | 3.5                         |
| Water level of sea side (cm)   | 28.0                        | 28.5                        |
| Water level of harbor side (cm)| 15.5                        | 15.5                        |
| Water flow (L/min)             | 440.0                       | 440.0                       |

Behavior of breakwater during tsunami overflow in Case 1 breakwater are shown in Fig. 7. The time when the pump started supplying water was t = 0 minutes, and pictures are shown at intervals of three minutes. As shown in t = 3 minutes, seepage flow through the rubble mound and the foundation soil occurred from sea side to harbor side because of water level difference. This seepage flow scoured the foundation ground under the caissons. At the same time, the rubble mound at the harbor side was scoured by water flow and whirlpools of overflow water. Until t = 6 minutes, seepage water and overflow water continued to scour the mound and the ground, then the caissons settled and inclined towards the sea side because scouring by seepage was more dominant than that of overflow water at that time. At t = 6 minutes, the settlement and the inclination of the caissons gradually stopped, and they started to settle and incline towards the harbor side. This was because of collapse of the developed hole in the harbor side mound. Until t = 12 minutes, damage to the mound and the ground by seepage water continued, and boiling of sand was also observed. At t = 17 minutes, when the pump stopped supplying water, all three caissons inclined towards the harbor side.

3 TEST RESULTS

3.1 Behavior of breakwater during tsunami overflow

Behavior of breakwater during tsunami overflow in Case 2 (reinforced breakwater) are shown in Fig. 8. The time when the pump started supplying water was t = 0 minutes, and pictures are shown at intervals of three minutes. A kind of V-shaped settlement of the mound was observed along sheet pile model, but this occurred because of small gap between the sheet pile model and the acryl wall of the apparatus due to some error during setup. In the actual construction of the technique, such boundary effect will not exist and this V-shaped settlement will not occur. As shown in t = 3 minutes, scouring by seepage flow and scouring by overflowed water were not occurred, but small scouring was observed in the harbor side ground. From t = 3 minutes to t = 9 minutes, scattering of gabions were observed at several places, but damage to rubble mound was insignificant as compared to Case 1 because of the
presence of gabions. At \( t = 14 \) minutes, when the pump stopped supplying water, it was found that the settlement and the inclination of the caisson were remarkably reduced compared with that of Case 2.

From the above, it was revealed that steel sheet piles and gabions had excellent reinforcing effect for tsunami. Steel sheet piles could block off the seepage flow through the mound and the ground, thus scouring by seepage flow was greatly reduced. Gabions could decrease forces of overflow water, thus they protected the mound from scouring. Therefore, the proposed reinforcing method using steel sheet piles and gabions could make breakwaters resilient against tsunami overflow.

![Fig. 8. Behavior the reinforced breakwater](image)

3.2 Horizontal and Vertical Displacement of the Caisson

The horizontal displacement and vertical displacement of the caisson at the end of test are shown in Fig. 9 and Fig. 10, respectively. The location of displacement gauges, D-1, D-2, D-3, and D-4 are shown in Fig. 5. In Case 1, the caisson moved towards the harbor side drastically, thus the settlement and the inclination were extremely large. However, both displacement of the caisson were significantly reduced in Case 2. The displacement of D-4 was higher than that of D-3, implying that the caissons inclined towards the harbor side. Therefore, it could be inferred that the displacement of the caisson models could be significantly reduced by reinforcing with steel sheet piles and gabions.

![Fig. 9. Horizontal displacement of the caisson](image)

3.3 Damage of the Mound and Gabions

The states of the mound and gabions before and after test are shown in Fig. 11. Those pictures were upper view of the breakwater model in the harbor side. In Case 1, it was seen that the mound was completely scoured by overflow water, and scouring reached the ground in several places. The caissons moved significantly, thus it can be seen that the breakwater was completely destroyed. On the other hand, in Case 2, the scouring of the mound was significantly reduced, and only the scattering of gabions were observed in both sides of the waterway. The reason for this could be attributed to the water flow between the sheet pile model and the acryl wall, which imparted uplift force to gabions, and, as a result, they were prone to be carried away by the overflowed water.

![Fig. 11. The states of the mound and gabions before and after the test](image)

4 CONCLUSIONS

The following conclusions could be made based on this research. The authors deduced that factors such as seepage and scouring weakened the foundation of breakwaters. It could be confirmed that proposed reinforcing technique had dominant effects against seepage and scouring.
1) Seepage flow took place through the rubble mound from the sea side to the harbor side because of water level difference. This seepage flow scoured the foundation ground under the caissons, and this caused the settlement and the inclination of the caissons.

2) Water current and whirlpools generated by the overflowed water scoured the rubble mound in the harbor side. This caused the settlement and the inclination of the caissons.

3) Steel sheet piles could block off the seepage flow through the mound and the ground, thus scouring by seepage flow was greatly reduced. On the other hand, gabions could decrease forces of overflow water, and, thus they protected the mound from scouring.

4) The horizontal and vertical displacement of the caissons were significantly reduced by reinforcing with steel sheet piles and gabions.

However, there are few points for improvement in the setup of the model, such as mistake in installing pore water pressure gauges and small gap produced between the sheet pile model and the acryl wall which resulted in the V-shaped damage. Furthermore, from the point of seepage and scouring, it was estimated that the two sheet piles installed in the toe of the mound were not important for tsunami overflow, however, from the earthquake damage point of view those two are very important. The tests were carried out this time without considering the effect of earthquakes. In the future such effects (combining shaking and overflowing) needs to be considered.

ACKNOWLEDGEMENTS

This study was funded by the Japan Iron and Steel Federation under priority themes research grant (2012-2015). The authors express their deep gratitude for this financial support.

REFERENCES

1) Arikawa, T., Sato, M., Shimosako, K., Tomita, T., Yeom, G.S., and Niwa, T. (2013): Failure Mechanism and Resiliency of Breakwater under Tsunami, Technical Note of the Port and Airport Research Institute, No.1269 (in Japanese).

2) Hazarika, H. (2013): Development of seismic and tsunami resistant breakwater using steel sheet piles and gabions, Annual proceedings of Japan Iron and Steel Federation, Tokyo, Japan, 83-88 (in Japanese).

3) Hazarika, H., Chaudhary, B., Monji, N., Ishikura, R., Kasama, K., Hara, T., Yamazaki, N., Noda, T., and Yamada, S. (2015a): 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.

4) Hazarika, H., Hara, T., Nishimura, K., Yamasaki, N., Monji, N., Chaudhary, B., Ishikura, R., and Kasama, K. (2015b): 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 (Accepted for publication in Japanese).

5) Kasama, K., Zen, K., and Kasugai, Y. (2014): Stability evaluation for the caisson-type composite breakwater under tsunami condition. Proceedings of the Special Symposium of Japanese Geotechnical Society on the Great East Japan Disaster, Tokyo, Japan, 696-702 (in Japanese).

6) Maruyama, S., Matsumoto, A., and Hanzawa, M. (2012): Experimental Study on Stability of Armor Units for Harbor-Side Rubble Mound of Composite Breakwater against Tsunami, Journal of Japan Society of Civil Engineers, Ser. B3 (Ocean Engineering), Vol. 68, No. 2, I.7-1 12 (in Japanese).

7) 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).

8) MLIT (2013): Guidelines for tsunami resistant design of breakwaters. Reference Materials, Ministry of Land, Infrastructure, Transport and Tourism, Government of Japan (in Japanese).

9) Oikawa, S., Kikuchi, Y., Kawabe, S., Mizuno, R., Moriyasu, S., Tanaka, R., and Taenaka, S. (2014): An Experimental Study for Reinforcing Construction of Breakwater with Structural Steel, Proceedings of the Special Symposium of Japanese Geotechnical Society on the Great East Japan Disaster, Tokyo, Japan, 703-709 (in Japanese). (reference with DOI is also recommended)