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Development of New Type of Breakwater Reinforced with Steel Piles against a Huge Tsunami

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Abstract

"Persistence" is needed for breakwaters, since the coastal areas of Tohoku have been extensive damaged by Great East Japan Earthquake (Mw 9.0). Therefore, Nippon Steel & Sumitomo Metal Corporation has been developing a reinforcement method for breakwaters with steel piles. This method has showed persistent characteristic on the lateral load experiment, and clarified the resistance mechanism by FEM. In addition, this method has showed stability for the breakwaters on the hydraulic experiment. This paper shows the main of the study results, and introduces the original plan for the design method and construction method.

1. Introduction

1.1 Breakwater damage by the Great East Japan Earthquake and the changes thereafter

Devastating damage was incurred by the huge tsunamis that followed the gigantic Great East Japan Earthquake. With respect to breakwaters being the first defense against tsunamis, about 90%, 70%, and 50% of the breakwaters at Soma Port, Kamaishi Port, and Hachinohe Port were destroyed, respectively, and those facilities failed to sufficiently prevent tsunami damage in their respective hinterlands. **Photos 1** [1] **and 2** [2] show examples of the breakwater damage by the tsunami. While these breakwaters were extensively damaged, as is evident in the photos, their worth was also proven as it is estimated that the breakwaters resisted the tsunami for a certain period of time, which elongated additional time for residents to evacuate.[1]

In response to the damage experienced and in preparation for the Tonankai and Nankai Earthquakes that are highly likely to occur in the near future, an effort to build national resilience is being promoted. To support the vital themes of disaster prevention and mitigation, in September 2013, the Ministry of Land, Infrastructure, Transport, and Tourism provided Guidelines for the Tsunami-Resistant Design of Breakwaters.[3] With details to be explained later, these guidelines require breakwaters to be resistant to a gigantic tsunami,

Photo 1 Dameged breakwaters in Kamaishi Port [1]

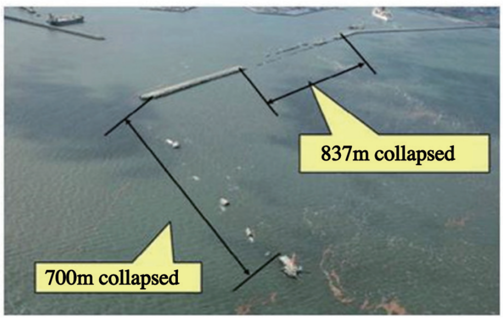

Photo 2 Dameged breakwaters in Hachinohe Port [2]

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such as the one that occurred following the Great East Japan Earthquake, without undergoing brittle failure. In the disaster prevention and mitigation effort, in addition to structural measures, it is important to take comprehensive measures with respect to non-structural issues, such as the provision of disaster damage information and guidance of evacuees. The inclusion of breakwaters is particularly important, which play pivotal roles that include delaying the run-up of tsunami waves to elongate time for evacuation and save evacuee lives and providing one of multiple hinterland defenses along with storm surge barriers.

1.2 Outline of the steel-pile reinforcement method with existing breakwaters

To construct tough breakwaters, Nippon Steel & Sumitomo Metal Corporation, jointly with the Port and Airport Research Institute, Tokyo University of Science, and the Coastal Development Institute of Technology, developed a system for reinforcing existing breakwaters with steel piles (hereafter, the steel pile method). **Figure 1** shows the structure of the steel pile method, in which steel piles are driven a short distance away from the port side of the caisson, and the clearance between the caisson and the steel piles is filled with rubble. Steel piles and fill are located longitudinally alongside the caissons. What characterizes this method is that the steel piles transform caisson-type composite breakwaters from gravity construction to embedded construction, to obtain sufficient toughness by actively utilizing the inherent toughness of steel and the resistance of the ground. When a breakwater is small in scale, steel sheet piles may be used instead of steel pipe pile.

The reinforcement method presented in the aforementioned guidelines is basically the reinforcement of a caisson-type composite breakwater with backfilling of rubble at the port-side base of the breakwater [3] (hereafter, the widening works), as schematically diagrammed in **Fig. 2**. Widening work was originally adopted to reduce wave action and improve the calmness of waters in the port area. Its function has now been extended to help stabilize ports against tsunamis. However, as shown in **Fig. 3**, the reinforcement of widening work involves an area that is wider than that of the existing breakwater. It may, therefore, interfere with the fairway when there is not enough space around the breakwater. In contrast, the reinforced area of the steel pile method is contained within the area of the existing mound, and therefore has only a small impact on fairways.

In this paper, we describe our major research outcomes, compare the reinforcement effect of the steel pile method with that of widening work, and present the design and construction procedures we used in applying the steel pile method to an actual breakwater in order to evaluate its tsunami-resistant capabilities.

2. Development

2.1 Understanding of basic resistance characteristics by aerial model loading experiment

To determine the basic resistance characteristics and reinforcement effects of a steel-pile reinforced breakwater, we conducted a sandbox laboratory experiment without water. [4] The geometric scale of our model is 1/60 the actual size. We formed an area of sandy ground in a rectangular sand box, in which we placed a caisson and a steel plate to simulate a steel pile, and then applied force to the caisson in the lateral direction with a jack (0.6 mm/min). **Photo 3** shows the experimental procedure, and **Table 1** lists the experimental cases and major details of each case.

Figure 4 shows the relationship between the resistance and displacement of each case. The resistance force of the case with no reinforcement (Case 1) reached an upper limit of 1.1 N/mm, and that of the widening work (Case 2) increased to 1.5 N/mm, which indi-

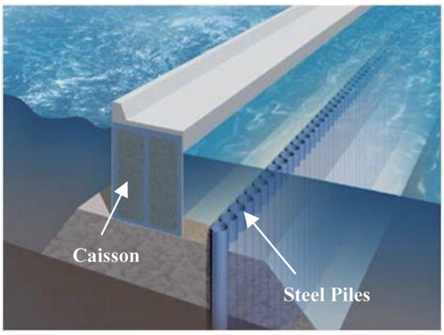


Fig. 1 Breakwater reinforced with steel piles

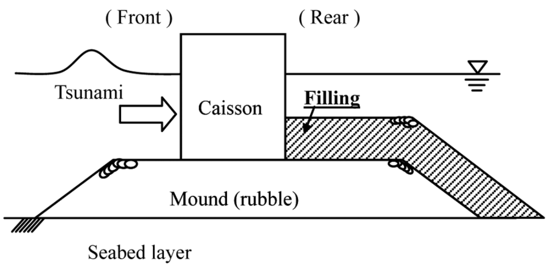


Fig. 2 Breakwater with widening works

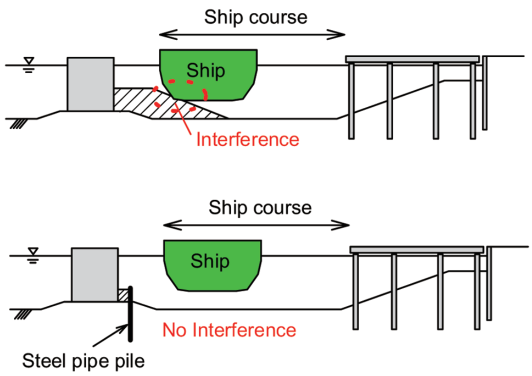


Fig. 3 Comparison of the reinforcement space between the widening works and steel piles

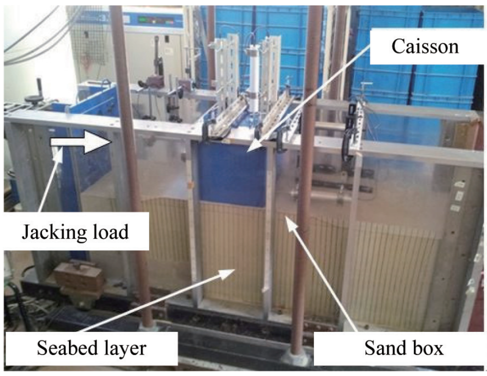
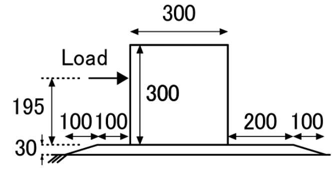
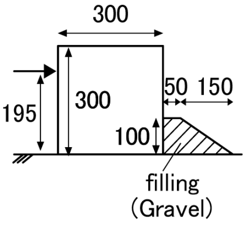
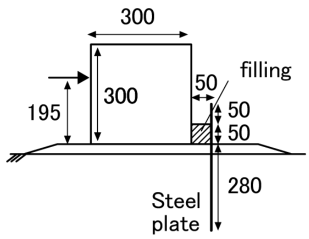
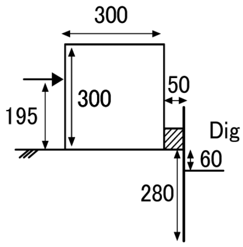


Photo 3 Photo of the lateral load experiment

Table 1 Cases of the lateral load experiment

Case 1	Case 2	Case 3	Case 4
Non reinforcement	Widening works	Reinforced with steel piles	Digging of Case 3
			
Unit weight of caisson: 22 kN/m³ Friction factor of caisson bottom: 0.6		Steel plate 380 depth × 380 width × 3.2 thickness	Digging depth: 60

(mm)

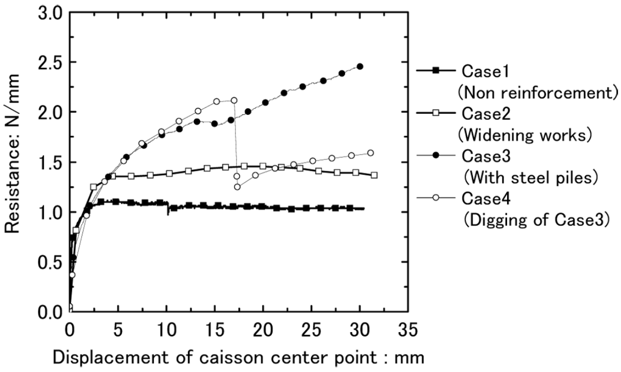


Fig. 4 Relationship between resistance and displacement

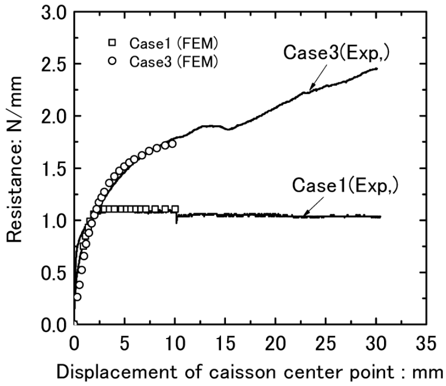


Fig. 5 Comparison of the load-displacement relationship between the experiment and FEM

cates that this method has a reinforcement effect. However, once the resistance reached the upper limit, no further increase occurred in either case. In contrast, although deformation rigidity decreased at a rate of about 1.5 N/mm in the steel pile method case (Case 3) (hereafter, yield load), the resistance force continued to gradually grow with an increase in horizontal displacement. We confirmed that the stress that occurs in the steel plate reached a maximum at the middle of the widened body and remained in the elastic range under the ultimate load. For the cross-section assumed to be scoured (Case 4), the load was temporarily released when the caisson displacement reached about 17 mm, whereupon the ground behind the steel plate was excavated to a depth of 60 mm, and the load was reapplied. While the resistance immediately after excavation dropped, it went up again. As explained above, these results suggest that the steel pile method has tough resistance characteristics that work under large loads and deformation, and also have applicability for scour control.

2.2 Clarification of the resistance mechanism by numerical analysis

Next, we again conducted the experimental simulation discussed in the previous section using the finite element method (FEM) to clarify the resistance mechanism.[5] In this experiment, we simulated Case 1 (without reinforcement) and Case 3 (steel pile method) only. We used the same model dimensions and physical values as those in the previous experiment, and applied the Mohr-Coulomb model for the constitutive law for the ground. For our analysis, we applied PLAXIS2012 program software. **Figure 5** shows the relationship between resistance and displacement, as revealed by our FEM results. By applying the infinitesimal deformation theory, our simulation calculation reached a horizontal displacement range of about 10 mm (or 600 mm in the actual size). The results in this range almost agree with our experiment results, and we also reproduced the yield load and subsequent increase in gradual residence. This calculation range is excellent in terms of the analysis of major behavior, and thus confirmed the validity of our use of FEM.

We analyzed the resistance mechanism of the steel pile method from the FEM analysis results, as follows. To begin with, the lateral stress distribution in **Fig. 6** shows that the loaded weight is transmitted from the caisson's steel pile bottom side to the steel piles via the backfill and the ground just beneath it. Great compressive stress occurred in the ground outside the steel pile, or opposite the caisson. This means that this area of ground resists the load.

As shown in **Fig. 7**, when we extracted the bottom frictional force of the caisson (R1) and the backfill reaction force (R2), the bottom frictional force (R1) reached the upper limit when the entire resistance (R) almost reached the yield load, and the backfill reaction force (R2) alone increased thereafter. This indicates that, after the yield load, resistance is provided by the backfill reaction force.

Lastly, **Fig. 8** shows the distribution of the subgrade reaction of the steel piles. Subgrade reaction distribution is the distribution of stress in the lateral direction and is the difference between the stress in the soil acting on the caisson side to the steel piles in the vertical direction and the resistance stress acting on the opposite side of the caisson. It indicates that the subgrade reaction of the area in contact

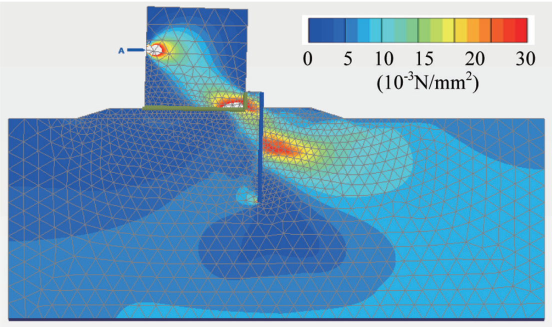


Fig. 6 Compressive soil stress in lateral direction

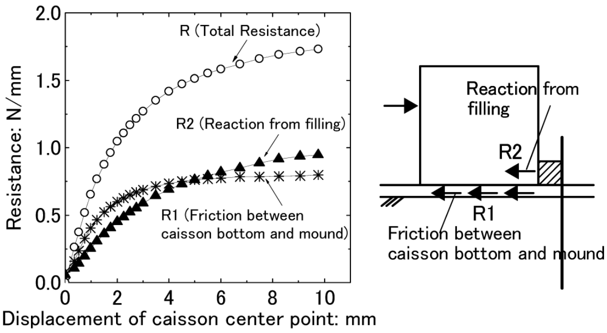


Fig. 7 Reaction force in horizontal direction

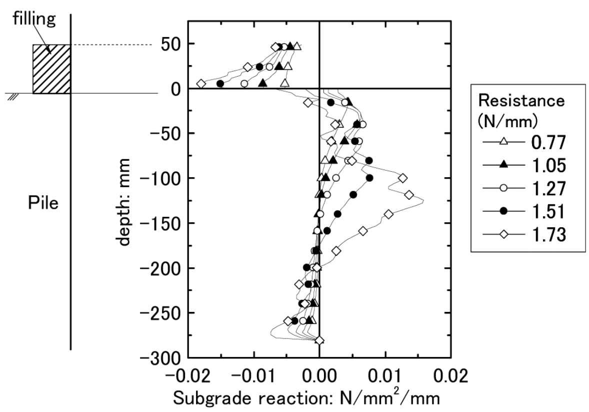


Fig. 8 Subgrade reaction of steel pile

with the backfill is negative, that the steel piles are pushed from the caisson side, that the reaction is positive in the seabed ground, and that the ground opposite the caisson resists the load. The greater the load, the deeper is the maximum value of the subgrade reaction, indicating the resistance being provided by the deeper ground.

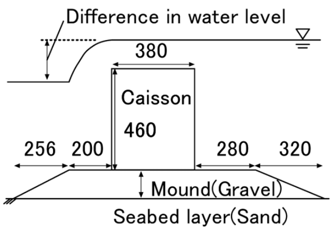
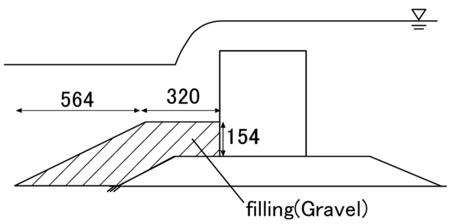
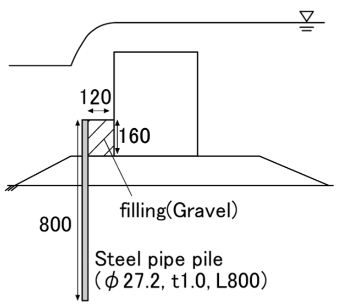
2.3 Examination of failure mode under tsunami overflow in hydraulic model experiment

When an actual breakwater is destroyed, it is affected by the overflowing waves. As such, in addition to the aerial model loading experiment discussed earlier, we conducted a hydraulic model experiment in order to examine the failure mode under a tsunami overflow.[6] The geometrical scale of the model is 1/25 the actual size, and we made a gravel mound on the sandy seabed. **Table 2** lists the experimental cases and their major details. The bottom of the mound was widened by gravel in Case B (widening work), while stainless steel pipes were driven underground, and backfilling was carried out with the gravel in Case C (steel pile method). We simulated a tsunami by filling the box with water, with a water level difference between the port and ocean sides of the caisson, such that when the ocean-side water level exceeded the caisson top, the water overflowed the caisson.

Photo 4 shows the experimental results. In Case A with no reinforcement, the overflowing tsunami scoured the mound and seabed at a designed water level difference of 20 cm (5 m in the actual size), and the mound collapsed due to the load exceeding the bearing capacity (Photo 4 (b)). In Case B with widening work, the widened part was scoured at the designed water level of 20 cm, but the scattered gravel settled near the slope end of the mound. As a result, scouring did not reach to the existed mound, and the caisson remained stable (Photo 4 (c)). When the designed water level difference rose to 30 cm (7.5 in actual size) while maintaining the sectional shape, the scouring of the foundation mound progressed to finally cause failure (Photo 4 (d)).

In Case C with steel piles, scouring progressed from the mound slope end toward the caisson at the designed water level difference of 20 cm, but no scouring occurred in the caisson side from the steel piles (Photo 4 (e)). This indicates that the steel piles were effective in preventing scouring, and stabilized the caisson. Then, when the designed water level difference rose to 30 cm, scouring behind the steel piles eventually spread, and the caisson and steel piles gradually slanted toward the port side. However, the steel piles were supported by the ground, so did not fall down completely, and managed

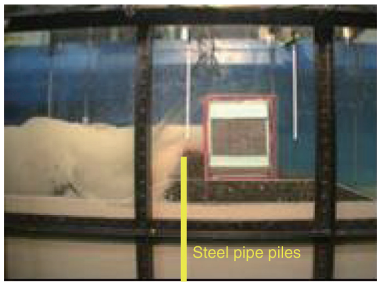
Table 2 Cases of the hydraulic experiment

Case A	Case B	Case C
Non reinforcement	Widening works	Reinforced with steel piles
 Unit weight of caisson: 22 kN/m^3 Friction factor of caisson bottom: 0.6		

(mm)

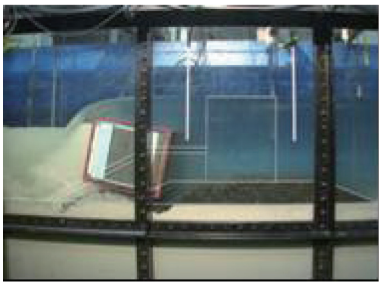
(a) Case A Water-dif, −20 cm (on the way)

(c) Case B Water-dif, −20 cm (final)



(e) Case C Water-dif, −20 cm (final)

(b) Case A Water-dif, −20 cm (final)



(d) Case B Water-dif, −30cm (final)

(f) Case C Water-dif, −30 cm (final)

Photo 4 Deformation of the hydraulic experiment

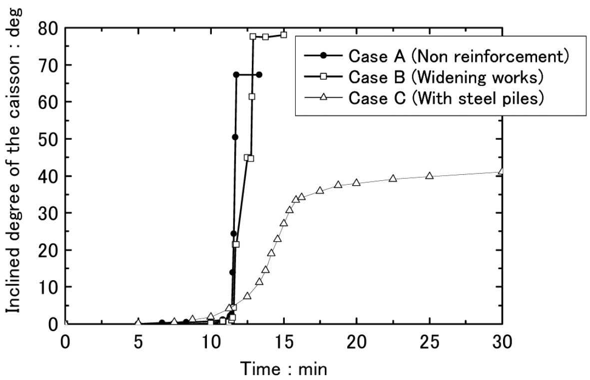


Fig. 9 Time history of the caisson gradient

to continue to support the caisson (Photo 4 (f)). Ultimately, the caisson slanted, but the top level was only slightly lowered below the initial level (white frame line), which suggests that a certain level of protection function was maintained.

Figure 9 summarizes the time history of the caisson slanting angle for each case. We converted the time with respect to the lateral axis to the actual scale. As shown, Case C successfully reduced the slanting angle for a longer duration than the other cases. When we elongate time until failure, that time is directly used for evacuation, which is highly important from the viewpoint of saving lives.

2.4 Reinforcement effect of the steel pile method

Based on the results of the above experiments and numerical analysis, we confirmed that the steel pile method is as resistant as widening work in the range of a small caisson displacement. As the displacement increases, the resistance force of the widening work reaches the upper limit, while the steel pile method continues to increase its resistance, although its deformation rigidity decreases. The resistance mechanism of the steel pile method is the transmission of the load to the ground through the steel piles and backfill and the resistance of the structure to the load with the ground acting as an embedded structure. In the experiment, when tsunami overflow occurred, the caisson slanted as scouring progressed, but did not completely fall and maintained crown height. The steel pile method promises high reinforcement effects against the action of a large tsunami or scouring and can truly toughen a breakwater's resistance.

3. Tsunami-resistant Design

The steel pile method should be designed according to the basic Guidelines for Tsunami-Resistant Design of Breakwaters, in which a tsunami is categorized as being one of two classes in scale. One is a highly likely class of tsunami that occurs once in relatively short time scales, from decades to a hundred years plus a few decades. The other is the largest class of tsunami that very rarely occurs but has extremely serious impacts on human life, assets, and socioeconomic activities. Based on this categorization, the designed tsunami, which corresponds to the designed external force, should be appropriately determined for the type of tsunami that frequently occurs as a reference, depending on the socioeconomic importance of the hinterland, while also considering the largest class tsunami. The cross-section of a breakwater should be designed against the designed tsunami in a way that will not compromise its intended functions, including its mitigation effect against tsunami damage. In addition, with respect to the determined cross-section of the breakwater, additional measures should be taken to make the breakwater a tough structure that can resist a "tsunami that exceeds the designed tsunami." In reviewing those measures, we recommend that a hydraulic model experiment or numerical analysis be put to maximum use.[3)]

According to this design policy, when a breakwater is constructed with steel pile reinforcement, it should have a tough construction that maintains stability against the designed tsunami and tolerates deformation while preventing failure against a tsunami that exceeds the designed tsunami. As shown in the schematic representation of **Fig. 10**, the relationship between load and displacement is that a designed tsunami is in the elastic range and a tsunami that exceeds the designed tsunami falls into a region where deformation rigidity is decreased. When a breakwater is designed to resist the forces of the designed tsunami, the reactive force to the steel piles should be determined by the elastic stress solution, using the calculation model shown in **Fig. 11**. In addition, the resistive force of the steel piles should be expressed with respect to the soil spring, as by, for example, Japan's Port and Harbor Research Institute (PHRI) method. According to this model, when a breakwater is designed under the conditions of the experiment explained in section 2.1, we can derive the bending moment diagram shown in **Fig. 12**. The designed value turned out to be slightly larger than the experimental value, or the safe-side value, which indicates that there is a consistency in the maximum value. For tsunamis that exceed the designed tsunami, it is necessary to consider the deformation of the breakwater, so it is desirable to utilize numerical fluid analysis or structural numerical calculation, as described in section 2.2.

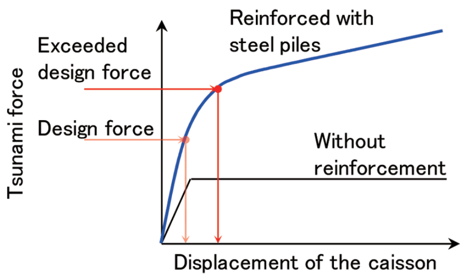


Fig. 10 Image of the relationship between tsunami force and resistance

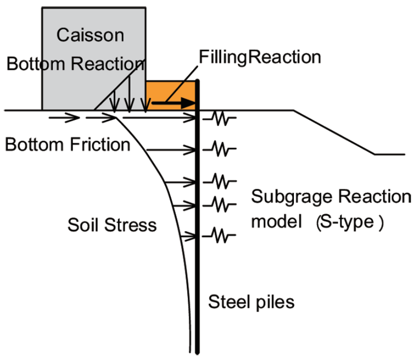


Fig. 11 Design model about the steel piles

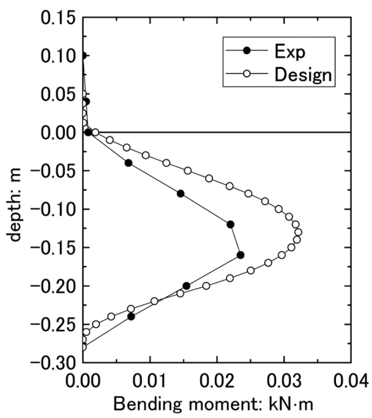


Fig. 12 Comparison of bending moment between the experiment and design

4. Construction Method

In the steel pile method, steel piles must be embedded near the caisson, and it is necessary to drive through the rubble layer that forms the mound. There are three methods to do so, as outlined in the following:

4.1 Full-slewing all-casing method

A casing fitted with a hard bit at the front end is screwed into the ground with a full-slewing jack to penetrate the rubble layer. Rubble collected inside the casing is removed with a hammer grab, and the drilled ground is replaced with sand. Then, steel piles are driven into the ground by, for example, hammer pile driving. This method, however, has some drawbacks when the work is on the seabed as it requires the construction of a temporary pier on which to place a full-slewing jack and also requires a lot of time to carry out a variety of tasks, including advance excavation and sand replacement.

4.2 Gyropress method™

This method uses a "gyro piler," which is capable of screw-piling and is designed to work independently, using reaction force as it firmly grasps a driven pile to construct steel piles with end bits in a wall pattern in the ground. It is capable of executing integrated operations and penetrating rubble layers. As shown in **Photo 5**, piles were driven by this method through a rubble layer about 7-m thick deposited near the lighthouse foundation in Miike Port.[7] We conducted trial screw-piling on the ground at the Yawata Steel Works of Nippon Steel & Sumitomo Metal compound to visually check how well the rubble is penetrated, as shown in **Photo 6**.

4.3 Rock vibro method[8]

In the rock vibro method, very hard steel is attached at the front end of a steel pile, which cuts the rock mass with the impact of the vibro hammer, cleans the crushed rocks with water (seawater) fed through the pile head, and drives the steel pile. Although this method is often used in port areas, since it vibrates the ground, it is necessary to consider the impact of vibration depending on the distance from the existing caisson.

5. Conclusion

When the Japanese people witnessed the devastating damage incurred by the Great East Japan Earthquake, their disaster prevention awareness completely changed. As people anxiously await the enhancement of disaster prevention and mitigation technologies, we have been dedicated to the development of the reinforcement methods reported in this paper. The authors intend to contribute to disaster prevention in Japan through the use of this method and hope to create further technological innovations.

Photo 5 Example of construction that Gyropress method surged the layer of rubbles[7]

(a) Surging the rubbles by Gyropress method

(b) Hollowed rubbles by Gyropress method

Photo 6 Test that Gyropress method surged the layer of rubbles on shore

Acknowledgments

The authors acknowledge Prof. Kikuchi of the Tokyo University of Science for his great instruction and guidance as early as in the initial stage of development. We are also grateful to the Port and Airport Research Institute and Coastal Development Institute of Technology for their contribution and cooperation in our efforts to commercialize the reported method, including performance verification with a hydraulic model experiment and establishment of the design method.

References

1) Takahashi, S. et al.: Urgent Survey for 2011 Great East Japan Earthquake and Tsunami Disaster in the Technical Note of the Port and Airport Research Institute. No. 1231, 2011
2) Developed by Modifying the Data in the Ministry of Land, Infrastructure, Transport and Tourism Website (http://www.mlit.go.jp/policy/shingikai/port01_sg_000098.html), Reference Material of Reference 2, Port and Harbor Subcommittee, 3rd Disaster Prevention Section. 2011
3) Port and Harbour Bureau, Ministry of Land, Infrastructure, Transport and Tourism: Guidelines for Tsunami-Resistant Design of Breakwaters. 2013
4) Kikuchi, Y. et al.: Horizontal Loading Experiments on Reinforced Gravity Type Breakwater with Steel Walls. The 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering. 2015
5) Moriyasu, T. et al.: Finite Element Analysis on the Resistant Behaviour of a Gravity Type Breakwater Reinforced with Steel Walls. Journal of Hydraulic, Coastal and Environmental Engineering B3 (Marine Development). 71 (2), 611–616 (2015)
6) Arikawa, T. et al.: Stability of the Breakwater with Steel Pipe Piles under Tsunami Overflow. Technical Note of the Port and Airport Research Institute. No. 1298, 2015
7) Giken Ltd.: Website (Projects: Miike Port (Inner Port North area), Shipping Route (−10 m) (Groundsill) Slope Reinforcement (3rd))
8) Hirose Marine Operation Co., Ltd.: Website (Rock Vibro Method, Piling Work)

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