Proceedings of the Second International Conference on Press-in Engineering 2021, Kochi, Japan – Matsumoto et al (eds)

Influence of horizontal loading height on subgrade reaction behavior acting on a pile

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ABSTRACT: Coastal areas along the Pacific Ocean suffered extensive damage due to the 2011 tsunami caused by the Tohoku earthquake. Installing a row of piles behind the caisson and filling the space in between with rubble are proposed as a method of reinforcement against tsunamis. Understanding the load conditions acting on a pile is necessary to determine the cross-section and embedment length of the pile used in the structure. Model experiments were conducted based on the bending moment distribution to estimate the external force acting as a distributed load on the offshore side of the pile. The behavior of the subgrade reaction on the horizontal resistance characteristics of a pile depends on its deformation mode. In this study, horizontal loading experiments were conducted on piles with different loading heights. The deformation mode of the pile changed the value of the subgrade reaction and its behavior with depth.

1 INTRODUCTION

The 2011 tsunami due to the Tohoku earthquake off the Pacific coast of Japan caused extensive damage to coastal areas. Several breakwaters that were structurally classified as gravity-type composite breakwaters were destroyed. The primary reasons for the damage to the gravity-type composite breakwaters were the presence of extensive horizontal forces caused by water level differences between the two sides of the caisson and erosion of the foundation at the rear side of the caisson caused by overflowing water transported by the tsunami (Arikawa et al. 2012). Therefore, tsunami-resistant breakwaters are necessary to reduce damage.

Moriyasu et al. (2016) proposed a method of reinforcing breakwaters by installing steel pipe piles behind a breakwater and filling the space in between with aggregates (Figure 1). The passive resistance exerted by the ground can be used to support the steel piles, because the horizontal forces acting on the caisson are effectively transferred to the steel piles through the rubble that fills the space between the piles and the caisson. The fundamental effectiveness of this reinforcement method was examined by performing static loading (Kikuchi et al. 2015, Suguro et al. 2015) and hydraulic flume (Arikawa et al. 2015) experiments.

To design the piles, the cross-section and embedment length of the steel pipe pile must be set in such a way that the stress level of the piles generated by the tsunami force acting on the caisson does not exceed the yield stress level. It is necessary to comprehensively understand the load conditions acting on the piles to determine the cross-section and embedment length.

Here, the loads acting on the piles used in the structure are classified into three types (Figure 2): (1) the pressure of the ground acting on the part of the piles protruding from the filling with the displacement of the caisson, (2) the pressure of the ground acting on the rooted part of the piles from the foundation due to the slope of the caisson, and (3) the subgrade reaction acting on the piles from the onshore side.

DOI: 10.1201/9781003215226-20

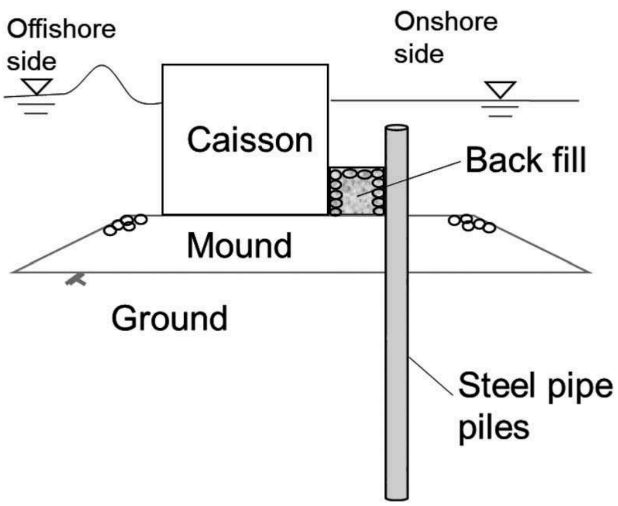


Figure 1. Schematic diagram of a reinforced gravity type breakwater (Moriyasu et al., 2016).

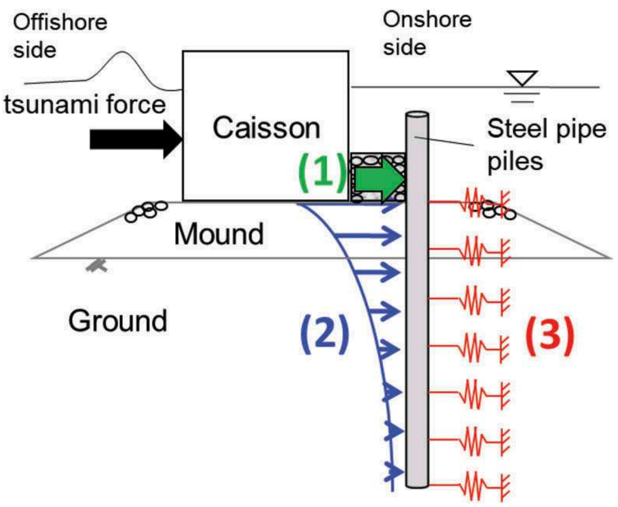


Figure 2. Classification of loads acting on the pile.

Loads (1) and (2) are external forces acting on the piles as distributed loads. Understanding the subgrade reaction received by the piles from the onshore side against the external forces is important for predicting the maximum bending moment and its depth of occurrence.

In this study, static model experiments were conducted to generalize the external force distribution acting on the piles from the offshore side of the structure (Hikichi et al. 2018, Mohri et al. 2018). In the experiment, the bending strain and bending moment distribution of the pile were calculated.

The deflection distribution was obtained by second-order integration of the bending moment distribution, and the load distribution acting on the pile was obtained by the second-order difference of the bending moment distribution. Here, the estimation of the external force distribution was studied by subtracting the assumed subgrade reaction distribution based on the deflection distribution from the load distribution. The insufficient points regarding the external force distribution estimated using this method are due to a problem with the assumption of the coefficients of the subgrade reaction with depth, which was used to calculate the subgrade reaction distribution.

The behavior of the subgrade reaction on the horizontal resistance characteristics of a pile depends on the deformation mode of the pile (Iwata et al. 2007, Nakai 1985). In this study, horizontal loading experiments were conducted on piles with different loading heights, and the difference in the horizontal resistance of the piles was investigated.

2 MODEL LOADING TEST OF REINFORCED GRAVITY TYPE BREAKWATER

2.1 *Experimental outline*

A schematic diagram of the model setup is shown in Figure 3. A rigid container 1600 mm long, 800 mm high, and 400 mm wide was used to prepare the model ground (Figure 3). Tohoku silica sand #5 (ρ_s = 2.647 g/cm^3, D_{50} = 0.591 mm, e_{max} = 1.072, and e_{min} = 0.689) was used to prepare the model ground using a relative density of 90% and an air pluviation method.

The model caisson was 380 mm long, 300 mm high, and 300 mm wide and had a controlled weight of 752 N. The average contact pressure acting on the ground was 8.4 kN/m^2. The caisson model was designed at a 1/60 scale with a width of 300 mm.

Twelve steel piles (800 mm long, 30 mm wide, 2.3 mm thick, and E = 2.05 × 10^5 N/mm^2) were set 50 mm behind the caisson. The center-to-center distance of the piles was 33 mm, and the embedment length was 500 mm. A backfill was maintained at a height of 50 mm between the caisson and the steel piles (D_{50} ≈ 10 mm, G_s =2.65, γ_d = 12.1 kN/m^3).

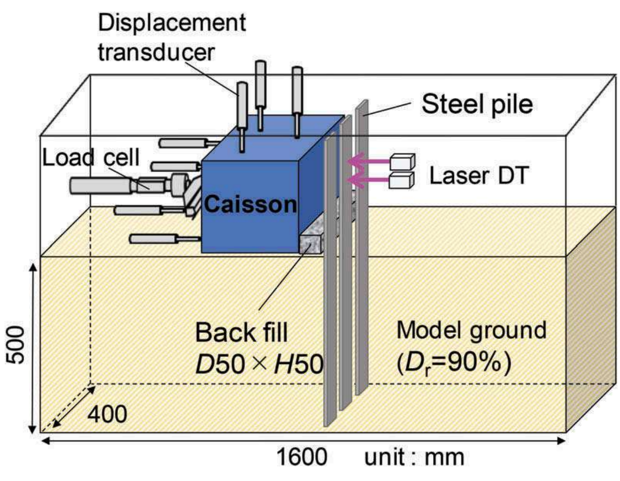


Figure 3. Schematic diagram of the experimental model set up.

The friction on the contact surface between the caisson and the loading blade was reduced using a Teflon sheet and silicone grease. Sandpaper #150 was attached to the bottom of the caisson. In the loading experiment, a tsunami force horizontal load was applied under displacement control at a height of 150 mm; the monotonous loading speed was 1 mm/min.

Twenty strain gauges were attached to both sides of the central pile and the pile at the end to measure the bending strains (Figure 4).

2.2 *Experimental results*

Figure 5 shows (a) bending moment distribution, (b) deflection distribution, and (c) load distribution in the central pile. The bending moment distribution was obtained by approximating the bending moment obtained from the strain gauges using the smoothing spline function. The deflection and load distributions were calculated as follows: the deflection distribution was obtained by the second-order integration of the bending moment distribution by the bending stiffness *EI* of the pile; the load distribution was obtained by the second-order difference of the bending moment distribution.

Figure 5 shows the results of applied loads of 670 and 800 N on the caisson. The maximum bending moment tends to increase as the applied load on the caisson increases. However, the generation depth $l_{m,max}$ and first zero-point depth of the bending moment l_{m1}—an important index for determining the embedment length of the pile—do not change significantly. Piles receiving horizontal force at the pile head generally experience increased $l_{m,max}$ and l_{m1} characteristics as the load level increases. In this experiment, the horizontal force acting on the piles from the offshore side is considered a distributed load, which is different from the general tendency. The load distribution is obtained by second-order differentiation of the bending moment distribution of the central

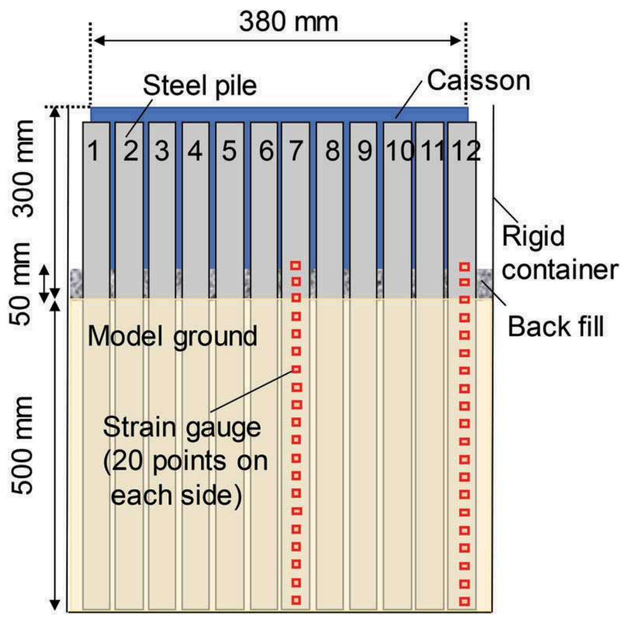
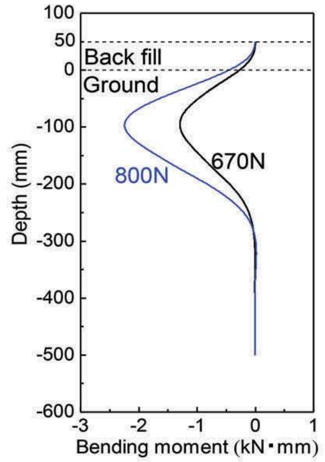
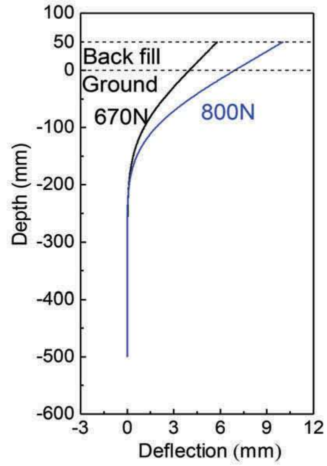


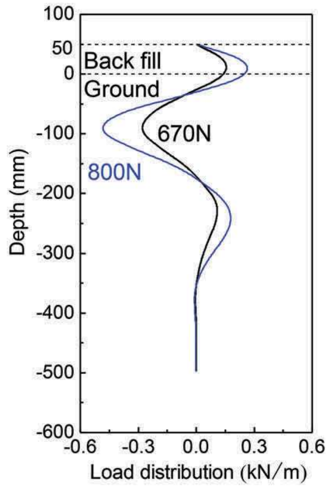
Figure 4. Schematic diagram of the pile condition (the view from the rear of the caisson).



(a) Bending moment distribution



(b) Deflection distribution



(c) Load distribution

Figure 5. Bending moment distribution and deflection distribution of the central pile.

pile and is considered the resultant force, which is classified into three categories (Figure 2). Therefore, the subgrade reaction model (Kubo 1964) of the PHRI method of the type S model (Equation (1)), was applied to the subgrade reaction that was received from the onshore side owing to pile displacement.

$$p = k_s x y^{0.5} \tag{1}$$

In the PHRI method of the type S model, the subgrade reaction coefficient is considered unique to the ground when a horizontal load acts on the pile head. Therefore, a constant subgrade reaction coefficient can be used without depending on the flexural rigidity, *EI*, or pile displacement. This model is derived based on the results of horizontal loading tests of piles under various conditions and represents the behavior of the pile by assuming nonlinearity in the p–y relationship (Kikuchi 2009).

The subgrade reaction behavior of a pile under a horizontal load generally depends on the deformation mode of the pile. Considering this phenomenon using the Winkler–Spring type model requires changing the coefficient of the subgrade reaction depending on the deformation mode of the pile. The depth distribution of the subgrade reaction coefficient used in the PHRI method of the type S model was modified based on the results obtained from the horizontal loading test of the pile. The subgrade reaction distribution was calculated using the deflection distribution shown in Figure 5 (b) and the corrected subgrade reaction coefficient.

The external force distribution acting on the pile from the offshore side was estimated by subtracting the subgrade reaction distribution based on the assumed load distribution. The external force distribution estimated in this experiment (Figure 6) presents discontinuous behavioral problems with depth and imbalance between the resultant force of the external force and the force of the load acting on the caisson.

The accuracy of the coefficient distribution of the subgrade reaction used in the assumption of the subgrade reaction distribution is assumed to be responsible for the insufficient points in the estimated external force distribution. As the behavior of the subgrade reaction varies depending on the deformation mode of the pile, the coefficient distribution of the subgrade reaction must be assumed to correspond to the deformation mode of the pile. Therefore, to change the deformation mode of the pile, loading experiments with different loading heights were conducted. The behavior of the subgrade reaction acting on the pile was examined based on the behavior of the pile.

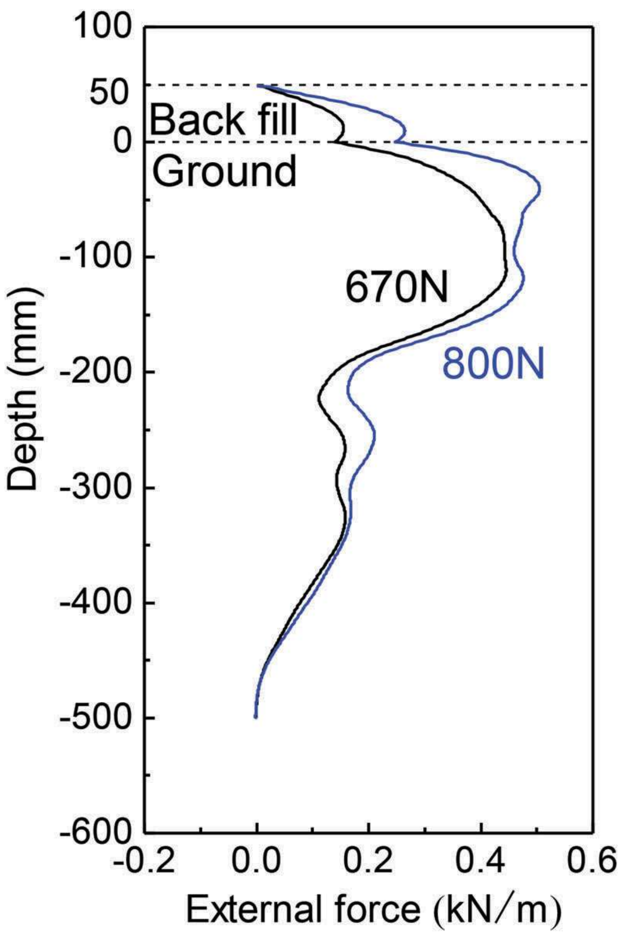


Figure 6. Estimated external force distribution.

3 HORIZONTAL LOADING EXPERIMENTS ON THE PILES

3.1 *Experimental outline*

A schematic diagram of the model setup is shown in Figure 7. To change the loading height on the pile, the ground height on the front side of the pile was lowered by 200 mm from the ground surface on the rear side. Tohoku silica sand #5 was used at a relative density of 90%. The model ground was made by excavating 200 mm on the front side after preparing the horizontal ground surface based on that of the rear side.

The model piles comprised 50 mm and 30 mm wide steel plate piles (2.3 mm thick, $E = 2.05 \times 10^5$ N/mm^2). The pile behavior was analyzed based on the bending strain obtained by the strain gauges attached to both sides of the No. 5 (central) and No. 3 piles (Figure 8).

A horizontal load was applied under load control. The blade shown in Figure 9 was attached to the shaft of the Berofram cylinder and divided into three parts at the contact point with the piles. LC1 and LC2 are load cells. LC1 measured the total load on the piles arranged in a row, and LC2 measured the

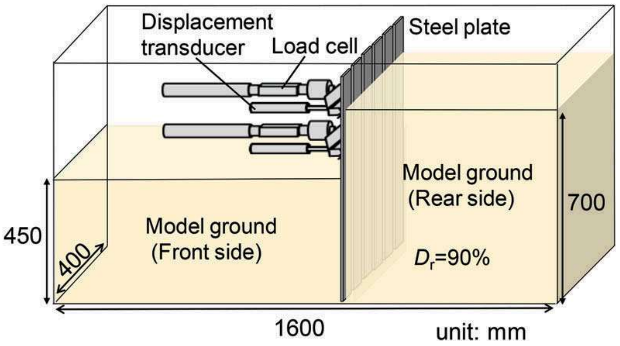


Figure 7. Schematic diagram of the experimental model set up.

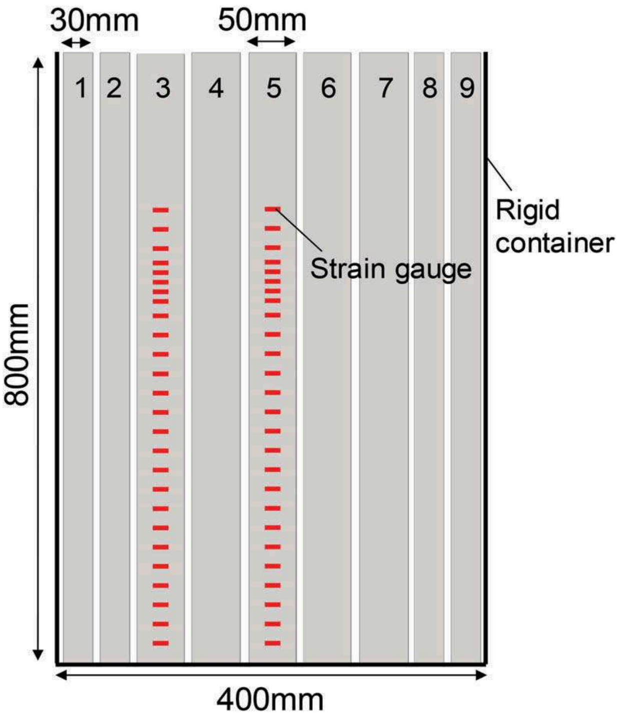


Figure 8. Schematic diagram of the pile condition.

load acting on the central pile. Additionally, the horizontal displacement of the loading point was measured using a displacement meter fixed to the rigid container frame.

Figure 10 shows the experimental conditions. Case-1 is a horizontal ground condition where the ground height is the same on the front and rear sides of the pile. Cases-2–5 are ground conditions, in which the ground surface on the front side is lowered by 200 mm (Figure 7). The loading heights of each case differ by 0, −100, or −150 mm based on the ground surface on the rear side.

In this loading test, as the penetration length of the pile with respect to the horizontal force becomes sufficient, the difference in the ground height for each test case has a negligible effect on the pile behavior.

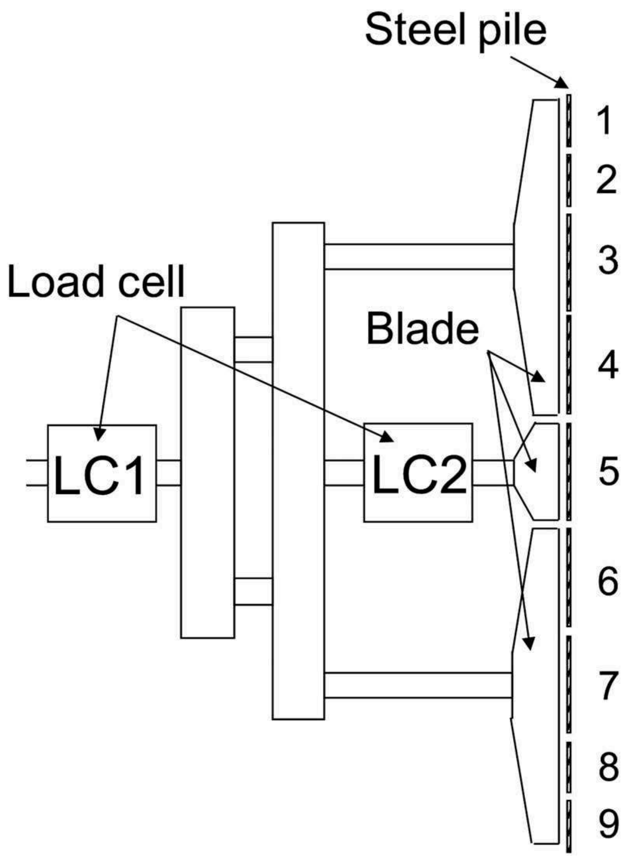


Figure 9. Structure of loading blade.

3.2 *Experimental results*

Figure 11 Shows the relationship between the horizontal load on the central pile and the displacement of the ground surface for each case. The horizontal load on the central pile is directly measured by LC2 (Figure 10). The height of the ground surface is that on the rear side of the piles.

The results show that the displacement of the ground surface of the pile with the same horizontal load differs greatly depending on the loading height. The displacement of the pile decreases with the same load for deeper external forces. However, Case-1 and Case-2, which have the same loading height and different ground conditions, do not differ significantly. Therefore, the effect of excavating 200 mm on the front side is small.

Figure 12 shows (a) bending moment distribution, (b) deflection distribution, and (c) subgrade reaction distribution for each case with a ground surface displacement of 4 mm. This result shows that the bending moment distribution varies greatly and that the deformation mode of the pile varies as the loading height changes.

When determining the subgrade reaction distribution, the bending moment distribution is approximated using a smoothing spline function (Kikuchi 2003). For Case-4 and Case-5, the bending moment distribution is not smoothed at the loading height. The smoothing spline function is applied separately above and below the loading

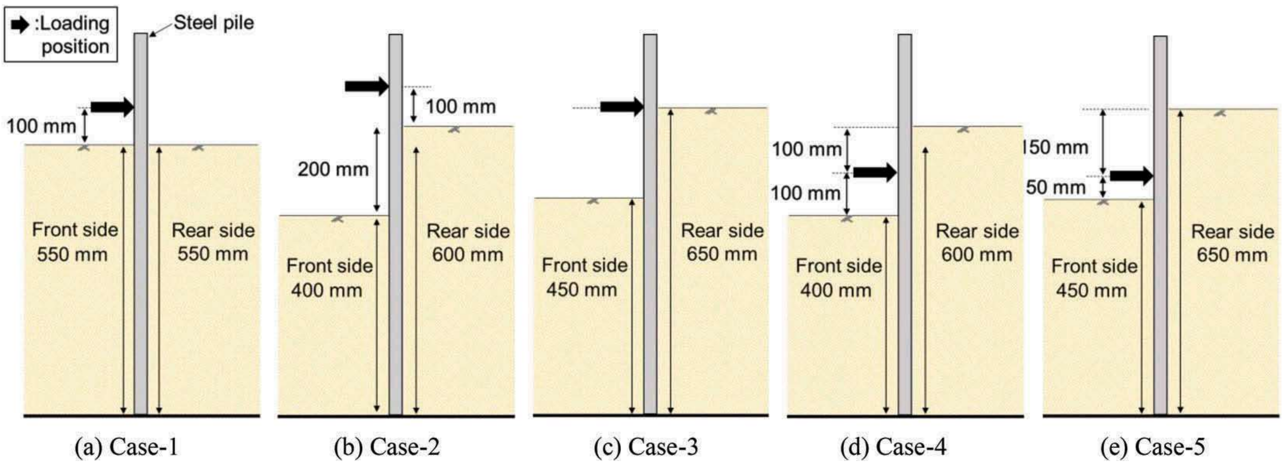


Figure 10. Details of the experimental cases.

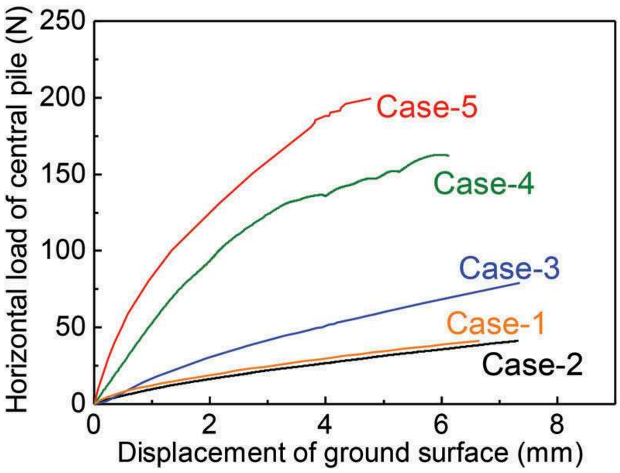


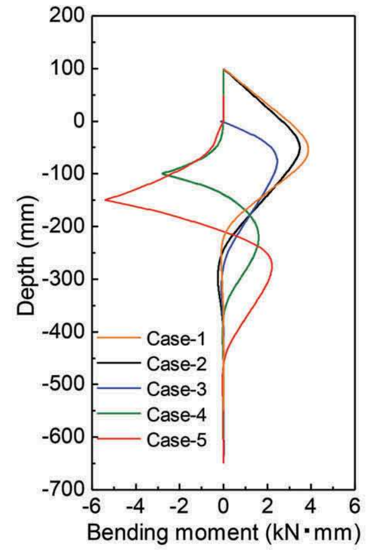
Figure 11. Relationship between horizontal load on central pile and displacement of ground surface.

height of the bending moment distribution (Morikawa et al. 2011). At this time, the discontinuity of the shear force at the loading height obtained by the differentiation of the bending moment distribution should be equal to the horizontal load. Additionally, the subgrade reaction obtained by the differentiation of the shear force distribution should be continuous at the loading height.

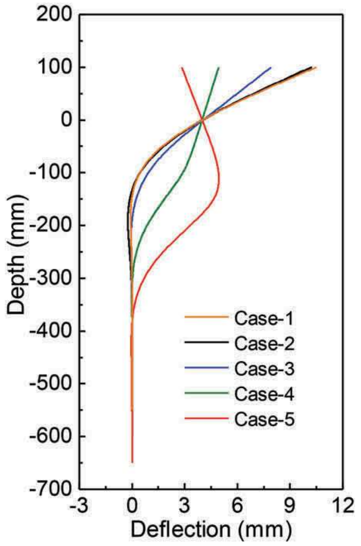
Figure 13 compares the *p*-*y* relationship at a depth of −60 mm and shows the relational lines based on the PHRI method of the type S model using several subgrade reaction coefficients. This result shows the differences in the *p*-*y* relationship depend on the loading height. The subgrade reaction at the same displacement is generally smaller for deeper loading heights. The subgrade coefficient in Case-5 is approximately 30% that of Cases 1–3. The difference (even when the ground conditions remain unchanged) is thought to be due to the different deformation modes of the piles (Figure 13).

Figure 14 shows the depth distribution of the subgrade reaction coefficients calculated using the results of the (b) deflection distribution and (c) subgrade reaction distribution. Figure 12 shows the results of the section from the surface to a depth of −250 mm. These results show that the values of the subgrade reaction coefficient and the change behavior with depth depend on the loading height. In Cases-1–3, the subgrade reaction coefficient changes rapidly with depth, and the depth at which the change appears tends to correspond to the depth of occurrence of the maximum bending moment of the pile in each case. In Cases-4 and 5, the change in the subgrade reaction coefficient with depth is gradual. Further, the magnitude of the subgrade reaction coefficient is different from that in Cases-1–3, which is inconsistent with the idea that the ground reaction force coefficient used in the PHRI method of the type S model is unique to the ground.

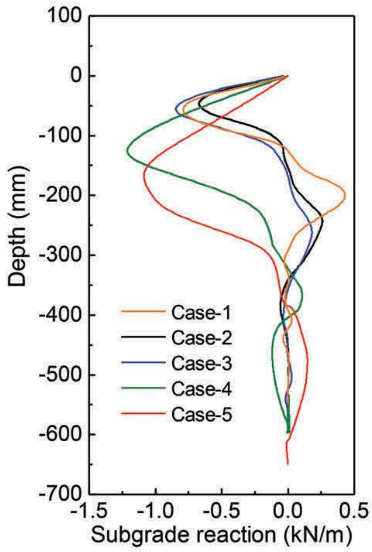
Figure 15 shows the result of superimposing the deflection distribution at 670 N in Figure 5 (b) on the deflection distribution shown in Figure 12 (b). These results show that the deformation mode of the pile in the model experiment of the breakwater reinforcement structure is most similar to the pile deformation mode in Case-3. Multi-stage loading must be performed with an increased number of loading points to match the pile deformation mode in the model experiment. Assuming the distribution of the subgrade reaction coefficients in this experiment to be the same as those in Case-3 is necessary to obtain a subgrade reaction corresponding to the deformation mode of the pile in the reinforcement structure of the breakwater. Moreover, the external force acting on the pile may change depending on the difference in the



(a) Bending moment distribution



(b) Deflection distribution



(c) Subgrade reaction

Figure 12. Pile behavior in each case at y_0=4mm.

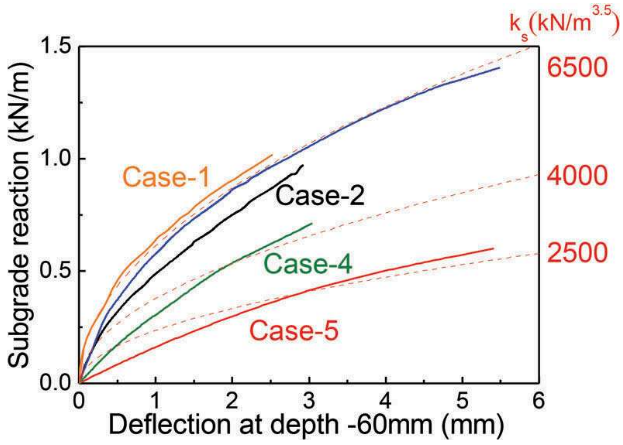


Figure 13. *P*-*y* relationship at a depth of -60 mm.

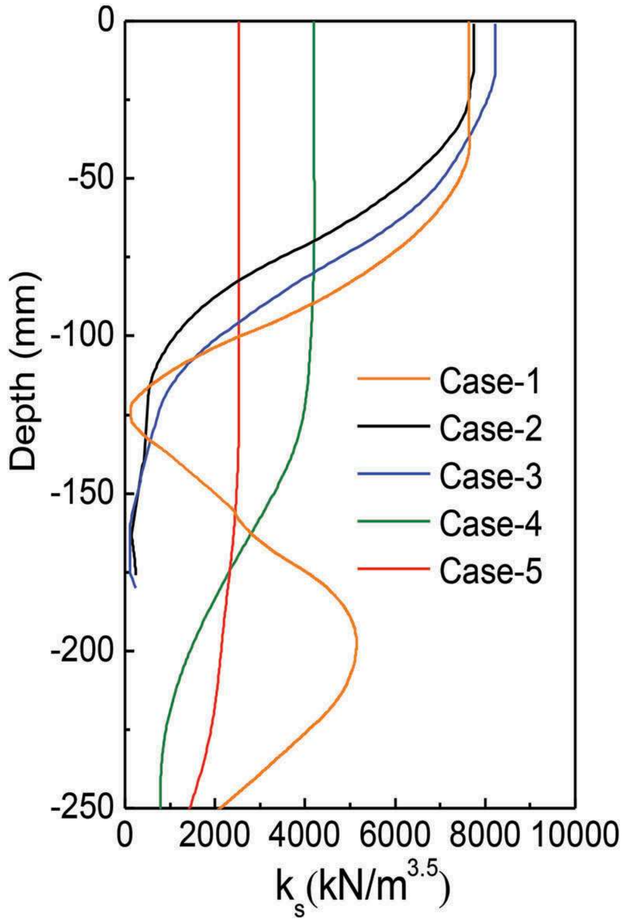


Figure 14. K_s distribution in Case1~Case5.

foundation ground and the rigidity of the pile. Figure 14 shows that the values and depth distributions of the subgrade reaction coefficients differ according to the deformation mode of the pile. Therefore, the subgrade reaction coefficient distribution corresponding to the deformation mode of the pile must be used.

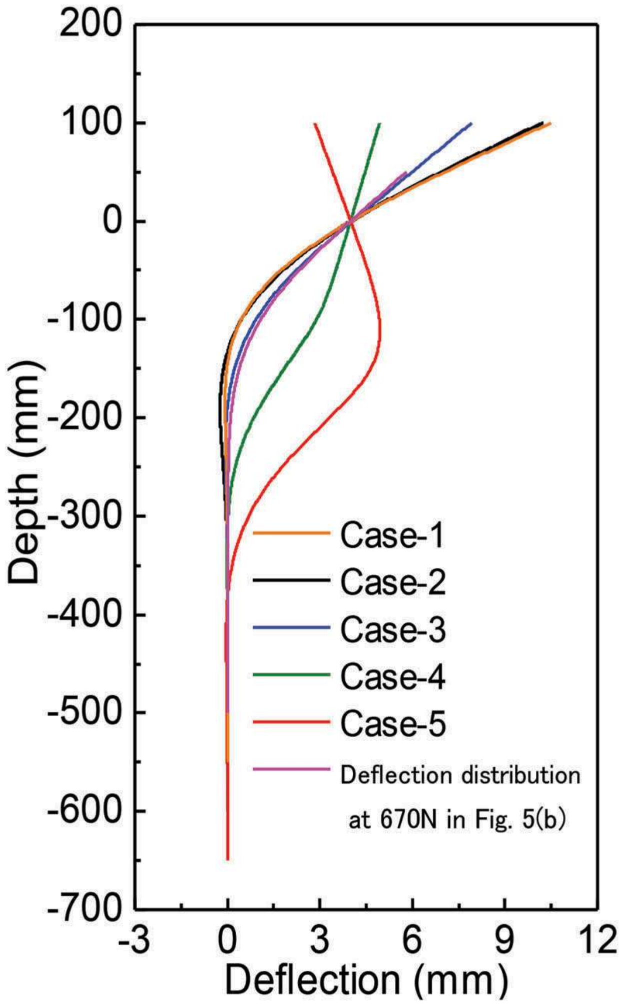


Figure 15. Comparison of deflection distribution.

4 CONCLUSIONS

The cross-section and embedment length of the pile are important for the design of a breakwater structure reinforced with steel pipe piles. Understanding the subgrade reaction received by the pile from the onshore side against external forces is important for predicting the maximum bending moment of the pile and the depth of occurrence. The piles used in this structure received a distributed load along the perpendicular pile axis direction from the offshore side. However, insufficient knowledge has been obtained on pile resistance for a load distributed in this manner. The change in the reaction force behavior cannot be considered. Therefore, the change in the subgrade reaction due to the difference in the deformation mode of the pile cannot be considered. In this study, horizontal loading experiments were conducted with different horizontal loading heights to examine the differences in the horizontal resistance characteristics of the piles.

The displacement of the pile decreases with the same load as the height of the external force moves deeper in the ground. The bending moment distribution varies greatly, and the deformation mode of the pile changes with different loading heights.

The behavior of the piles in the experiment was compared using the subgrade reaction coefficient used in the PHRI method of the type S model, which considers it unique to the ground when the horizontal load acts on the pile head. However, because of the influence of the pile deformation mode, the subgrade reaction coefficient does not acquire value with depth. Therefore, the depth distribution of the subgrade reaction coefficient was calculated based on the bending moment distribution of the pile in the experimental results, and a difference was observed for different loading methods. Consequently, the values of the subgrade reaction coefficients differed as the loading height on the pile changed. Further, the behavior of the subgrade reaction coefficient varied with depth. These results were believed to be caused by different deformation modes of the pile depending on the loading height.

The value and depth distribution of the subgrade reaction coefficient must be assumed according to the deformation mode of the pile to express the subgrade reaction using the Winkler-Spring type PHRI method. Future studies on generalization will be necessary.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI (Grant Number JP1804352).

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