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Physical and numerical modeling of self-supporting retaining structure using double sheet pile walls

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ABSTRACT: The main objective of this research was to observe the mechanical behavior of double sheet pile walls with model experiments and FE analysis. The model experiments were conducted in 1/4 scale under Earth's gravity conditions. The experiments were conducted in the following steps: first, excavating the ground, then loading the head of the sheet piles by hydraulic jacks. The physical model experiments showed a much smaller deformation compared to the conventional method and proved the earth-retaining mechanisms. The connection of the heads was thought to be the main reason for minimizing the deformation. Furthermore, the monitored axial forces of double sheet pile walls indicated the frictional resistance between the sheet pile walls and the ground contributes to resisting the load. These findings are supported by a 2D FEM with an elastoplastic constitutive model.

1 INTRODUCTION

1.1 *Background*

In excavation projects, members, such as struts and pin piles, are often used to support temporary earth retaining walls. These support members obstruct the construction work in excavated space and reduce efficiency. The self-supporting method, which does not need support members, is one of the solutions to this issue. Ground anchors and soil mixing walls (SMWs) are typical self-supporting methods. They, however, are not always applicable because of the limitation of space, high costs, and special equipment. This was our motivation to develop a cost-effective, self-supporting retaining structure by double sheet pile walls for urban construction.

Historically, double sheet pile walls have been used for cofferdams and breakwaters. One of the early studies is Sawaguchi (1974), who conducted model experiments and developed analytical solutions for the deflection of double sheet pile walls. In his work, the importance of the interaction between both sheet piles and the filling material was emphasized. Kikuchi et al. (2001) performed centrifuge model experiments and Finite Element analysis to investigate the effect of the filling material by comparing sand and cemented dredged soil. It was concluded that the adhesion with the sheet pile needs to be strong enough for the cemented filling material to utilize its rigidity. Khan et al. (2006) performed centrifuge model experiments to study the stability of cofferdams against high floodwater. They also compared the stability of cofferdams on a thick clay deposit and a sand deposit. One of their key findings was that the failure mechanism of such cofferdams was dominated by the shear deformation of the filling material. More recently, Fujiwara et al. (2017) studied the reinforcement of bank using double sheet piles with diaphragm walls. They reported that the settlement was reduced by 10% against an earthquake compared to the case without the reinforcement.

1.2 *Concept of double sheet pile walls*

Figure 1 illustrates the concept of double sheet pile walls as a temporary earth retaining structure. In this method, two sheet piles are pressed into the ground in parallel, typically with a distance of 1 m. The heads of both sheet piles are connected by a rigid member. The relatively narrow distance between the sheet piles distinguishes our study from previous studies on cofferdams and breakwaters. This structure utilizes the following effects to resist horizontal loads.

i. Rigidity enhancement by head fixing
ii. Frictional resistance between the sheet pile walls and the ground
iii. Shear stiffness of internal soil

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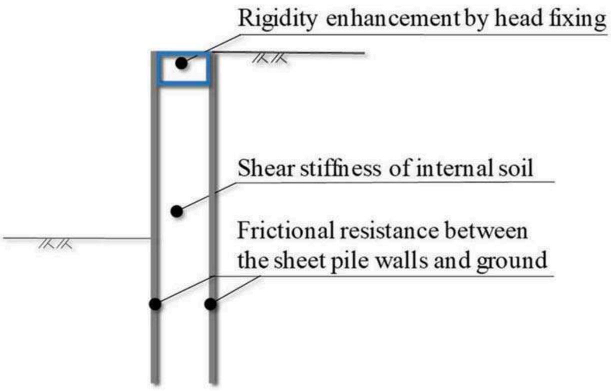


Figure 1. The concept of temporary earth retaining by the double sheet pile walls.

The main objective of this research was to observe the mechanical behavior of the double sheet pile walls through physical model experiments. The model experiments were conducted in 1/4 scale under the Earth's gravity conditions. The experiment procedure consisted of two phases: excavating the ground and loading the head of the structure using hydraulic jacks. In addition, a series of numerical modeling was performed to examine the results of the model experiments.

2 PHYSICAL MODEL EXPERIMENTS

2.1 *Overview*

Figure 2 shows a schematic view of the model experiments in 1/4 scale under the Earth's gravity. The model ground was 2,500 mm in width, 6,000 mm in length, and 3,700 mm in depth. Two model experiments were conducted in this study. Case 1 was a single sheet pile wall (conventional method), and Case 2 was a double sheet pile wall. For both cases, sheet piles had a length of

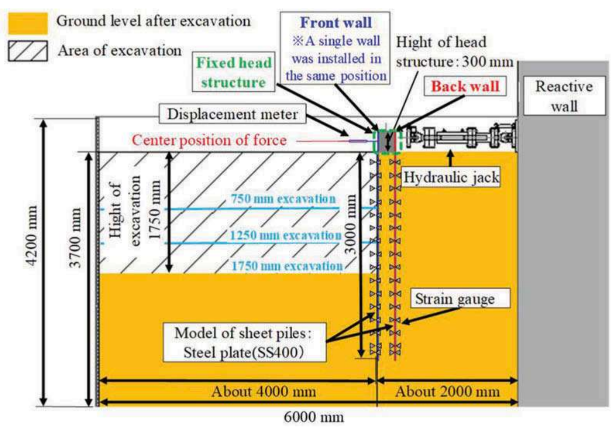


Figure 2. A schematic view of the physical modeling experiments in 1/4 scale under the Earth's gravity conditions.

3,300 mm. A rubber plate was attached to the end of the sheet pile to reduce friction between the sheet pile and the soil tank wall. Parameters for model sheet piles are shown in Table 1. For Case 2 the horizontal distance between the front and the back sheet piles was 250 mm. A total 1,750 mm excavation was performed in a stepwise manner.

2.2 *Material and method*

Natural sand in Chiba Prefecture was used as the ground material. Figure 3 shows the basic properties and the grain size distribution of the sand. After the steel sheet piles were placed, a certain amount of sand was poured and compacted every 30 cm per layer to achieve the degree of compaction of 85%. Soil samples were acquired after the experiments to determine the density and water content of the model ground. Measured values for each test are listed in Table 2. Because of the natural water content of the soil, apparent cohesion existed due to suction forces between the particles.

2.3 *Experiment procedures*

The model experiments consisted of two steps. First, the ground was excavated by manpower down to 1,750 mm in depth. The excavation was separated into steps of 750 mm, 1,250 mm, and 1,750 mm to evaluate the gradual deformation behavior of the walls. Second, the head of the walls was loaded statically with 0.2-0.3 mm per minute in horizontal direction by using jacks up to 190 mm. The horizontal earth pressure due to the excavation was not large enough to deform the sheet piles to a demanded

Table 1. Parameters for model sheet piles.

Parameters		Steel plate (SS400)	
Young's modulus	E	1.9×10^8	kN/m^2
Thickness	t	12	mm
Moment of inertia of area	I	14	cm^4/m
Flexural rigidity	EI	2.8×10	kN·m

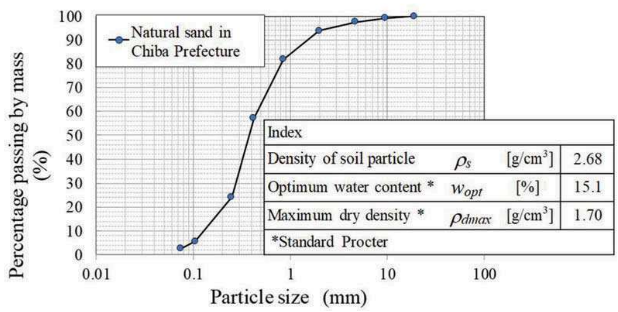


Figure 3. Basic properties and particle size distribution of natural sand in Chiba Prefecture.

Table 2. Measured values of the model grounds.

Parameters		Case 1	Case 2	
Water content	w	15.2	14.5	%
Dry density	ρ_d	1.45	1.48	g/cm^3
Wet density	ρ_t	1.70	1.70	g/cm^3
	D_{50}	0.37	0.37	mm
Coefficient of Uniformity	U_c	3.2	3.2	
Degree of Compaction	D_c	85	87	%

level in the model scale. Thus, the jacks were used to apply further horizontal displacement at the head although the mode of deformation differed from that of the excavation. The deformation behavior of the retaining wall was evaluated using strain gauges attached to the steel sheet piles and a horizontal displacement gauge for the head. Figure 4 shows an image of the excavation and the horizontal loading.

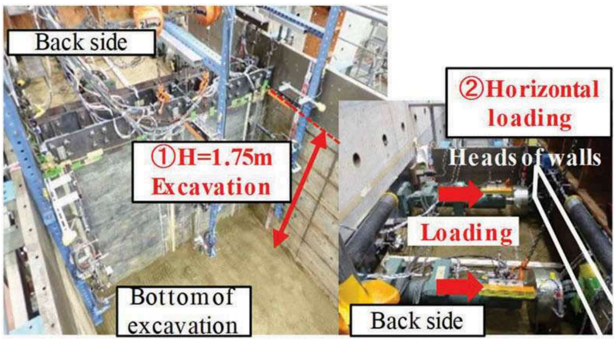


Figure 4. An overview of the model experiments in 1/4 scale under the Earth's gravity.

2.4 *Results*

2.4.1 *Excavation*

Figure 5 shows the change in head displacement with excavation depth. In Case 1, the single sheet pile wall did not show significant displacement up to an excavation depth of 1,250 mm. Then, the head displacement was increased to 35 mm with the depth from 1,250 to 1,750 mm. In Case 2, the head displacement of the double sheet pile walls was only 2 mm at the end of the excavation.

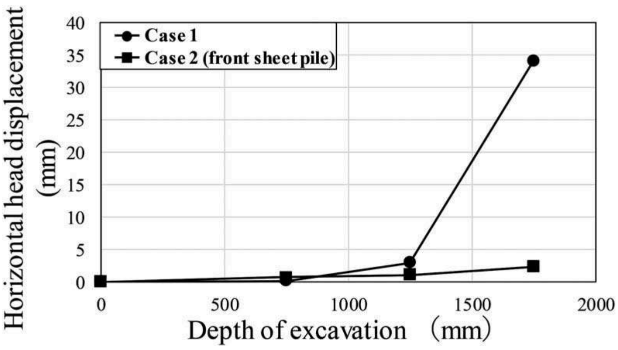


Figure 5. The head displacement with excavation depth.

Figure 6 shows the distribution of horizontal displacement in the sheet plies after the 1,750 mm-deep excavation. Displacement was calculated by integrating the strain values with the bottom of the sheet pile as a fixed point. In Case 1, the single sheet pile showed a cantilevered mode from near the excavation bottom to the top of the sheet pile. On the other hand, the front sheet pile in Case 2 showed a deformation mode in which the displacement was largest in the middle. This behavior is similar to those of anchor-supported sheet piles.

Figure 7 shows the distribution of bending moments after the excavation of 1750 mm. The bending moment was calculated from the strain gauges attached to the front and back of the sheet pile. In Case 1, positive bending moment was largest near the bottom of excavation. The negative bending moment above the bottom of excavation is assumed to be caused by frictional resistance between the edge of the sheet pile and the container or the shear resistance between the sheet pile and the soil. In Case 2, the front and back sheet piles showed different distributions of bending moment. In the back sheet pile, only a negative peak appeared near the head indicating the back sheet pile behaved like a raked pile to resist the earth pressure.

2.4.2 *Horizontal loading*

Figure 8 shows the horizontal displacement of the head during horizontal loading by the jacks. The

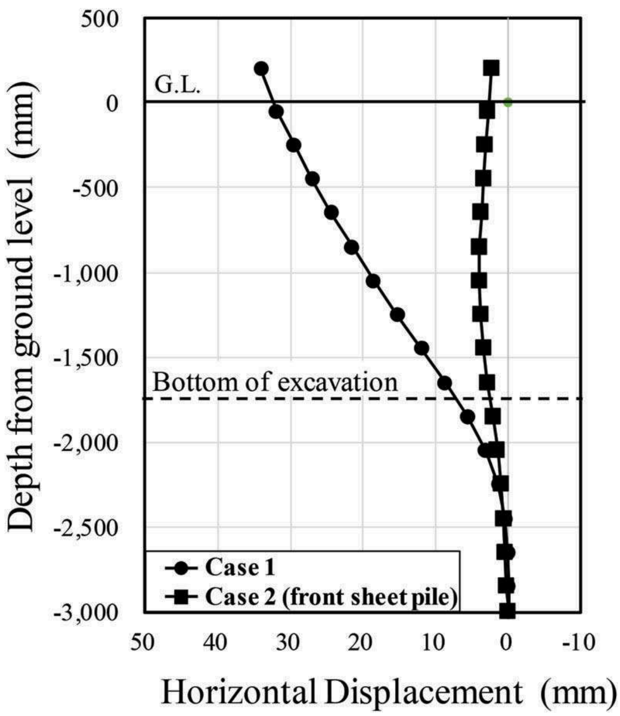
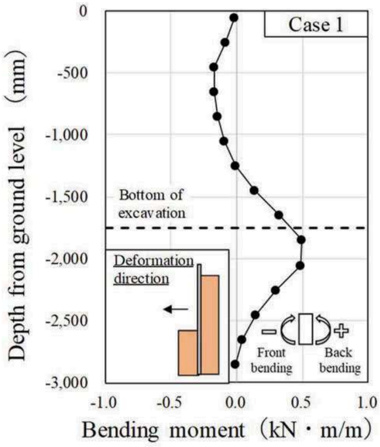
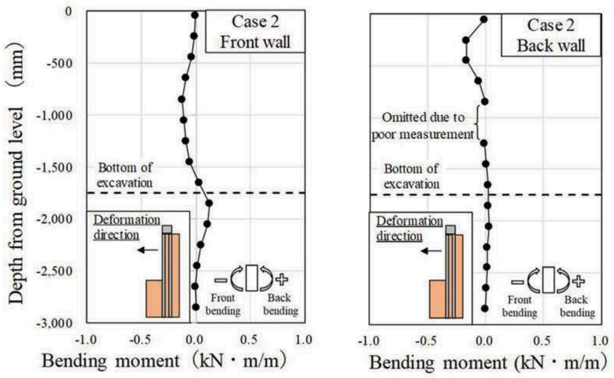


Figure 6. The distribution of horizontal displacement after 1750 mm excavation.



(a) Case 1



(b) Case 2

Figure 7. The distribution of bending moments after 1750 mm excavation.

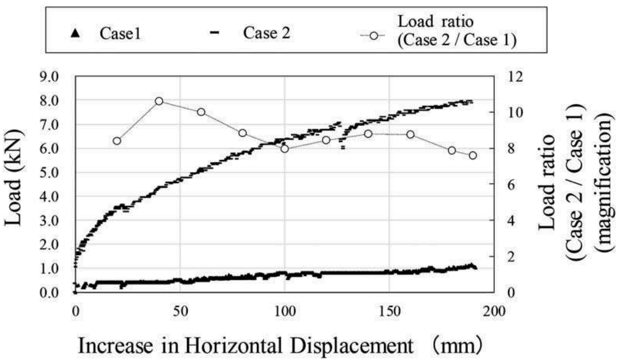


Figure 8. The relationship between the horizontal displacement of the head during loading and the load.

ratio of the load of Case 2 to Case 1 for the same amount of displacement is also shown by hollow circles. Note that the horizontal displacement discussed here is the incremental value after the end of excavation. At the displacement of 190 mm, the load required was 1.1 kN with the single sheet pile wall and 8.0 kN with the double sheet pile walls. Throughout the loading process, the load was about 7.6 to 10.6 times higher in the double sheet pile walls than in the single sheet pile wall.

Figure 9 shows the horizontal displacement distribution when the head displacement was 100 mm. In Case 1, the displacement showed a cantilevered mode. While, in Case 2, the displacement of the back sheet pile was slightly larger than that of the front sheet plie at the ground level of -500 mm. This result may indicate the contraction of internal soil in this particular part.

Figure 10 shows the distribution of the bending moment before applying the horizontal load, at 100 mm displacement, and at 190 mm displacement of the pile head. In Case 2, as the head displacement increased, bending moment distributions of both the front and the back sheet piles showed similar modes. The front sheet pile had a sharper positive peak below the bottom of excavation. Moreover, the back sheet pile showed a larger negative bending moment near the head.

Figure 11 shows the distributions of axial forces in the loading experiments in Case2. Compressive and tensile forces were observed in the front and back sheet plies, respectively. Below the bottom of excavation, axial forces decrease with depth in both sheet piles. This trend indicates the shear resistance of the soil against the push-in and pull-out of each sheet pile.

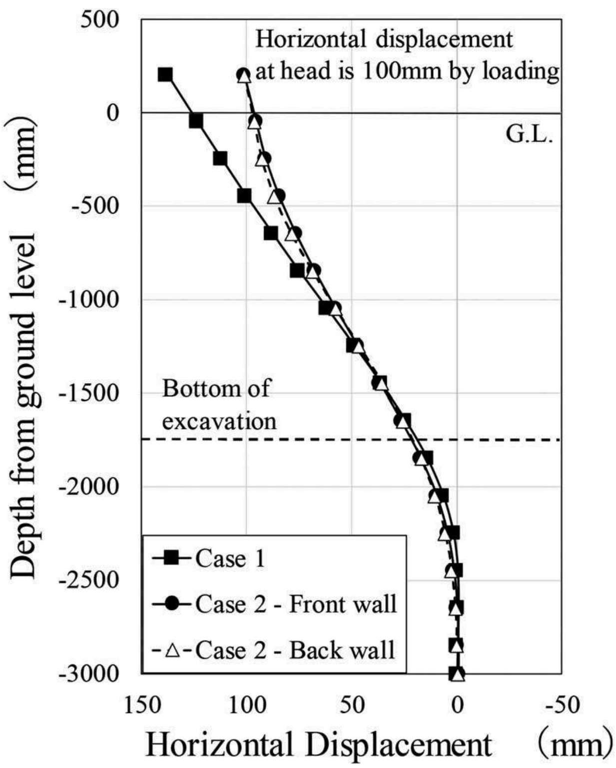
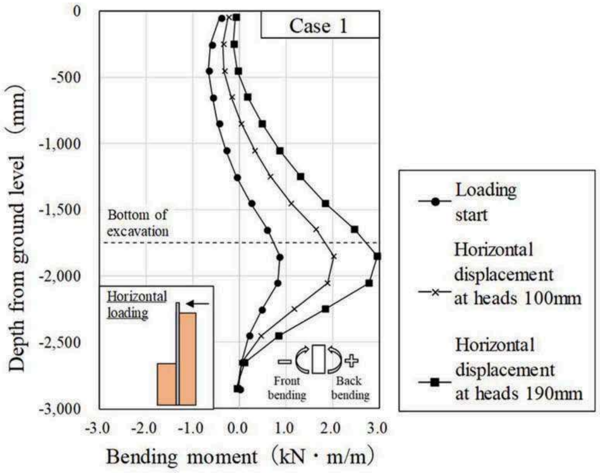
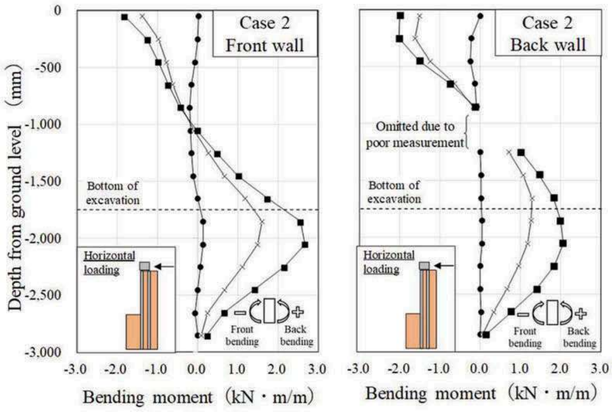


Figure 9. The distribution of horizontal displacement of the compulsory head horizontal displacement for 100 mm by loading.



(a) A single sheet pile (conventional method)



(b) Double sheet pile walls

Figure 10. The distribution of bending moments of the compulsory head horizontal displacement by loading.

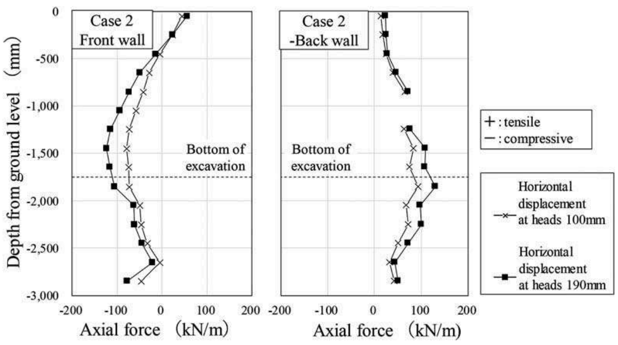


Figure 11. The distribution of axial forces of Case 2 in the loading experiments.

3 NUMERICAL MODELING

3.1 *Conditions for numerical analysis*

A series of numerical analyses was conducted to study the retaining mechanism of the double sheet piles in greater detail. Our purpose was to get an insight into the behavior of the soil and its interaction with the double sheep piles. Such behavior is difficult to observe directly in physical modeling experiments. The process of the physical modeling experiment was simulated by a 2D Finite Element (FE) program. The model for the FE analysis is shown in Figure 12. For the soil, the Drucker-Prager model whose parameters are given in Table 3 was used. These parameters are derived by laboratory testing of the same soil used in the physical modeling experiments. Young's modulus varies with depth, and it is proportional to the 0.5 power of the mean effective stress of soil σ'_m. Both sheet piles and the head-fixing member are modeled by beam elements. Between the solid and the beam elements, Goodman's joint elements are placed to account for slip and separation. Displacements are fixed at the lower boundary while only horizontal displacement is fixed at the left and right boundaries. The process of the excavation is modeled by removing the corresponding soil elements layer by layer. At the same time, equivalent force is released at the adjacent nodes. For the process of the jack-loading, horizontal displacement is prescribed at the head of the double sheet piles.

3.2 *Results and Discussion*

First, the results of the FE analysis were compared to the physical modeling experiment to examine its

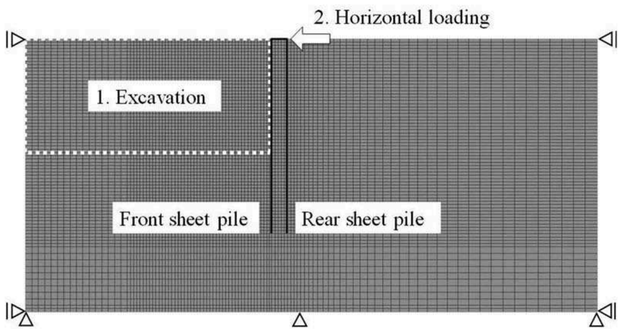


Figure 12. The model for the FE analysis. First, the part of the soil shown by the white dashed line was excavated. Second, horizontal loading was applied at the head of the double sheet piles.

Table 3. Parameters for the Drucker-Prager model used in the FE analysis.

Parameters				
Unit weight	ρ_t	16.5	kN/m^3	
Young's modulus	E	15500	kN/m^2	(at σ'_m = 90 kN/m^2)
Poisson's ratio	ν	0.31		
Friction angle	φ	34.5	degrees	
Cohesion	c	2.0	kN/m^2	
Dilatancy angle	ψ	0.0	degrees	

validity. Here, we focused on the experiment conducted with the double sheet piles (Case 2). Figure 13 shows the horizontal displacements of the sheet piles when the excavation was finished and when the head-displacement reached 100 mm. The markers indicate the physical modeling while the solid line indicates the FE analysis. The mode of deformation was similar between the experiment and the FE analysis both at the excavation and the jack loading. Moreover, the bending moments of both sheet piles were compared in the same manner in Figure 14. Both results agreed well except the peaks

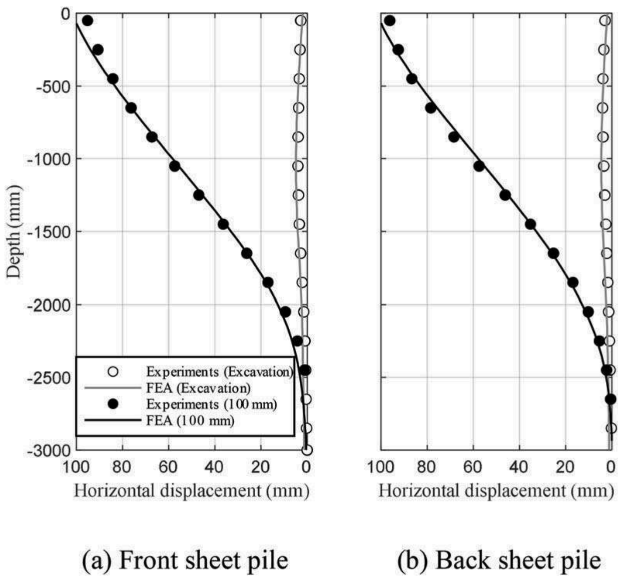


Figure 13. Horizontal displacements of the (a) front and (b) back sheet piles. The experiment and FEA results are compared at the end of the excavation and at the head displacement of 100 mm.

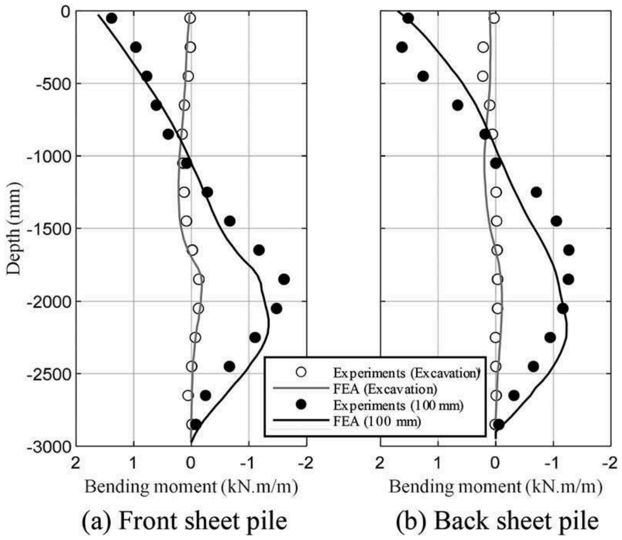


Figure 14. Bending moments of the (a) front and (b) back sheet piles. Note that the values of the bending moments are shown for a unit width of 1 m.

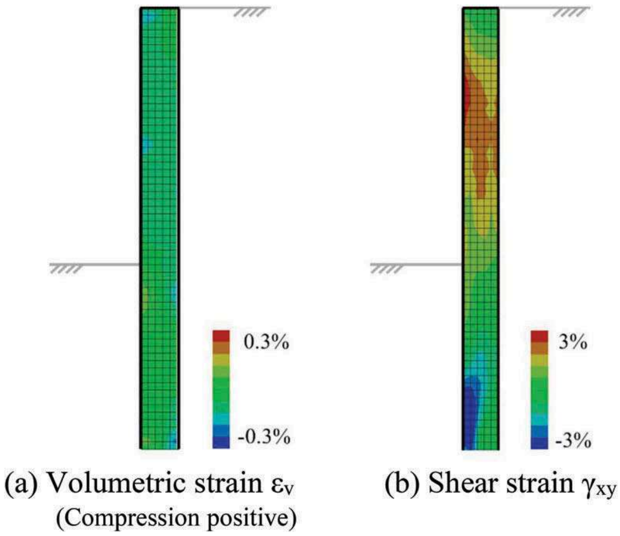


Figure 15. Strain distributions of the soil elements in the double sheet piles when the head displacement is 100 mm. The shear is dominant over the volumetric change.

of the bending moment occurred at slightly deeper positions in the FE analysis. Overall, the behavior of the double sheet piles was well demonstrated by the FE analysis.

Second, the behavior of the soil between the double sheet piles was investigated. Figure 15 illustrates the strain distributions of the inner soil when the head displacement is 100 mm. The volumetric strain is less than 0.3% but the shear strain is as large as 3% at maximum. The positive peak of shear strain is at the middle depth of the excavation. This implies that the shear resistance of the inner soil takes an important role in the retaining mechanism of the structure. If the inner soil is dense enough to dilate, which is not considered in this analysis, the shear resistance is expected to be even larger. The effect of the inner soil could possibly be an advantage of the double sheet piles over the conventional method.

4 CONCLUSIONS

The following conclusions were drawn from the model experiments in 1/4 scale under the Earth's gravity and the FE analysis.

(1) The horizontal displacement at the end of 1,750 mm-deep excavation was 2 mm in double sheet pile walls compared to 35 mm in the single sheet pile wall.
(2) The distribution of bending moment indicated that the back sheet pile behaved as a raked pile to resist the earth pressure.
(3) The distributions of axial forces indicated the frictional resistance of the soil against the push-in and pull-out of both sheet piles.

(4) The FE analysis showed that the shear resistance of the inner soil may take an important role in resisting the earth pressure.

For applications of this method to urban construction projects, further study will be undertaken to develop and verify the design method.

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