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Model test on double sheet-pile method for excavation works using X-ray CT

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ABSTRACT: Steel sheet-piles are driven into the ground to prevent failure of soils and intrusion of water. The current main function of constructing sheet-piles used as a temporary structure has problems such as low productivity, few adoption opportunities, and high cost. Therefore, a double sheet-pile method has been developed. Also, from centrifugal model tests or full-scale experiments, the effectiveness of this method had been confirmed. However, the soil behavior between two sheet-piles has not been clarified yet. Hence, the purpose of this study is to clarify the soil behavior between two sheet-piles and the mechanism of its effectiveness of the structure using X-ray CT. From experimental results,, X-ray CT images were able to visualize the location where the maximum force is applied during excavation and the form of sliding failure, and also confirmed the importance of the soil between the two sheet-piles.

1 INTRODUCTION

Steel sheet-piles are driven into the ground to prevent failure of soils and intrusion of water. The specific type of sheet-piles makes the construction easier, its period shorter and the cost lower, as well as it is environmentally friendly. Also, sheet-piles are used in temporary structures such as earth retaining and temporary revetments. Furthermore, permanent structures such as revetments and embankments prevent slippage damage and ground settlement.

In this study, sheet-piles used as temporary structures are the subject of this study. There are some construction methods that include the beam type, the retaining pile type, the anchor type, and the free-standing wall type. The most general construction method is the beam type; however, it has a problem of low productivity and a long construction period because of limited space (Sugimoto et al. 1993). In the case of the retaining pile type and the anchor type, the productivity is high, however, it needs sufficient space on the background of the sheet-pile (Tamano. 1983) (Miyoshi et al. 2009). The free-standing wall type costs much money because it requires the use of more substantial materials. (Eto et al. 2002). Thus, there is a demand for the development of a new construction method that can (1) make an open space inside the construction area, (2) reduce the area of the background of sheet-pile (3) minimize costs.

Takahashi et al. (2013) developed the diagonal earth retaining method as a new construction technology. In general, a sheet-pile needs support work to prevent large deformation. Thus, the diagonal earth retaining method is used at a relatively shallow excavation depth. On the other hand, this method has been confirmed to reduce the earth pressure acting on the retaining wall and the horizontal displacement of the sheet-pile, and it is possible to perform deep excavation.

Furthermore, as an alternative diagonal earth retaining construction method, the double sheet-pile method has been developed. In this method, the heads of two sheet-piles are joined together. Thus, it is expected that the two sheet piles and the soil between the two sheet-piles become one rigid material and that the effect as the earth retaining material will become more than two times. The effect of the double sheet-pile method under certain conditions has been confirmed from centrifugal model tests or full-scale experiments. On the other hand, the soil behavior between two sheet-piles and adequate construction conditions have not been clarified yet.

Besides, recently, in the field of geotechnical engineering, an X-ray CT system that enables non-destructive and three-dimensional visualization of geotechnical phenomena has been attracting attention. It is one of the most effective methods to study soil behavior at the micro-level using the X-ray CT system because a mechanical method to directly observe the internal structure of soil has not been

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established yet. Thus, actual understanding phenomena, such as soil mechanics, have been improved, and previously unidentified phenomena have been clarified (Otani et al. 2000).

The purpose of this study is to investigate the reinforcement mechanism of double steel sheet piles using model experiments with X-ray CT and to investigate adequate construction conditions. In this study, the experiment equipment used in the X-ray CT system is developed, and the authors conducted model tests with this equipment. Besides, the behavior of the soil is quantitatively evaluated by visualizing the inside of the soil with an X-ray CT scan.

2 EQUIPMENT AND METHOD

2.1 *Experimental equipment*

In this study, a new experimental equipment was developed to perform experiments in the X-ray CT room. In this chapter, a newly developed experimental equipment is introduced. In addition, the experiment equipment for horizontal loading of the head of the sheet-pile is also introduced.

Figure 1(a) shows a photo of the developed equipment for this study. Furthermore, the side view of the developed experimental equipment in this study is shown in Figure 1(b). The top and the bottom of the soil box are made of aluminum, and the sides are made of polyvinyl chloride. These materials are highly permeable to X-rays, which minimizes the negative effects of using the X-ray CT system. When creating the ground, a shaking table is mounted under the soil box. The lower part of the sheet pile is fixed with acrylic material in order to install the sheet-pile vertically. Polycarbonate was selected to be used for the model sheet pile in this experiment considering the permeability of X-rays. Also, Figure 2(a) and (b) show that the bottom and the top of sheet-piles on this experimental equipment. On the bottom of the sheet-piles, both sides of the sheet-piles are fixed by the fixture to put soil between the two sheet-piles, like Figure 2(a). During the experiment, the two sheet-piles are set by a fixture on the top of the sheet-piles, like Figure 2(b).

In this experiment, a 300 mm-deep excavation was conducted. During the excavation, the depth of the excavation was measured by a ruler. Simultaneously, the horizontal displacement of the head was measured every 50 mm using a laser displacement meter.

Next, sheet-piles were loaded by a horizontal loading device after excavation because the displacement caused by the excavation was minimal. Figure 3 shows the equipment for the horizontal load. This equipment was made with reference to the horizontal load experiments (Matsumura et al. 2017) (Takano et al. 2006).

2.2 *Overview of model test*

Toyoura sand was used for this model test. Table 1 shows the physical property of Toyoura sand. The model ground was prepared using the vibration method, and the relative density of the model ground was between 80% and 82%.

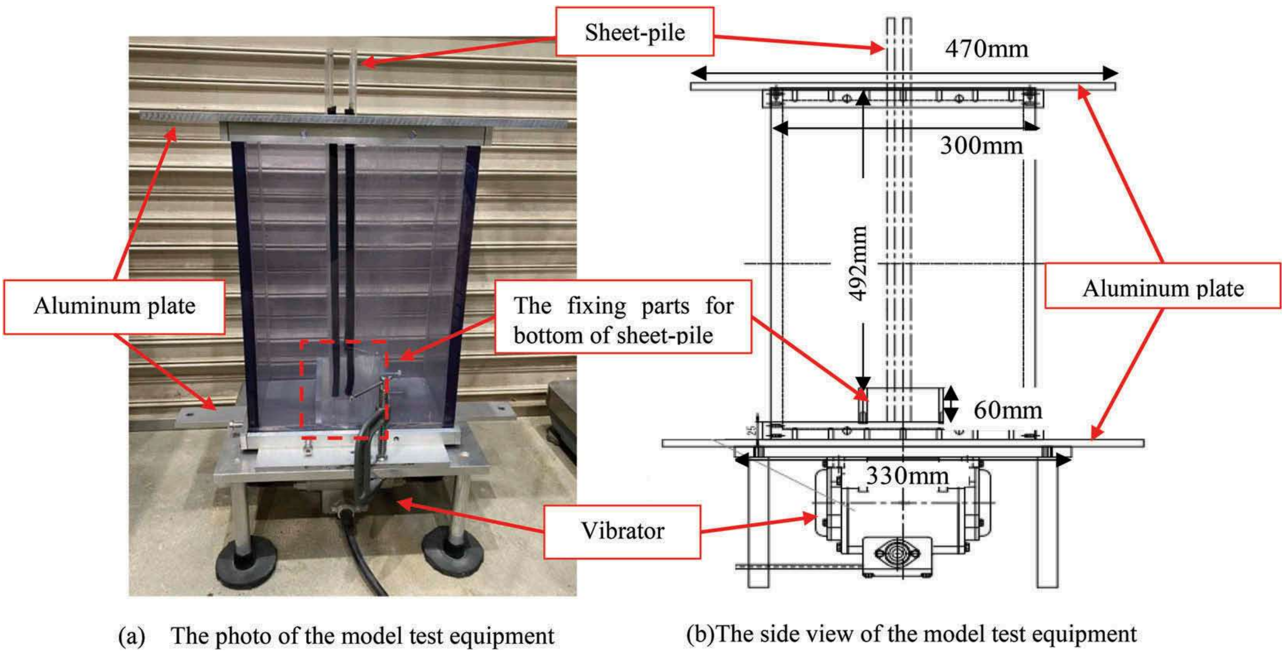
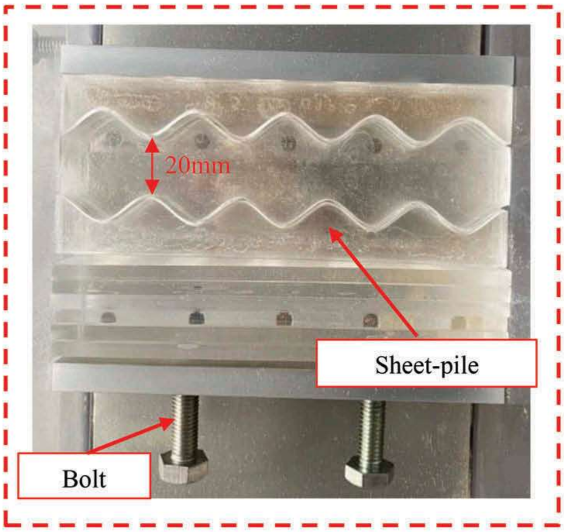
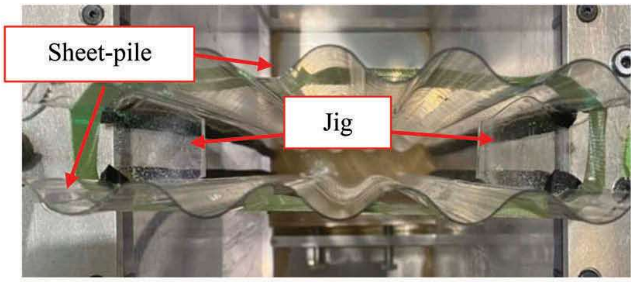


Figure 1. The photo of developed equipment.



(a) Jig for bottom of the sheet-pile



(b) Jig for top of the sheet-pile during making ground

Figure 2. The photo of bottom and top of experiment equipment.

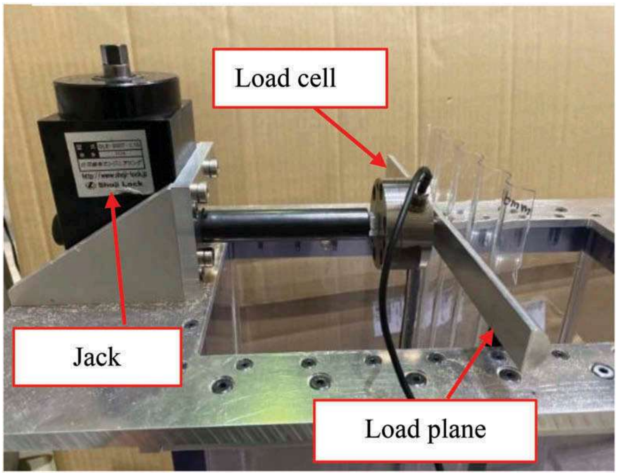


Figure 3. Experiment equipment for the horizontal load.

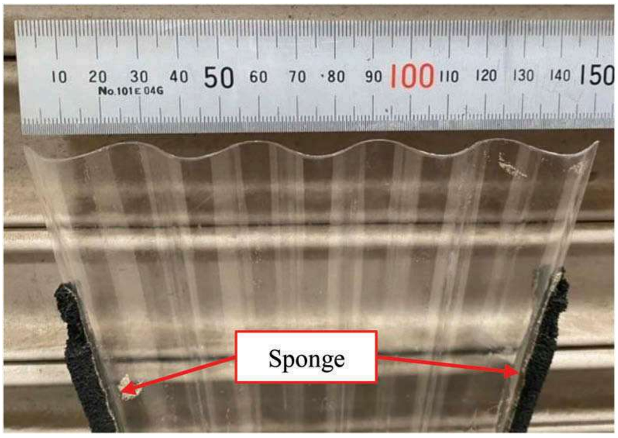


Figure 4. The model sheet-pile.

Figure 4 shows the model sheet-pile in this study. The model sheet pile was selected based on the results of preliminary experiments, considering the deflection of the material due to its rigidity. From the results of preliminary experiments, polycarbonate was selected. The model sheet-pile was 565mm long and 6mm thick. This model sheet-pile had a wave shape, and in the case of using two sheet-piles, the two waves were put so that they were in opposite phases, and the narrowest point was 20mm. The wavelength of this was 32mm, and the amplitude was 9mm. The sponge was also used to prevent leaking out the sand between the sheet-pile and the soil box wall. The size of the sponge was 8mm thick and 12mm wide.

Figure 5 shows the procedure of this experiment. Initially, the head and the bottom of the sheet-pile were fixed and placed in the soil box center. After that, the ground was created at the same height on both sides of the sheet-piles. Next, the ground on one side was excavated to a depth of 300 mm. During the excavation, a laser displacement meter was used to measure the horizontal displacement of the head per 50 mm mining. Additionally, the top of the sheet-pile was loaded by the horizontal load equipment, and load and horizontal displacement

Table 1. The property of Toyoura sand.

Soil particle density	2.65(g/cm³)
Maximum dry density	1.65(g/cm³)
Minimum dry density	1.33(g/cm³)
Average diameter	0.18(mm)
Uniformity coefficient	1.29

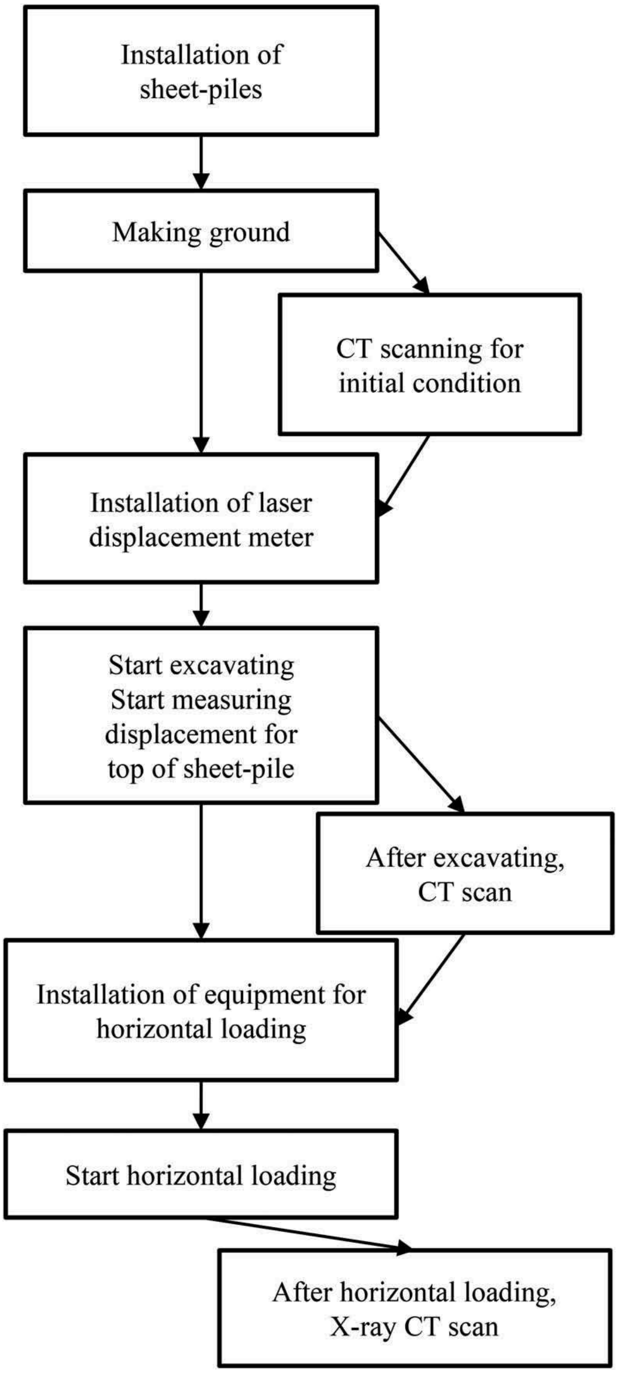


Figure 5. The procedure of this experiments.

were measured. In this model experiment, the horizontal load was measured with the load cell as shown in Figure 3, and the horizontal displacement is measured with a laser displacement meter on the other side.

Table 2 shows the data of this experiment. In this study, a single sheet-pile, a double sheet-pile without being fixed at the top of the sheet-pile, and the double sheet-piles being fixed at the top of the sheet-pile were tested. Additionally, a test in which the soil between the double sheet-pile was excavated to a depth of 140mm was conducted.

2.3 *X-ray CT scan*

X-ray CT scanners have been used mainly for medical purposes, but nowadays, they are widely used for industrial purposes. Especially in recent years, non-destructive and three-dimensional understanding of phenomena at the microscale has been attracting attention in geotechnical engineering as a new method for elucidating the mechanical behavior of soils. (Otani et al. 2005)

In this study, an industrial X-ray CT scanner owned by Kumamoto University X-Earth Center was used. Figure 6 shows the setup for the experiment during the X-ray CT scanning. When CT imaging is started, an X-ray is first irradiated, and the projection information from one direction is obtained. When the specimen table reaches the end-point, it rotates and then moves parallel to obtain the projection information from a new direction. By repeating this process, the information is accumulated, and the cross-sectional image is constructed. CT images consist of values called CT values, which are highly correlated with the specimen's density and are calculated by the computer. The images are displayed in 256 gray and white levels. The CT value is calculated by

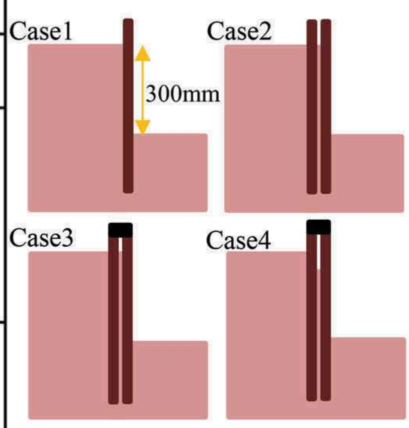
$$CTvalue = \frac{\mu_t - \mu_w}{\mu_w} K \qquad (1)$$

where μ_t is the coefficient of absorption at the scanning point; μ_w is the coefficient of absorption for water, and K is the material constant. It is noted that this constant is fixed to a value of 1000. Thus, the CT value of air should be -1000, and the coefficient of absorption for air is zero. (Otnai et al. 2005)

The scanning conditions are shown in Table 3. The voltage is 300 kV, the current is 2.00 mA, the filter function is FC1, the scan area is 400 mm diameter, the slice thickness is 1 mm, the scan speed is FINE, the matrix size is 2048×2048, and the scan mode is double full scan.

Furthermore, Table 4 shows the imaging cases and the area to be photographed. In the beginning, three cross-sections with a pitch of 100 mm were scanned for Case 1 (single sheet-pile), Case 2 (double sheet-piles without head fixing), and Case 3 (double sheet-piles with head fixing) in the range from 50mm to 250mm of the initial condition and after excavation. Besides, in Case 3, 28 cross-sections with a pitch of 10 mm were imaged in the range of 50-320 mm at the depth of the soil layer in the initial state, after excavation and horizontal loading of the head. In addition, based on the results of these CT scans, 150 cross-sections at a 0.2 mm pitch were taken at the depth of 210-240 mm, where the slip surface could be identified, and the soil behavior was studied in more detail.

Table 2. Test case.

Case	Condition	300mm Excavation	Horizontal loading	CT scanning (Pitch)	Model figure
1	Single sheet-pile	Done	Done	Done (100mm)	
2	Double sheet-pile without fixture			Done (100mm)	
3	Double sheet-pile with fixture			Done (100mm) (10mm) (0.2mm) Only 210mm~240mm	
4	Double sheet-pile with fixture (140mm excavation between double sheet-pile)			Not-Done	

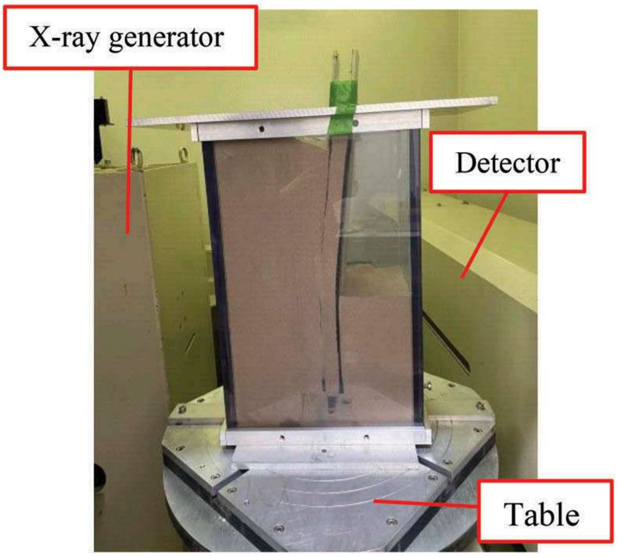


Figure 6. Model test using X-ray CT.

3 TEST RESULTS AND DISCUSSION

3.1 *Comparison of double sheet-piles with and without head fixing*

In this chapter, the Case1 (single sheet-pile), Case2 (double sheet-piles without head fixing), and Case3 (double sheet-piles with head fixing) are comparing the relationship between the excavation depths and horizontal displacements of the head of sheet-piles. Figure 7 shows the results. From these results, the horizontal displacement of Case1 (single sheet-pile) and Case2 (double sheet-pile without head fixing) at an excavation depth of 300mm was 16.89mm and 12.00mm, respectively. When two sheet piles are used, the rigidity should be more than twice as high, but Case 2 does not have more than twice the reinforcement effect than Case 1. On the other hand, in Case 3, the horizontal displacement of the head at an excavation depth of 300mm was 1.19 mm, and the displacement from the initial condition was very small. Thus, it is significant to use two sheet-piles and to fix the top of the sheet-piles.

Next, the results of CT scanning were compared among Case1 (single sheet-pile), Case2(double sheet-pile without head fixing), and Case3 (double sheet-pile with head fixing). Figure 8(a), (b), (c) show the cross-sectional images at the initial condition and after excavation at the depths of 50mm, 100mm and 150mm. The cross-sectional images were taken at depths of 50, 150, and 250mm. In the case of Case1(single sheet-pile), the sheet-pile deformed significantly from the initial condition, and some slip lines were found in the background of the sheet-pile. Comparing between Case 1 and Case 2, Case 2 did not show significant deformation of the sheet pile on the background side as in Case 1, but the sheet pile on the excavation side was found to be significantly deformed. Although no-slip lines were found on the ground behind the sheet-piles, a few slip lines were found in the soil between two sheet-piles. Thus, the sheet-pile of the excavation side is considered to be pressed by the soil between two sheet-piles.

In Case3, there were few deformations of the sheet-piles, and the slip line has not appeared on the

Table 3. Scanning condition.

Voltage	300kV
Current	2.000mA
Filter function	FC1
Scanning area	φ400mm
Scanning velocity	FINE
Matrix size	2048 × 2048
Scan mode	Double full scan (720 deg)

ground behind the sheet-piles or soil between them. No-slip lines were found on the background side of the excavation or the soil between the two sheet-piles because the two sheet-piles and the soil between them were unified as one rigid body. The X-ray CT scan results show that the head fixture of the two sheet-piles effectively increases the earth-retaining strength.

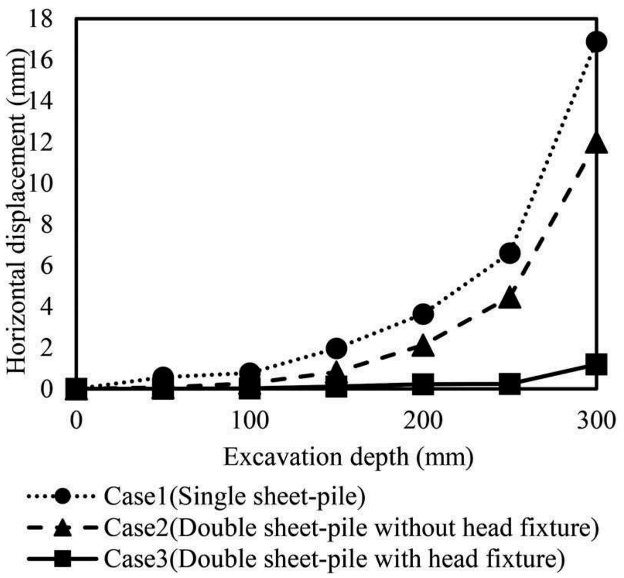


Figure 7. The relationship between horizonal displacement and Excavation depth.

3.2 *In-ground behavior and the importance of the soil between two sheet-piles*

3.2.1 *Investigating the behavior of the soil between two sheet-piles*

From Chapter 3.1, it is clarified that double sheet-piles with head fixing sufficiently increase the strength of the earth retaining. However, it is not clear from the experiments in Chapter 3.1 how the head fixing effect increases the retaining capacity of the sheet piles. Therefore, to understand the reinforcement mechanism of this construction method, in the Case3, 28 cross-sections of the initial condition, after excavation and after horizontal loading of the head were scanned by industrial X-ray CT at a pitch of 10mm for a depth range of 50 to 320mm. Since there was no significant change in the ground behavior after excavation, the behavior of the ground was observed from the X-ray CT images after the top of the sheet-piles was loaded horizontally.

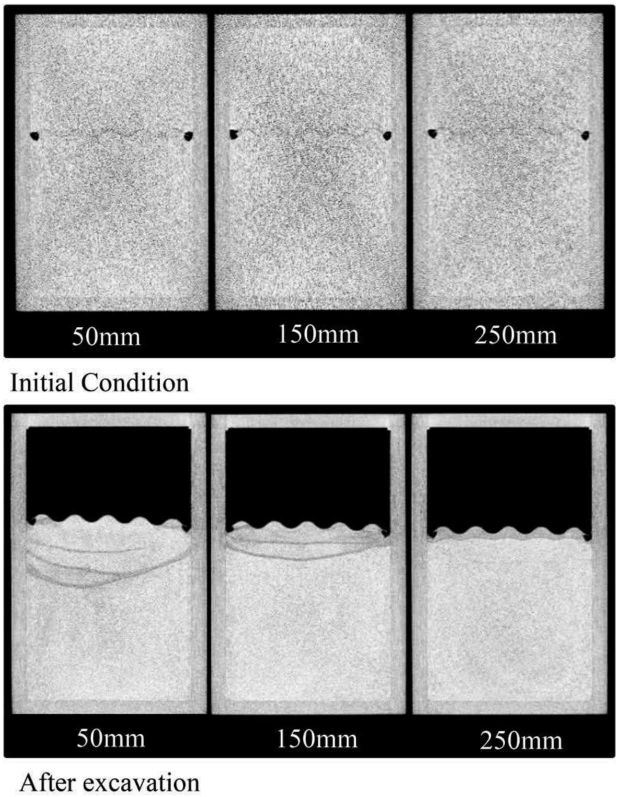
Figure 9 shows the cross-sectional images obtained from the X-ray CT scanning at the depth of 200mm~310mm of the sheet-piles after horizontal loading. This image confirmed that there were some slip lines in the soil between the two sheet-piles.

Besides, the 210mm to 240mm depth position was scanned in more detail to visualize some slip lines three-dimensionally. Figure 10 is the cross-sectional view of a combination of 150 CT images scanned at a pitch of 0.2mm for the depth range from 210 to 240mm. This figure shows that there were two slip lines between the two sheet-piles. Considering the direction of the slip line, it is assumed that the sheet-pile on the excavation side at the depth from 210 to 240mm moved and caused the soil to slide.

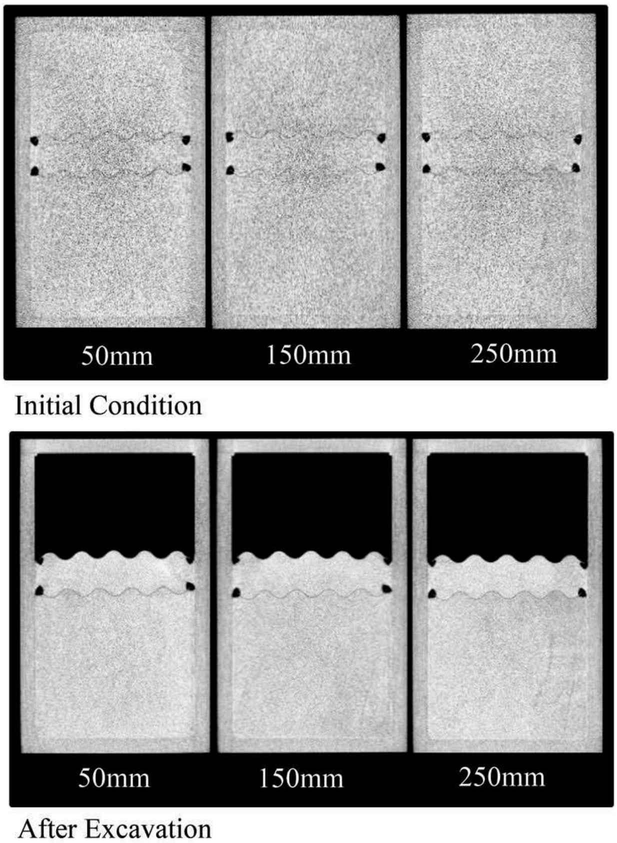
Moreover, the 28 images in Case3 at the after horizontal loading and Figure 10 were cut in half and combined vertically. The combined image is shown in Figure 11. In addition, the average data of the image of a specific section was made so that the positions of continuous slip lines could be identified even in a vertical section (Figure 12). From these results, it is estimated that the slip line between the

Table 4. The list of scanning case.

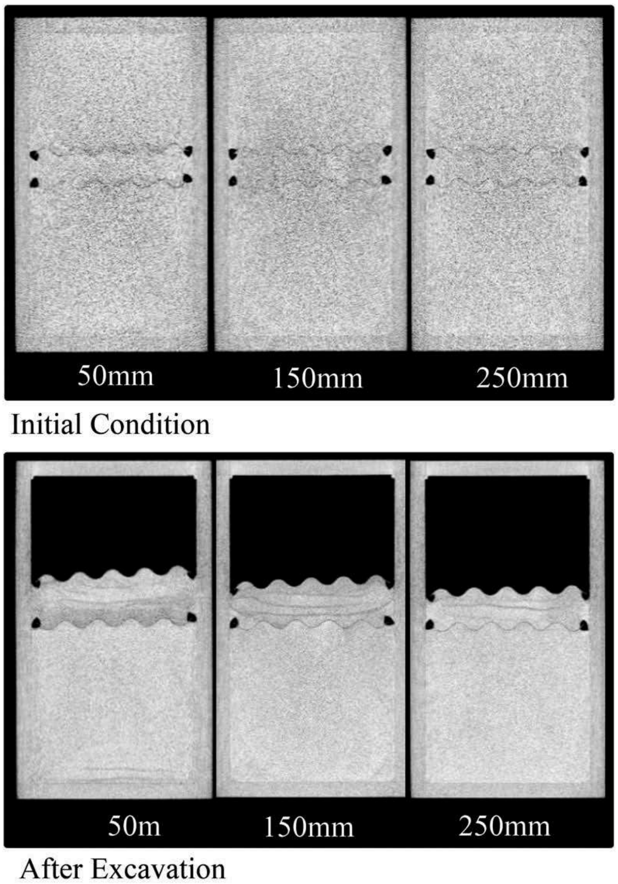
Scan Range (Depth)	Pitch	The number of cross-section	Case 1	2	3	4	Condition Initial	After Excavation	After Horizontal load
50mm〜250mm	100mm	3	Done	Done	Done	Not-Done	Done	Done	Not-Done
50mm〜320mm	10mm	28	Not-Done	Not-Done	Done	Not-Done	Done	Done	Done
210mm〜240mm	0.2mm	150	Not-Done	Not-Done	Done	Not-Done	Not-Done	Not-Done	Done



(a) Single sheet-pile



(c) Double sheet-pile with head fixing



(b) Double sheet-pile without head fixing

Figure 8. Cross-section image at each depth.

two sheet-piles was 150mm~230mm on the excavation side and 170mm~260mm on the background side of the excavation. Combining each cross-section into a three-dimensional form, the start and endpoints of the slip line were revealed.

Next, from the CT scan image of the Case3, the coordinate of the sheet-piles in each section was taken, and the displacement of the two sheet-piles was graphed (Figure 13). This Figure shows that the displacement of the sheet-piles on the excavation side is greater than the displacement of the sheet-piles on the background side of the excavation. In other words, when the soil between two sheet-piles slips, the sheet-pile on the excavation side was pushed by the soil, causing the sheet-pile to deflect. Also, it is considered that the slip of the soil between two sheet-pile was dominated by the earth pressure of the backside soil. The shear force on the soil between two sheet-piles was caused by the active failure of the backside soil, and the slip was caused.

Further, the difference in deflection between the two sheet-piles was graphed by correcting the deflection angle (3 to 6 degrees) from the Figure 13. Figure 14 shows the results after correction. This Figure shows that the difference between the two sheet-piles increases to the point where the slip line is found in the soil between the two sheet-piles.

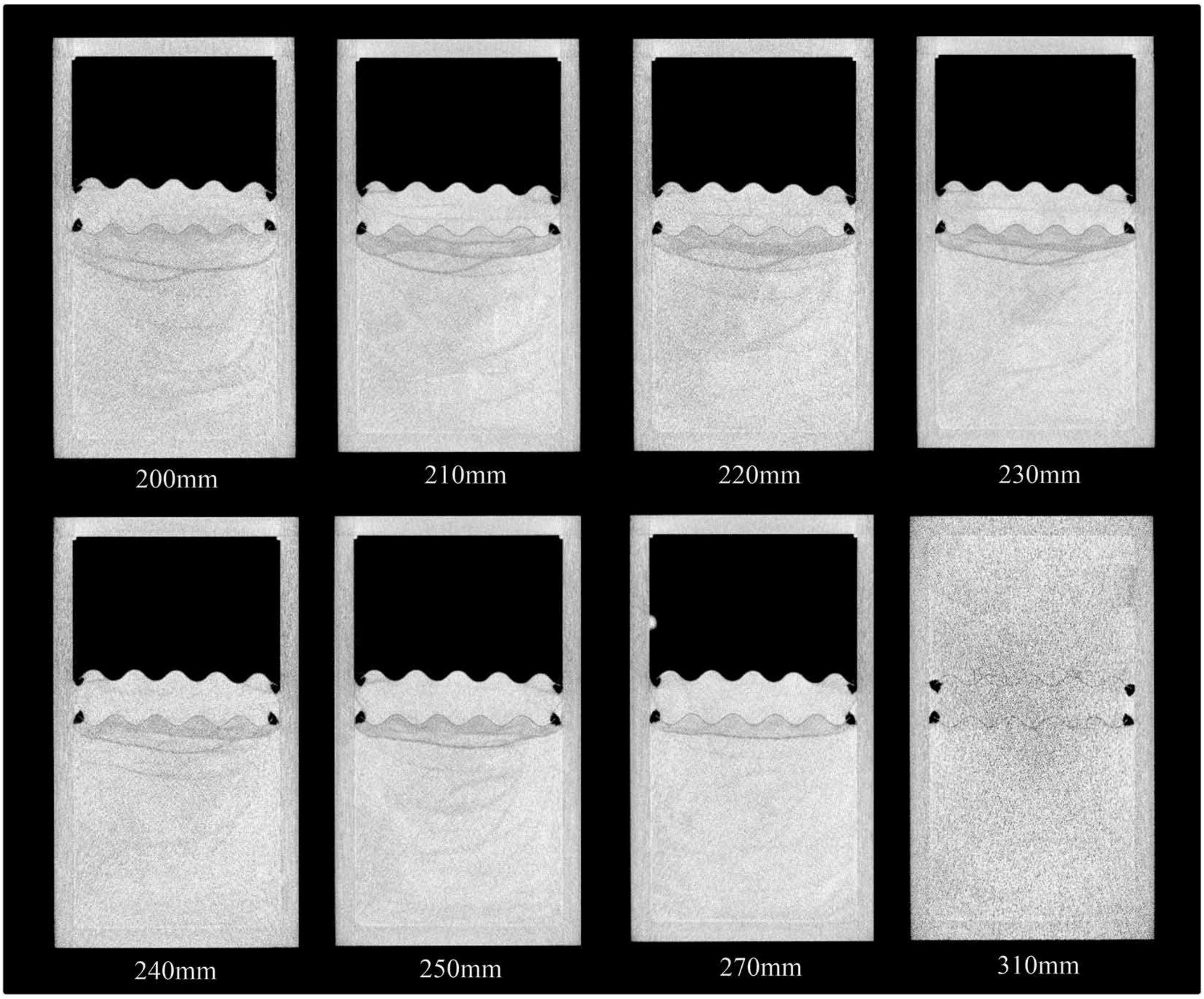


Figure 9. The cross-sectional image of case3(with head fixing) after horizontal loading.

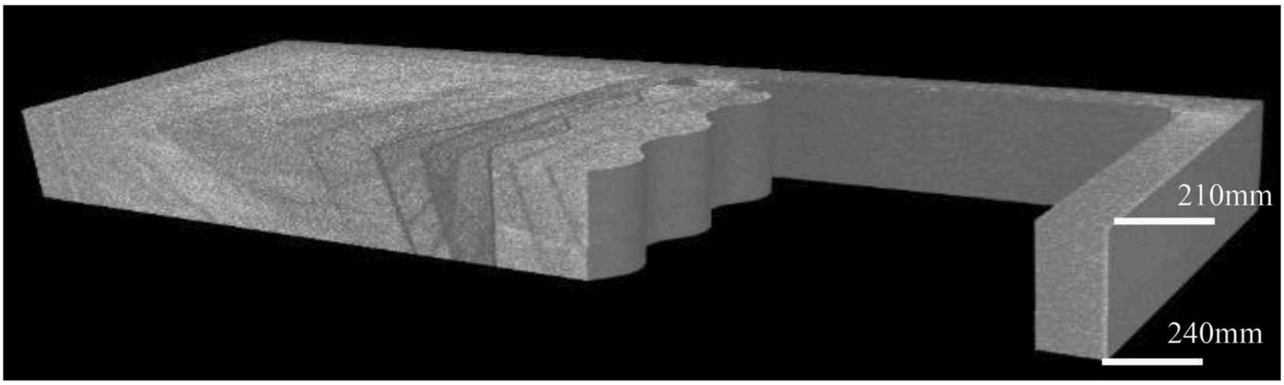


Figure 10. Three-dimensional CT image at the depth of 210~240mm in after excavation of case 3.

In consideration of the above results, it is suggested that the sheet piles on the excavation side were pushed out at the depth of 50-320 mm, where the slip line was found. Also, it is essential to increase the strength of the sheet pile because the rigidity of the sheet pile is low at the location where the slip line was found.

3.2.2 *Importance of soil between two sheet-piles*

From the X-ray CT scan results, in Case3(double sheet-piles with head fixing), slip lines were found in the soil between two sheet-piles at the depth of 150~260mm, a little above the excavation depth (300mm). However, no-slip lines were found in the upper part of the soil between the two sheet-piles.

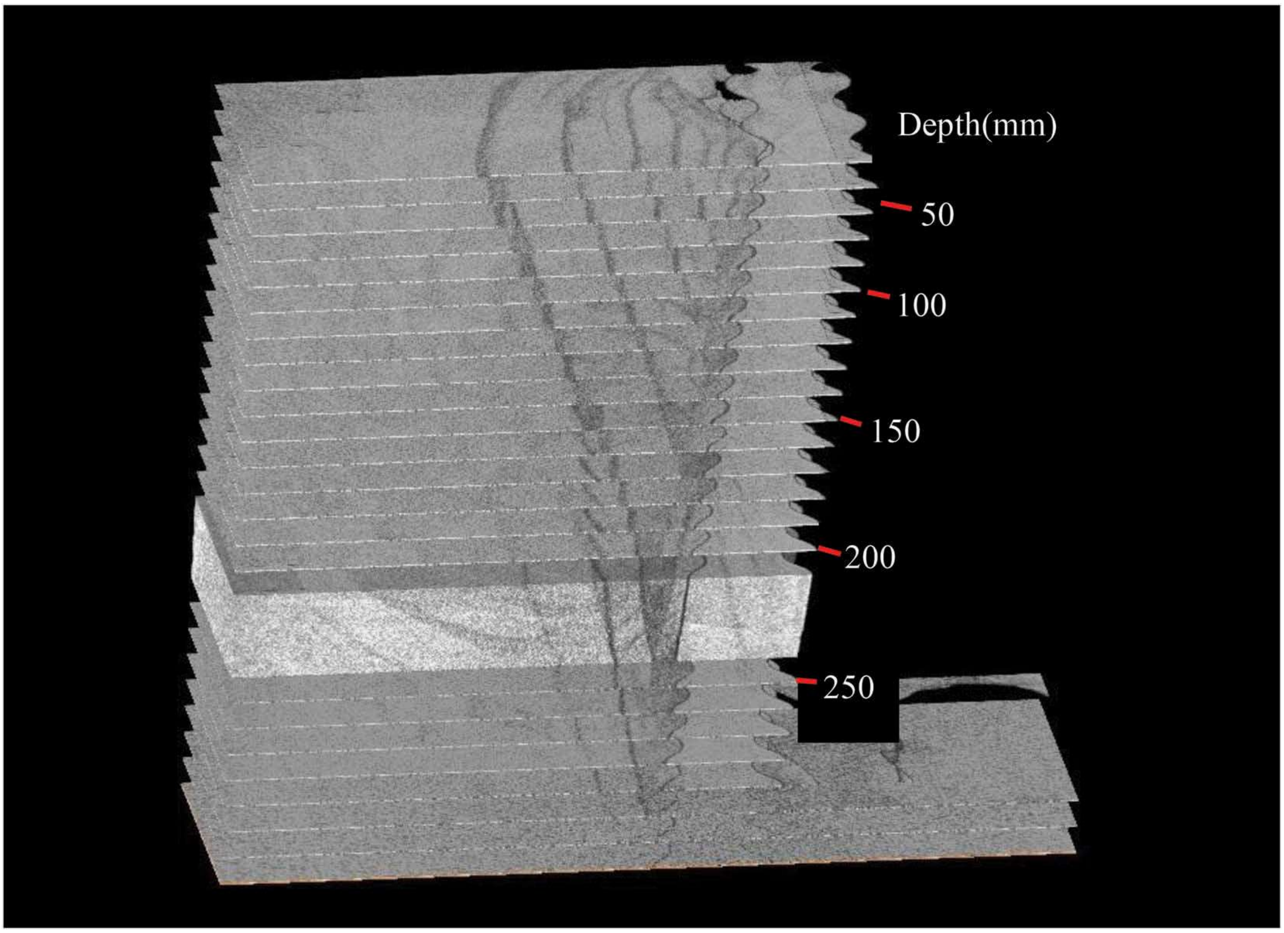


Figure 11. Three-dimensional CT image in after excavation of case3.

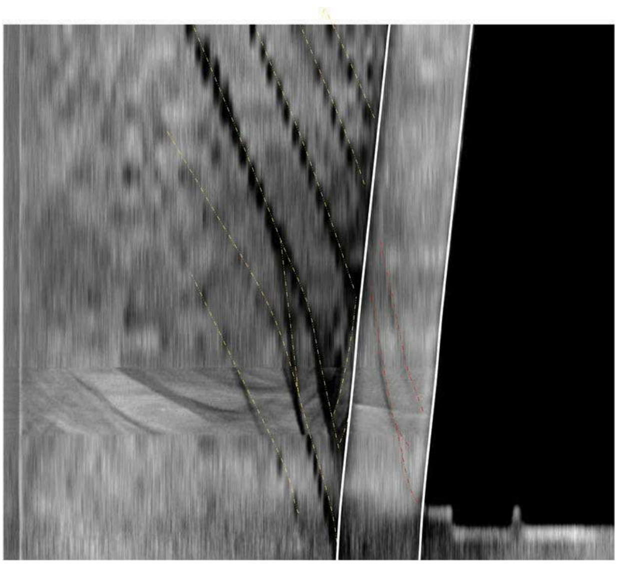


Figure 12. Average data of Figure 11.

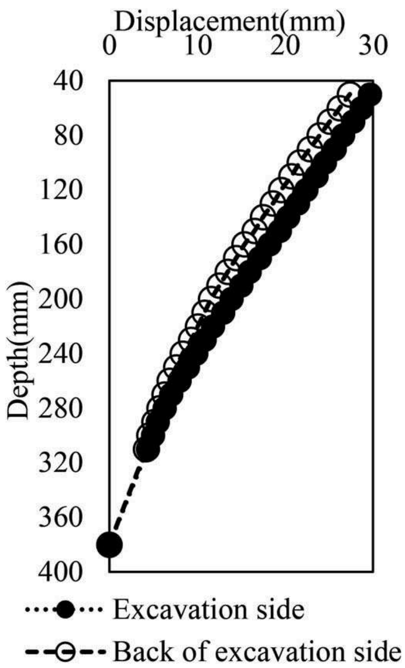


Figure 13. The value of displacement of two sheet-piles.

Therefore, to investigate the importance of the soil between the two sheet-piles in detail, the upper layer of the soil between the two sheet-piles was removed from which no slip line was found and we conducted an excavation experiment. (Case4). Figure 15 shows the result of the horizontal head displacement under excavation. A comparison of the horizontal head displacement between Case 1 (single sheet pile) and Case 3 (double steel sheet pile with head fixing) was carried out using this experiment as shown in

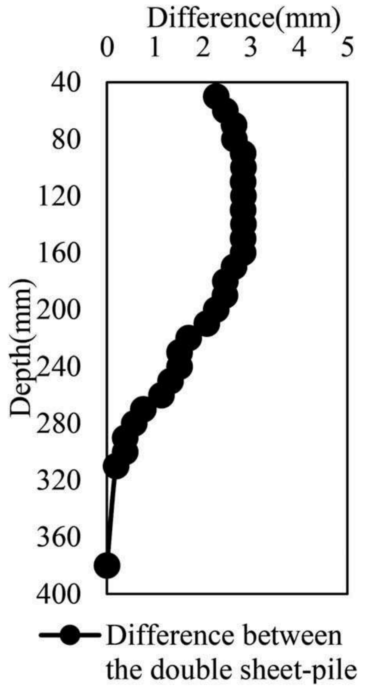


Figure 14. The value of difference between two sheet-piles.

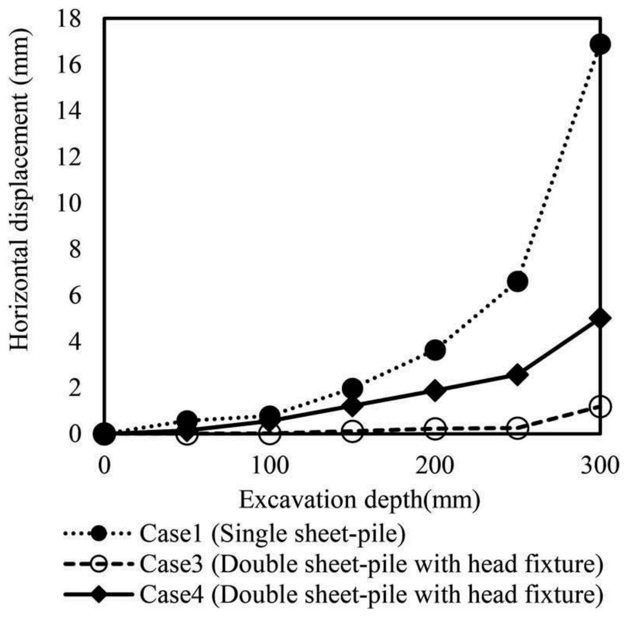


Figure 15. The relationship between excavation depth and horizontal displacement.

Case 4. From these results, the horizontal displacement of the head after the excavation of 300mm was larger in Case4 (140mm of the soil between two sheet-piles) than Case3 (double sheet-piles with head fixing). In other words, it was confirmed that the strength of the sheet piles as an earth retaining structure was lowered in case of the absence of the soil between two sheet-piles in the upper layers. Thus, it is essential not only to fix the head of the sheet pile but also to have the soil between two sheet-piles. It is possible to enhance the reinforcement effect of the sheet pile by increasing the density of the soil between two sheet piles and restraining the movement of the soil between two sheet-piles.

4 CONCLUSION

In this study, a new construction method using two sheet-piles was focused. Model experiments were conducted to evaluate the strength of double sheet-piles. The new experimental equipment that can take a CT scan was developed, and excavation experiments were conducted. Simultaneously, the effectiveness of this construction method was confirmed by measuring the horizontal displacement of the head of the sheet-piles. Besides, the behavior of the ground with the double sheet-piles was investigated by using industrial X-ray CT. Furthermore, this study focused on the soil between the two sheet-piles to effectively increase the reinforcement of the sheet-piles.

The displacement of the head with two sheet piles was smaller than that with only one sheet pile. Besides, the use of two sheet piles and simultaneous fixing of the head of the pile effectively reduced the displacement. The effectiveness of the proposed method was confirmed by the results of this construction method.

From the X-ray CT scan image, in the case where two sheet piles were used and the heads were fixed, multiple slip lines were found in the soil between two sheet-piles. The position of the slip lines was located a little above the excavation surface, and this position is considered to be essential for the effectiveness of this construction method. Also, the coordinates of the two sheet piles were calculated from the CT images, and the deformation mode of the sheet piles was discussed. The results confirmed that the sheet pile on the excavation side was more deflected than the sheet pile on the background side. Furthermore, the direction of the slip line was identified by visualizing the CT image.

Since the reduction of the soil between two sheet-piles decreases the overall stiffness of the sheet pile, the condition of the soil between two sheet-piles might have a significant effect on the behavior of the sheet-pile. This result suggests that increasing the density of the soil between two sheet-piles and constraining the movement of the soil between two sheet-piles may further increase the strength of the sheet-pile.

These findings indicate that the strength of the sheet piles as a retaining wall was increased by using two sheet piles to fix the head. The ground behavior of the two sheet piles used to fix the head in place was also clarified. In addition to the fixation of the heads, the presence of soil between two sheet-piles was also found to be important for increasing the strength of the sheet piles as retaining walls.

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