

Quantitative evaluation of the behavior of the sand sandwiched by two sheet piles using X-ray CT

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ABSTRACT: The head-fixed double sheet pile method is an innovative construction technique designed to mitigate soil collapse and water intrusion during excavations. Recognizing the importance of the soil enclosed between the two sheet piles (referred to as inner soil), this study conducts horizontal loading tests using two plates with inner soil under confining pressure. Furthermore, to qualitatively observe the behavior of the inner soil, X-ray CT scanning and DIC image analysis were conducted to evaluate the strain field. To facilitate experiments with X-ray CT scanning, a new testing apparatus was developed, considering X-ray penetration and horizontal loading while ensuring the setup remained stationary within the X-ray CT room. Two types of cases were examined: one in which the relative density of the inner soil was varied to assess its strength, and another in which the friction between the sheet pile and soil was adjusted to investigate soil-structure interaction effects. The results revealed that both the relative density of the inner soil and the friction between the soil and sheet pile significantly affect the horizontal bearing capacity. When the relative density was low, a localized shear band formed, preventing the sheet pile and inner soil from acting as a cohesive unit, leading to reduced bearing capacity. In contrast, higher relative density resulted in shear strain spreading over a larger area, allowing the sheet pile and inner soil to function as a unified structure, thereby enhancing bearing capacity. Additionally, increased friction restricted soil particle movement, causing shear strain to concentrate in the center of the specimen. These findings indicate that variations in relative density and friction significantly influence the behavior of the soil sandwiched between the two sheet piles, ultimately affecting the horizontal bearing capacity of the double sheet pile method.

KEYWORDS: Double-sheet pile, X-ray CT, Friction, Soil-structure interaction.

1 INTRODUCTION

The steel sheet pile method has long been utilized in both temporary and permanent underground construction projects. Over the years, various techniques have been developed to enhance its applicability, including the use of anchors, beams, and self-supporting wall systems. Despite these advancements, conventional methods still face challenges related to construction efficiency, spatial constraints, and cost-effectiveness. Consequently, there remains a pressing need to develop more efficient and practical construction approaches.

In this context, the present study considers sheet piles as temporary structural elements. To overcome the limitations of traditional methods, Kajima Corporation (Japan) has introduced an innovative technique known as the head-fixed double sheet pile method. The fundamental concept of this method is illustrated in Figure 1. In this approach, two parallel sheet piles are rigidly connected at their heads, forming a rigid-frame structure with significantly enhanced stiffness. This configuration offers several expected benefits, including improved displacement control through the push-pull effect, increased resistance from the confined inner soil, added rigidity due to the frame-like (Rahmen) structure, and additional reinforcement through the integration of the inner soil and the sheet piles themselves.

A series of experimental and numerical investigations—such as 1G model tests, centrifuge experiments, and finite element method (FEM) simulations—have demonstrated the effectiveness of this method in controlling ground displacement. Notably, Nasu et al. (2021) conducted a 1/4-scale 1G field test and reported that the deformation suppression achieved with the double sheet pile method was approximately six times greater than that of conventional single sheet piles.

Furthermore, Sugimoto et al. (2023) employed industrial X-ray computed tomography (CT) to visualize the behavior of the inner soil during excavation, emphasizing the critical role of soil–structure interaction. (Sato et al., 2018; Kido et al., 2022)

However, for a more rational and reliable design, as well as a deeper understanding of the sand behavior between the plates, it is essential to move beyond qualitative observations and conduct detailed strain-level evaluations. Therefore, the current study focuses on the mechanical behavior of sand confined between two sheet piles. To achieve a more comprehensive and quantitative understanding of inner soil behavior, horizontal loading experiments were carried out using microfocus X-ray CT. In addition, Digital Image Correlation (DIC) was applied to the captured images to calculate shear and volumetric strains. This enabled a detailed strain analysis of the

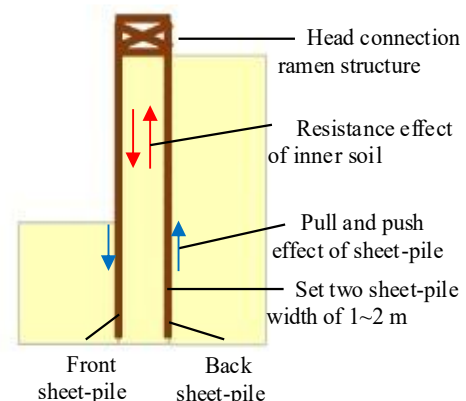


Figure 1. Concept of double sheet piles method

inner soil deformation. Based on these experimental results, the deformation characteristics and mechanical response of the inner soil under the unique loading conditions of the head-fixed double sheet pile method are discussed in depth.

2 TEST METHOD

2.1 Experiment equipment

Focusing on the behavior of inner soil sandwiched between two sheet piles, horizontal loading experiments were performed in which the specimen was sandwiched between two sheet piles and loaded horizontally under confining pressure. To simulate confining pressure, cell-pressure rubber soil box was used (Gotoh, 2018). This is an experimental apparatus adapted from the triaxial apparatus, employing a rubber-sleeved specimen enclosed within a sealed cell, and constrained by air pressure. Under these conditions, penetration of piles and horizontal loading test of sheet piles can be conducted to reproduce behavior closer to that of the actual ground compared to a rigid-soil box. The boundary conditions when we used this equipment do not restrict lateral movement, which also provides X-ray transparency due to the acrylic cell. These features improve the reproducibility of inner soil behavior compared to existing cylindrical aluminum soil box and make it suitable for X-ray CT imaging.

In this study, a double sheet pile horizontal loading test apparatus was developed by utilizing the above-mentioned cell pressure soil box. Figure 2 shows the experiment apparatus and Figure 3 shows a view during X-ray CT imaging. The size of specimen is 70mm-width, 70mm-depth and 180mm-height. The shaft attached to the apparatus is connected to the shaft of linear jack, and the shaft in the apparatus is loaded onto the two sheet piles to which the head is fixed.

2.2 Test Procedure

The procedure for this experiment is then described below:

- 1) Set a rubber sleeve, a model sheet pile and a square pillar mold in the apparatus and make a model ground between two sheet piles.
- 2) Apply negative pressure to the model ground to make the specimen self-standing.
- 3) Remove the mold. At the same time, confirm that the specimen is vertically self-supporting.
- 4) Place the cell over the specimen and attach the horizontal loading apparatus to the top of the cell.
- 5) Switch the pressure inside the cell from negative to confining pressure.
- 6) Attach a linear jack to the apparatus and conduct a horizontal loading test. Check the aluminum plate for damage after the test and replace it if damaged.

Table 1. Property of Toyoura sand

Soil particle density	2.65(g/cm ³)
Maximum dry density	1.65(g/cm ³)
Minimum dry density	1.33(g/cm ³)
Average diameter	0.18(mm)
Uniformity coefficient	1.29

2.3 Material and Test cases

The model ground in this experiment was made by dry Toyoura sand using the vibratory method. Table 1 shows the property of

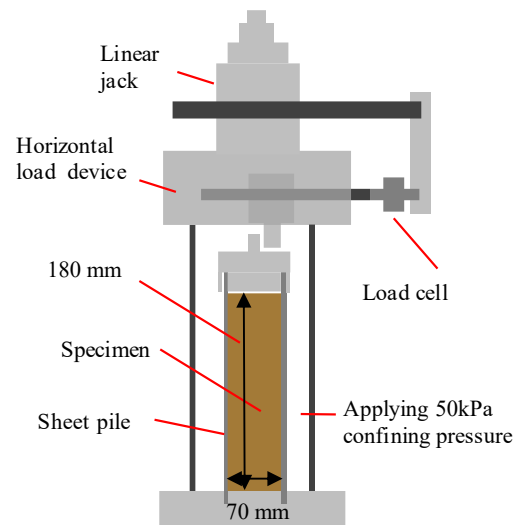


Figure 2. Horizontal load device

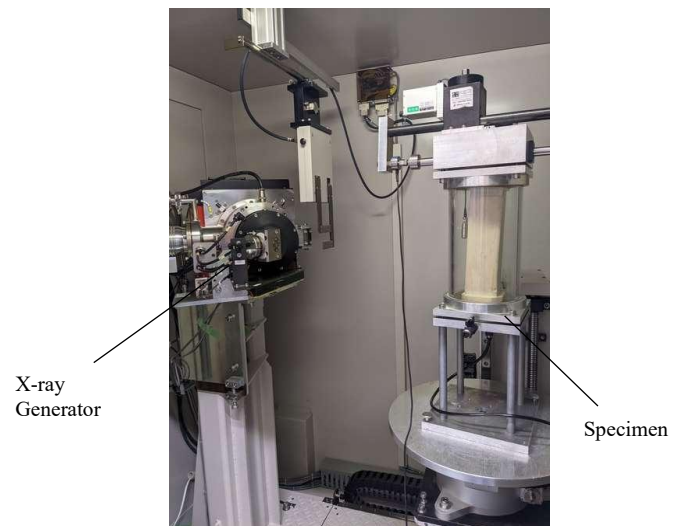


Figure 3. X-ray CT scan with experiment

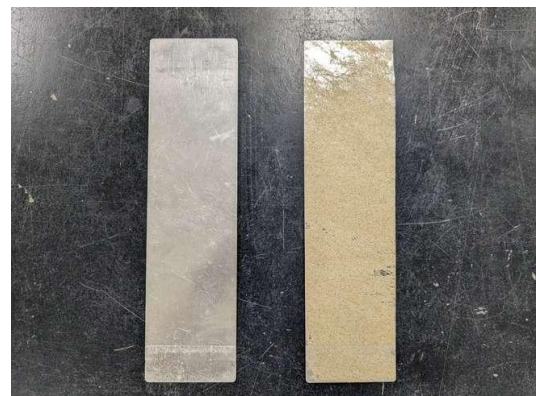


Figure 4. Model sheet pile

Table 2. Test cases

	Friction of Sheet pile	Relative density(%)	Confining Pressure(kPa)
Case1	Low	80	50
Case2	Low	60	50
Case3	Low	90	50
Case4	High	80	50

Toyoura sand. The relative density varied from case to case, however the reference case was made with $Dr=80\%$.

In the double sheet pile method, inner soil conditions significantly affect overall rigidity. Model tests of the double sheet piles results highlight the importance of friction between the sheet pile and inner soil²⁾. Thus, experimental cases were designed focusing on inner soil density and sheet pile-inner soil friction. Table 2 shows the experimental cases. To enhance friction, Toyoura sand was coated onto the sheet piles. Figure 4 shows the photo of model sheet pile for case1~3 and 4.

2.4 Micro-focus X-ray CT and Image analysis

In this study, X-ray CT scanning was conducted during experiments. Therefore, these experimental procedures were conducted in the X-ray CT room. The X-ray CT used in this study was a micro-focus X-ray CT scanner (TOSHIBA TOSCANER-32300FPD) owned by the Kumamoto University X-earth Center. The main feature is the ability to observe behavior inside geomaterials in a non-destructive and three-dimensional manner. The output of the X-rays is adjusted by adjusting parameters such as voltage and current, considering the density of the object being photographed. When the experiments are started, the sample table makes a rotation, during which X-rays are emitted intermittently from the X-ray generator. The X-ray that passes through the sample is detected by the detector, and the density of the material is calculated from the amount of X-ray absorbed by the sample by back calculating the amount of absorption. These operations are performed 360 degrees as the sample table rotates, and the obtained information on the absorbed amount is processed three-dimensionally using a computer to obtain an X-ray CT images.

For X-ray CT scanning of this study, images were captured every 2 mm of horizontal displacement, covering 10 mm to 180 mm from the specimen's top. The resolution of the CT images obtained is 1024×1024 voxels, therefore images divided into 1024 sections are obtained for this scanning area.

After scanning, digital image correlation (DIC) analysis was applied to evaluate specimen deformation. DIC quantifies deformation by pattern matching pre- and post-deformation images from X-ray CT. The SPAM software, developed at the University of Grenoble Alpes (3SR laboratory, France), was used for DIC analysis (Stamati et al., 2020). Shear and volumetric strain were evaluated by comparing images at 2 mm displacement intervals.

3 RESULTS AND DISCUSSION

3.1 Mechanical results

Figure 5 presents the horizontal loading test results for different relative densities of the inner soil. The peak load was 90N for $Dr=60\%$, 100N for $Dr=80\%$, and 140N for $Dr=90\%$. In all cases,

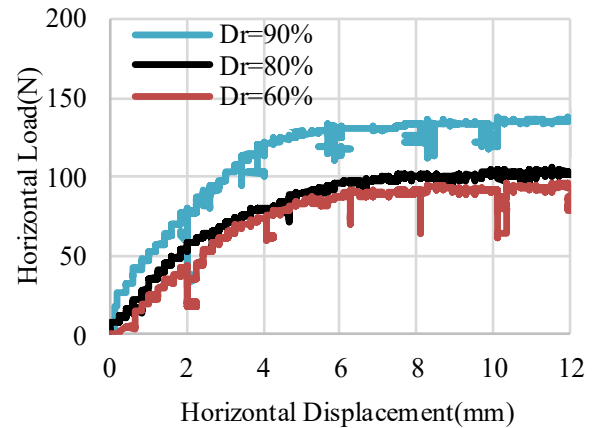


Figure 5. Load-displacement curve of Case 1~3

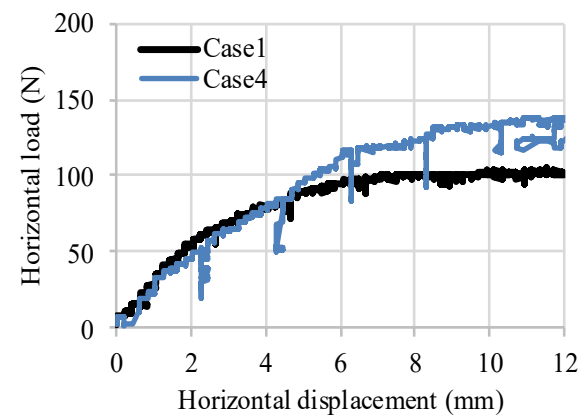


Figure 6. Load -displacement curve of Case 1 and 4

the load increased steadily up to horizontal displacement of approximately 4mm, after which the rate of increase slowed. However, the final peak strength differed, indicating that relative density affects the strength of specimens.

Figure 6 shows the results of the horizontal loading tests conducted to evaluate the effect of surface friction between the inner soil and the sheet pile. The peak load was 100N in Case 1 and 140N in Case 4 representing a 40% increase. When friction was increased, the horizontal load continued to rise until a displacement of 12 mm, after which the rate of increase slowed. Up to 6 mm displacement, the results were similar to those of Case 1, implying that the inner soil behavior remained consistent with Case 1 up to this point. Beyond 6 mm, a noticeable difference in inner soil behavior was observed, suggesting that the effect of increased friction became more significant at larger horizontal displacements. The increase in horizontal load capacity due to the difference between inner soil and sheet pile was also confirmed in the model test by Sugimoto et al. (2023), in indicating that the friction between the sheet pile and the soil contributes to the deformation control effect.

3.2 Scanned X-ray CT image

Figure 7 presents the X-ray CT images for Case 1, captured at three stages: the initial state, after 6 mm of horizontal displacement, and after 12 mm of horizontal displacement. In these images, areas with higher density appear white, while areas with lower density appear black. Since the sheet piles are

denser than Toyoura sand, they are clearly visible as white regions.

As the horizontal displacement increased, the entire specimen gradually shifted to the right. Although the horizontal force was applied to the upper part of the specimen, deformation was observed throughout the entire structure rather than being localized only at the top. This suggests that the whole specimen tilted as a single unit. However, the small grain size of Toyoura sand, relative to the resolution of X-ray CT, made it difficult to distinguish differences in the internal behavior of the inner soil through visual inspection alone. Therefore, Digital Image Correlation (DIC) analysis will be applied to these images to quantitatively evaluate the deformation of the sheet pile and inner soil.

3.3 Displacement and Strain field by DIC analysis

Figure 8 shows the displacement fields obtained through DIC analysis applied to the 2-4 mm and 10-12 mm images. The displacement fields are shown in both the X-direction (horizontal) and Z-direction (vertical). Parameters related to DIC were determined empirically with reference to Réthoré et al., 2008. In all cases, the largest displacement in the X-direction occurred at the top of the specimen, with displacement gradually decreasing toward the middle and bottom. The Z-direction displacement was observed on the right side of the specimen, and this area was notably larger in Case 2 compared to the other cases. In Case 3, however, the displacement area in the Z-direction was smaller. Although there were no major differences in the horizontal displacement across the cases, the variation in vertical displacement suggests that the volume change differed based on the relative density of the inner soil.

Secondly, Figure 9 presents the shear strain and volumetric strain calculated from the displacement data. Differences in strain fields were observed depending on the relative density of the specimen. In cases with lower relative density, the shear strain became more localized. For Case 1 and Case 2, shear strain zones extended from the upper left to the center of the specimen, visible at both the top and midsection. However, in Case 3, no distinct shear band appeared, suggesting that shear strain occurred mainly on the left side of the specimen. Additionally, slight volumetric shrinkage was observed in the middle of the specimen in Case 2, likely due to particle rearrangement caused by the lower relative density.

In contrast, in Case 4, where the friction between sheet pile and soil particles was increased, shear strain was concentrated in the center of the specimen. This is because the movement of soil particles around the sheet pile was restricted, and there was no escape from the strain caused by the forced displacement. As a result, shear strain was considered to have concentrated in the center of the specimen, where the effect of sheet pile friction was least likely to be felt. A similar phenomenon was observed in the model experiment described in Sugimoto et al., 2023. In the case of increased friction, the low-density area occurred not in the periphery of the sheet pile however in the inner soil.

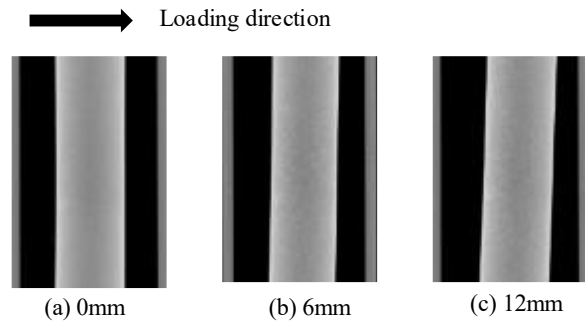


Figure 7. Example of X-ray CT image

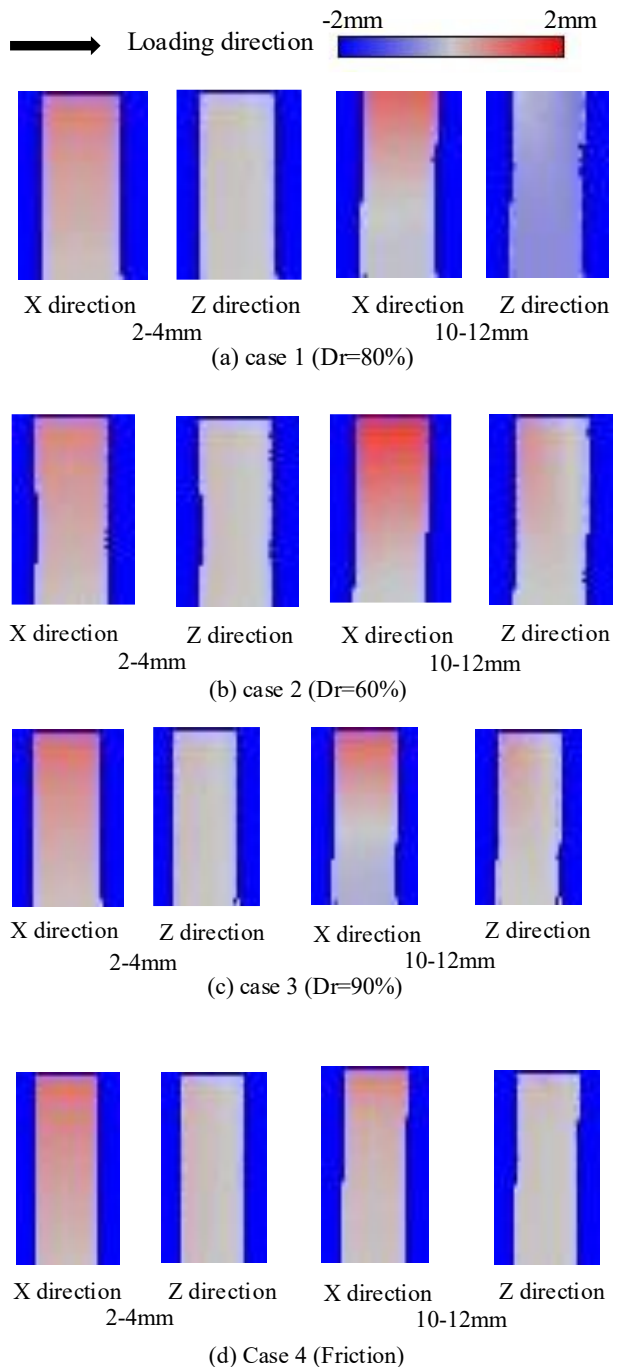


Figure 8. Displacement field of each cases by DIC

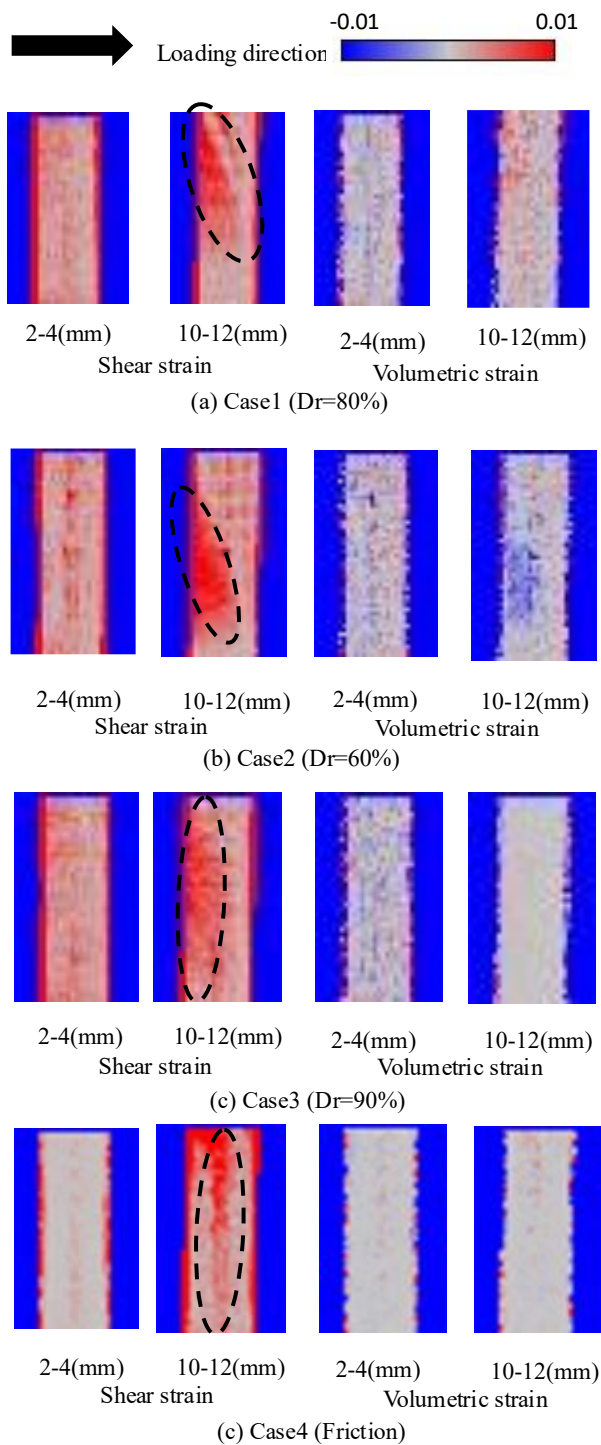


Figure 9. Strain field of each cases by DIC

3.4 Discussion

The experimental investigation conducted in this study, along with micro-focus X-ray CT and digital image correlations, clearly demonstrated that variation in the relative density of the inner soil significantly influences both the horizontal bearing capacity and the displacement control effectiveness of the head-fixed double sheet pile method. Among the various parameters considered, the relative density of the inner soil emerged as a particularly critical factor. This is because the fundamental principle of the method lies in achieving enhanced displacement control through the synergistic behavior and

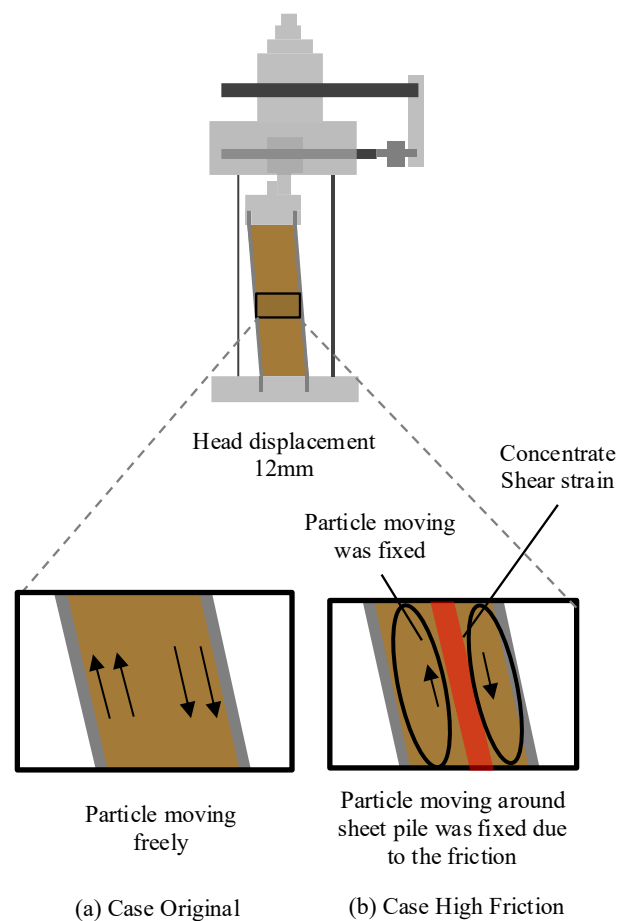


Figure 10. Comparison of behavior with soil and sheet pile with and without sheet pile friction

mechanical integration of the inner soil and the surrounding sheet piles.

Firstly, in Case 2, where the relative density of the inner soil was intentionally set to a low level, the DIC analysis revealed the formation of a distinct shear zone within the specimen. This localized strain concentration is believed to be the result of particle rearrangement and internal movement triggered by the applied horizontal loading. In such low-density conditions, the inner soil responded independently to the loading, exhibiting significant internal deformation. Consequently, the intended structural integration between the inner soil and the sheet pile was not realized, and the overall horizontal bearing capacity of the system was compromised.

In contrast, Case 3 involved an increase in the relative density of the inner soil. The experimental results in this case showed a more uniform distribution of shear strain, primarily toward the left side of the specimen, without any notable formation of local shear zones. Despite the application of forced displacement, no concentrated strain localization was observed. This indicates that the inner soil and the sheet piles functioned more cohesively, behaving as a single integrated structural unit. As a result, the system demonstrated a significantly higher horizontal bearing capacity, thereby validating the importance of inner soil densification in enhancing structural performance.

Lastly, in Case 4, the focus was placed on increasing the frictional resistance between the inner soil and the sheet pile surface. Under this condition, the shear strain was found to be concentrated in the central region of the specimen. This behavior is attributed to the restriction of particle movement near the sheet pile surface, which prevented strain dissipation

in the peripheral areas. Figure 10 shows the conceptual diagram interaction between soil and the sheet pile that can be discussed in this experiment. Consequently, the strain induced by the forced displacement accumulated in the central zone, where the influence of sheet pile–soil friction was minimal. A comparable phenomenon was also observed in the model experiments described in Sugimoto et al 2023. Notably, in cases where the interface friction was enhanced, low-density zones were not detected around the sheet pile but were instead located within the inner soil itself. The present study successfully quantified this behavior through CT-based strain analysis, offering a more rigorous understanding of the internal failure mechanisms.

These findings collectively suggest that while increasing the interface friction contributes to an overall improvement in structural strength, it also leads to a shift in the failure mode under large deformation conditions, with failure becoming concentrated within the inner soil rather than at the soil–sheet pile interface. This insight provides valuable guidance for the rational design and optimization of sheet pile systems in engineering practice.

4 CONCLUSION

In this study, we focused on the behavior of the inner soil sandwiched between two sheet piles to understand in detail the behavior of the inner soil in the head-fixed double sheet pile method. Horizontal loading experiments were conducted by placing the specimen between two sheet piles under confining pressure, complemented by X-ray CT imaging and subsequent image analysis by DIC. The following are the findings of this study:

- 1) The horizontal bearing capacity of the sheet pile structure was found to be influenced by variations in the relative density of the inner soil and the friction between the soil and sheet pile. An increase in both the relative density of the soil and the friction coefficient between the sheet pile and the soil enhanced the horizontal loading bearing capacity.
- 2) The development of shear strain in the inner soil varied with relative density. Higher relative density resulted in the spread of shear strain over a larger area under horizontal loading, indicating a more integrated interaction between the sheet pile and the soil.
- 3) When the friction between the sheet pile and inner soil was increased, the movement of soil particles around the sheet pile was constrained. As a result, shear strain became concentrated in the center of the specimen, where the movement was less restrained. This suggests that higher friction leads to the concentration of shear strain in the middle of the inner soil.

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