Model tests on the effects of head fixation and separation distances for double sheet pile earth retaining wall method

A. Kikuchi
Graduate School of Science and Engineering, Chuo University, Tokyo, Japan
H. Nishioka
Department of Civil and Environmental Engineering, Chuo University, Tokyo, Japan
Y. Kato
Department of Civil and Environmental Engineering, Chuo University, Tokyo, Japan (Former)
A. Nasu
Tokyo Civil Engineering Branch, Kajima Corporation, Tokyo, Japan
M. Okamoto
Technical Research Institute, Kajima Corporation, Tokyo, Japan
H. Nagatani
Technical Research Institute, Kajima Corporation, Tokyo, Japan

ABSTRACT

In deep excavation works, struts or soil nailing are often employed to support temporary earth retaining walls and prevent collapse due to earth pressure. However, these supports can impede the excavation or construction of structures and necessitate a substantial background space. Therefore, a head-fixed double sheet pile earth retaining wall method has been developed as a temporary, self-supporting earth retaining wall. In this method, the horizontal displacement of fixed-head double sheet piles can be adequately minimized without the use of struts or soil nailing. This proves advantageous for construction projects in urban areas with limited space. Nevertheless, the actual collapse behaviour of this method, particularly the distinctions in collapse behaviour depending on the fixation conditions and separation distances, remains unclear. In this study, we conducted model tests focusing on the effects of head fixation and separation distances, using a 1/20-scale aluminium rod model ground to simulate the excavation process. We explored the relationship between excavation depth and horizontal displacement. Head fixation significantly influenced the front retaining wall, resulting in a notable reduction in horizontal displacement. This finding underscores the effectiveness of fixed-head double-steel sheet piles in such scenarios.

Key words: *self-supporting earth retaining walls, aluminium rods, steel earth retaining, excavation works, image analysis*

1. Research background and objectives

Earth retaining works, employing soldier piles and laggings or steel sheet piles, are often adopted for underground construction. However, horizontal displacement arises due to earth pressure, which is influenced by the surrounding ground. Earth retaining supports, such as struts with postpiles and soil nailing, are mainly used to reduce horizontal displacement. However, struts can obstruct the use of large machinery, whereas soil nailing requires a large background space for penetration lengths and special equipment for installation, leading to increased costs.

To address these issues, the head-fixed double sheet pile earth retaining wall method has been developed as a self-supporting temporary earth retaining system (Nasu et al., 2021). In this method, a pair of steel sheet piles is embedded in parallel, and their heads are rigidly fixed by concrete or welded braces. This method is believed to

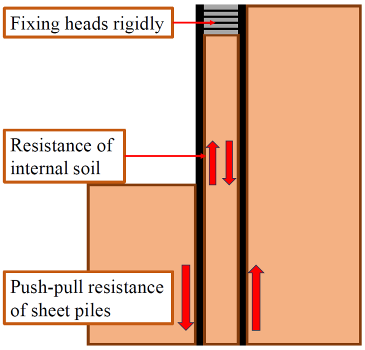


Figure 1. Image of the method

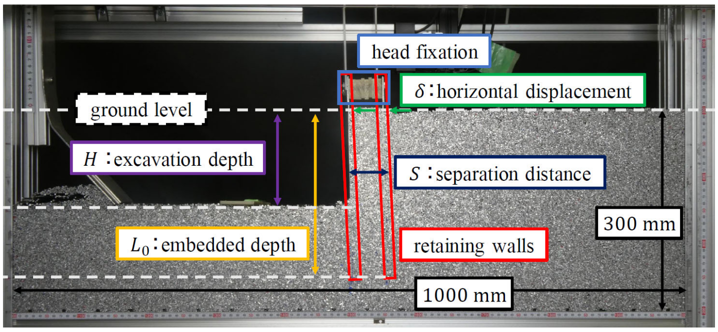


Figure 2. System configuration of the model test

sufficiently reduce horizontal displacements of earth retaining works during excavation because of push-pull resistance of the two sheet piles, and the resisting effects of the internal soil between the two sheet piles (**Figure 1.**). This system has been applied in some construction works to improve the economic efficiency and construction productivity by reducing the number of temporal struts. However, the effects of head fixation conditions or the separation distances between the two sheet piles on the stability of this method are not well understood.

The objective of this study is to examine the effects of head fixation and separation distances on the reduction of horizontal displacement of double earth retaining works with two-dimensional model tests using an aluminium rod model ground.

2. Model tests overview

2.1. Two-dimensional test on model ground of aluminium rods

To simulate excavation work in two dimensions, aluminium rods were employed in this study. Two-dimensional model experiments employing aluminium rods have several advantages: the rods themselves are self-supporting, allowing for the straightforward observation of displacement and its behaviour in the model ground through the movement of the aluminium rods; the strength and displacement properties closely resemble those of medium-dense sandy soil; and the grain size characteristics remain constant, ensuring high repeatability in experiments. Aluminium rods have been previously employed in two-dimensional model experiments to simulate earth retaining works with sheet piles (Matsumoto and Nishioka, 2021).

2.2. Model ground preparation

In this study, the model ground was prepared by blending aluminium rods of 150 mm length and diameters of 3.0 mm, 2.0 mm, and 1.5 mm in a weight ratio of 1:1:1. The blending took place in a rigid soil tank measuring 300 mm in height, 1000 mm in width, and 150 mm in depth (**Figure 2.**). The unit volume weight of the model ground was set at 21.5 kN/m^3. We used thin aluminium plates as model sheet piles (Young's modulus E=73 kN/mm^2) with a height of 300 mm and a depth of 200 mm, setting an embedded depth at 250 mm. The front model sheet piles for the single and double earth retaining works were placed at the centre of the model ground after the preparation of foundation ground reached a thickness of 100 mm. To simulate double earth retaining wall, the rear model sheet piles were manually embedded until they reached a depth of 250 mm at prescribed head separation distances, after piling up the model ground to 300 mm. To fix both heads of the sheet piles, acrylic resin blocks with two holes were placed between the two model sheet piles and bolted to simulate a rigid bond (**Figure 3.**). To prevent the rotational behaviours of the model sheet piles around the bolted fixing points during excavation, aluminium plates with a thickness of 1.0 mm were placed on both sides of the model sheet piles to disperse the stress applied by the bolts. Two holes were drilled in the heads of all aluminium sheets used in the model tests to allow the bolts for head fixation to pass through.

Table 1. Test cases

	Case	Thickness of model sheet pile	Separation distance	Head fixation	Embedded depth
Double earth retaining	CaseF50	1.0 mm	50 mm	Fixed	250 mm
	CaseU50			Not fixed	
	CaseF25		25 mm	Fixed	
	CaseU25			Not fixed	
Single earth retaining	CaseS		—	—	
	CaseS'	1.5 mm			

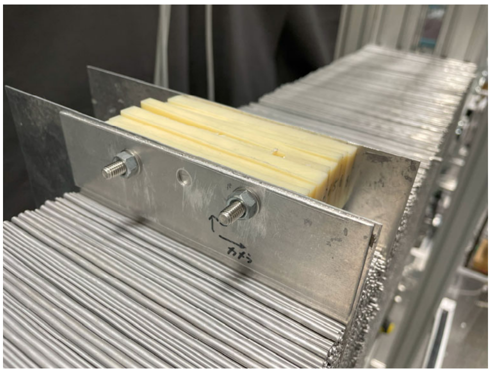


Figure 3. Enlarged image of head fixation

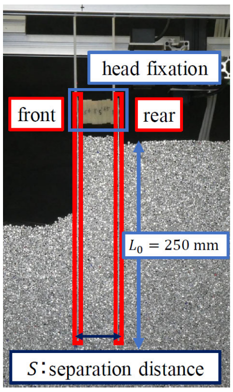


Figure 4. Enlarged image of model sheet piles

2.3. Model test procedures

The excavation process of the model ground was simulated by utilizing an aluminium-made excavation blade to scrape away from a front model sheet pile. Additionally, aluminium rods that had accumulated at the edge of the soil tank were manually removed. We excavated 5.0 mm at each excavation phase and measured the excavation depth from the pre-excavation ground surface, as well as the horizontal displacements of the model sheet piles (displacement at the pre-excavation ground surface height position) using laser displacement meters. Furthermore, photographs were captured during each excavation phase for image analysis. The excavation continued until the displacement exceeded 130 mm which is the measurement limit of the laser displacement meters.

2.4. Model test cases

In this study, we conducted four cases of double earth retaining wall model tests, both with and without head fixation, and varied the separation distances between the front and rear model sheet piles. Additionally, two cases of single earth retaining wall model tests were performed, featuring model sheet piles with thicknesses of 1.0 mm and 1.5 mm, as outlined in **Table 1**.

To account for real structure parameters, we assumed that βL_0, the product of the characteristic value β (expressing the relationship between the coefficient of earth pressure and the stiffness of sheet piles) and the embedded depth, was equivalent between the actual structures and the models, following the approach in Nishioka et al. (2022). The reciprocal $1/\beta$ of the characteristic values β for actual U-shaped steel sheet piles Type III and Type $\mathrm{VI_L}$, the latter having almost double the weight of steel compared to Type III, are 1.54 m and 2.31 m, respectively. The values of βL_0 for an intended embedded depth of 5 m, considering a model size ratio of 1/20, are 3.25 for Type III and 2.16 for Type $\mathrm{VI_L}$. In the single earth retaining wall model tests, the values of βL_0 for 1.0 mm and 1.5 mm aluminium sheets were 3.22 and 2.34, respectively, indicating approximately similar values. Therefore, CaseS and CaseS' in this study can be interpreted as corresponding to 1/20-scale models of U-shaped steel sheet piles Type III and Type $\mathrm{VI_L}$. However, it must be noted that this similarity rule does not account for the perspective on the failure of the model ground. Therefore, test results at the stage when the model ground is close to failure cannot be converted to actual values; they should be evaluated relative to each case.

3. Test results and discussion

3.1. Relationships between excavation depth and horizontal displacements

The relationships between the excavation depth and horizontal displacements of the front and rear model sheet piles are shown in **Figure 5** and **Figure 6** respectively, with enlarged views of the horizontal displacements of up to 20 mm, as shown in **Figure 7** and **Figure 8**. In addition, the horizontal displacement ratios normalised by the excavation depth for the horizontal displacements of the model sheet piles at excavation depths of 60 mm and 120 mm are summarised for each case in **Figure 9** and **Figure 10** respectively.

Compared to the single earth retaining walls, the horizontal displacements on the front and rear sheet piles were reduced in the double earth retaining walls, regardless of whether the heads were fixed, confirming the displacement reduction effect of the push-pull resistance of the front and rear sheet piles. For the front sheet piles, it was found that the horizontal displacements of the front sheet piles without head fixation were unaffected by the differences in the separation distances and were generally equal. On the other hand, at larger separation distances, the horizontal displacements of the front sheet piles with head fixation were reduced. For the rear sheet piles, it was observed that, at identical separation distances, the impact of head fixation on the horizontal displacements of the rear model sheet piles was limited. Additionally, it was found that the greater the separation distances between the front and rear sheet

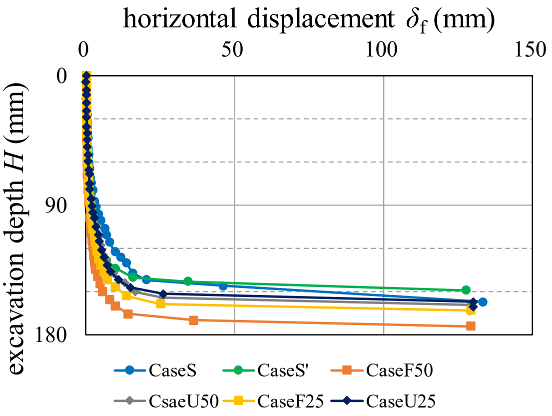


Figure 5. Horizontal displacements of front sheet piles

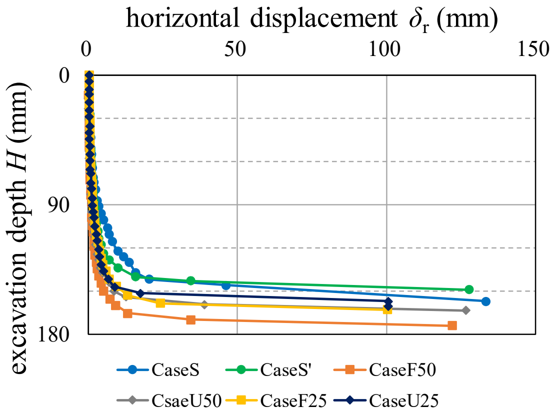


Figure 6. Horizontal displacements of rear sheet pile

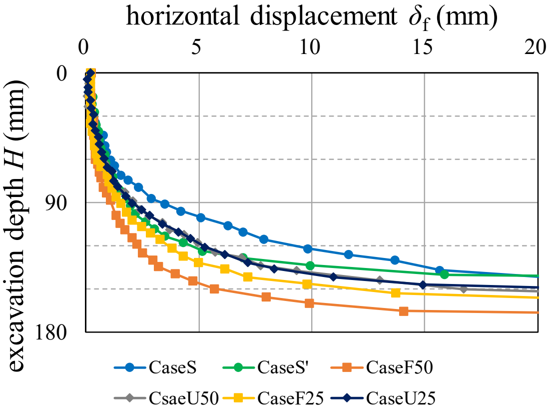


Figure 7. Horizontal displacements (enlarged to 20 mm) of front sheet piles

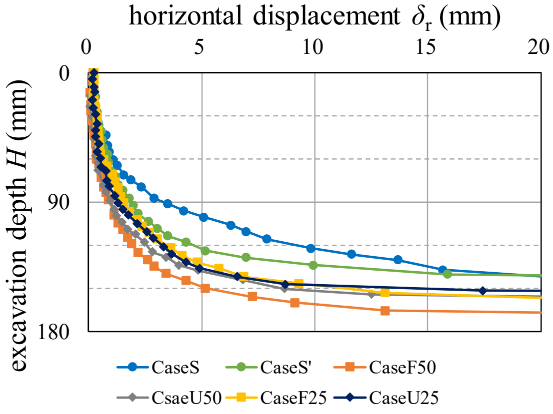


Figure 8. Horizontal displacements (enlarged to 20 mm) of rear sheet piles

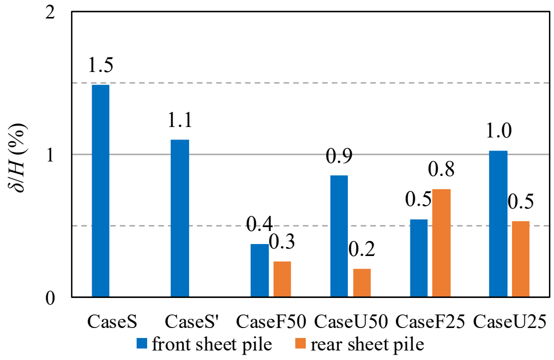


Figure 9. Displacement ratios at 60 mm excavation

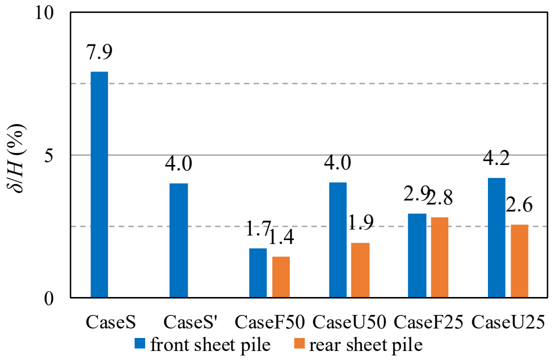
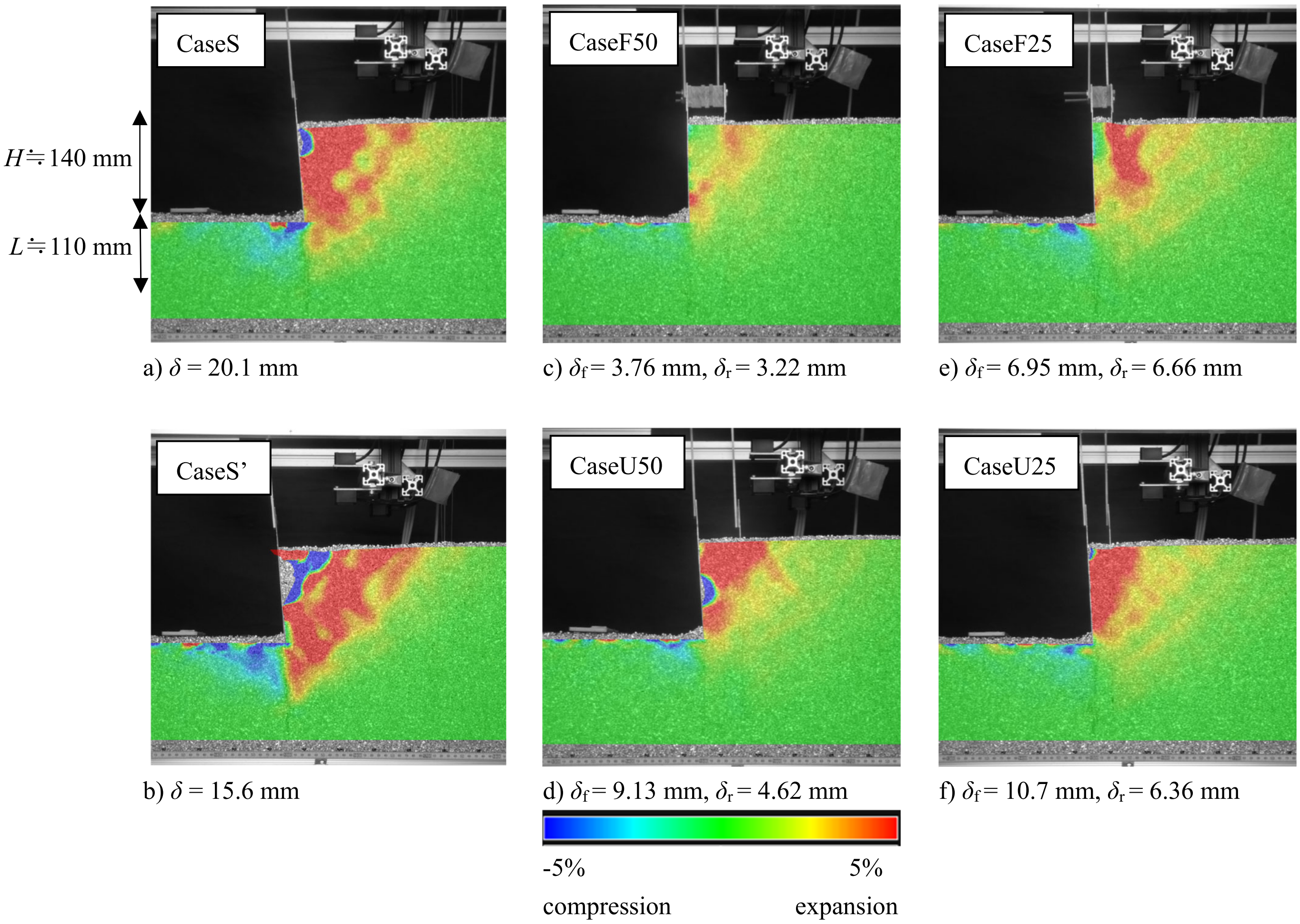


Figure 10. Displacement ratios at 120 mm excavation



a) $\delta = 20.1$ mm

c) $\delta_f = 3.76$ mm, $\delta_r = 3.22$ mm

e) $\delta_f = 6.95$ mm, $\delta_r = 6.66$ mm

b) $\delta = 15.6$ mm

d) $\delta_f = 9.13$ mm, $\delta_r = 4.62$ mm

f) $\delta_f = 10.7$ mm, $\delta_r = 6.36$ mm

Figure 11. Normal strains in horizontal direction by image analysis

piles, the more the horizontal displacements of the rear model sheet piles were reduced. These findings suggest that the difference in separation distances has a greater effect on the reduction in the displacement of the rear sheet piles than the head fixation.

Compared with CaseS’ and double earth retaining walls without head fixation, the horizontal displacements of the front sheet piles that occurred in each case were almost equal to those in CaseS’. However, the horizontal displacements of the front and rear sheet piles occurred in each case, with head fixation being more reduced than that in CaseS’. We believe that the head-fixed double sheet pile earth retaining wall method has a greater effect on reducing the displacement than a single sheet pile

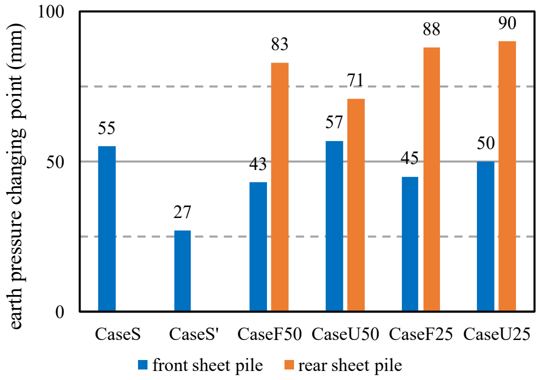


Figure 12. Distances from the bottom of each sheet pile to earth pressure changing points

earth retaining wall with a double steel weight.

3.2. Image Analysis

We investigated distributions of the normal strains in the horizontal direction by performing photographic image analysis using DippStrain, which was developed by Ditect. **Figure 11** shows the image analysis results for each case when the excavation depth is approximately 140 mm, just before the collapse of CaseS. The red areas indicate the expansion of the model ground, whereas the blue areas indicate compression. Due to smaller horizontal displacements, ground deformation at the back of the earth retaining walls was reduced in the cases of double earth retaining walls compared to the cases of single earth retaining walls. Additionally, with head fixation, deformations of the internal soil between the two sheet piles were smaller than those without head fixation. This reduction may be attributed to the increased stiffness caused by head fixation, influencing the formation process of the slip surface behind the earth retaining walls.

To better understanding the differences highlighted in **Figure 11**, we conducted another image analysis using DippMotion-V developed by Ditect. We investigated the impact of varying the distances from the bottom edge of the model sheet piles to earth pressure changing points, where displacements of the model sheet piles become zero. We did this by performing photographic image analysis, which is useful when studying displacement. The result of the image analysis is shown in **Figure 12**. It is known that the position of the earth pressure change point decreases, resulting in a collapse behaviour with brittle rotation, as the stiffness of a sheet pile increases in a single sheet pile retaining wall. Image analysis confirmed that the earth pressure change point became lower in CaseS' than in CaseS due to the increased stiffness of the model sheet piles. In the cases of double earth retaining walls, it was observed that the earth pressure change points for each model sheet pile were higher than that of CaseS'. This finding suggests that this method can be expected to reduce displacements while each sheet pile behaves independently in the ground.

4. Conclusions

The following conclusions were drawn from two-dimensional model tests to examine the effects of head fixation and separation distances on the head-fixed double sheet pile earth retaining wall method.

1) Double earth retaining walls have the effect of reducing the displacements of the rear sheet piles, regardless of whether heads are fixed.
2) Head fixation significantly reduces the horizontal displacements of the front sheet piles, while the separation distances affect the rear sheet piles.
3) The head-fixed double earth retaining wall method results in greater reduction in horizontal displacements compared to traditional single sheet pile earth retaining works with double the steel weight.
4) Head fixation significantly influences the formation process of the slip surface of the ground behind the earth retaining walls.
5) Double earth retaining walls can be expected to reduce displacements, with each sheet pile behaving independently in the ground.

Further investigation will be conducted to explore the effects of displacement reductions with the head-fixed double sheet pile earth retaining wall method by varying the conditions of the internal soil or model sheet piles, as well as by measuring the earth pressures applied on the model sheet piles.

5. Acknowledgements

We would like to thank Editage (www.editage.jp) for English language editing.

References

Nasu, A., Kobayashi, T., Nagatani, H., Ohno, S., Inoue, N., Taira, Y., Sakanashi, T., Kikuchi, Y. 2021. Physical and numerical modeling of self-supporting retaining structure using double sheet pile walls. Proceedings of the Second International Conference on Press-in Engineering 2021, Kochi, Japan, pp. 330-336.

Nishioka, H., Matsumoto, N., Fukuda, F., Ono, K. 2022. Model excavation tests simulating the collapse of high bending rigidity cantilever-type earth retaining walls and proposal of a simple calculating method for the reasonable embedding length. Japanese Geotechnical Journal, vol. 17, No. 3, pp. 401-420 (in Japanese).

Matsumoto, N., Nishioka, H. 2021. A study on the effect an earth retaining wall's rigidity and embedded depth on its behavior. Proceedings of the Second International Conference on Press-in Engineering 2021, Kochi, Japan, pp. 323-329.