The Effect of Underground Short Piles with High Rigidity on Shear Stress and Displacement along Ground Failure Surface

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ABSTRACT

This paper presents an idea of a new method to improve stability of geo-structures against shear failures due to service loads, seismic loads, heavy rainfalls, etc. In this method, a series of short piles, like steel bars or sheet piles, are pressed-in to the depth of the failure surface, which is considered to have the lowest safety factor in the design process. And they are left underground by decoupling from the rod used for press-in process. As the piles are arranged only around the failure surface, the total amount of piles is much smaller resulting in cost-effective improvement of stability of the geo-structures. In this study, the effects of the underground short piles are examined by simple models of underground section along the failure surface, using dry silica sand and rigid steel piles. The models were sheared under a direct shear condition with constant surcharge, and their shear stress and displacement, as well as the rotation of the short piles, were observed.

Key words: Failure surface, Shear resistance, Underground short piles

1. Introduction

This paper presents an idea of a new method to improve stability of geo-structures against shear failures due to service loads, seismic loads, heavy rainfalls, etc. In this method, a series of short piles, like steel bars or sheet piles, are pressed-in to the depth of the failure surface, which is considered to have the lowest safety factor in the design process (**Fig. 1**). Every pile is attached at the bottom end of a rod when it is pressed-in, and then detached from the rod and left underground.

As the piles are arranged along the failure surface only, the total amount of piles is much smaller than that of conventional structures, resulting in cost-effective improvement of stability of the geo-structures. The rod for press-in process can be reused repeatedly. By using self-moving press-in pilers, a limited workspace on top surface of the geo-structure is enough for construction. As the press-in rod is removed in the construction process, the area of the ground surface can be used without any interference with the underground piles.

This method will be also applicable for prevention of slope disasters. Hundreds to thousands of slope disasters occur every year in Japan and in the world. However, it is reported that most of landslides are shallow surface failures due to heavy rainfalls, whose thickness is 1.2 m on average (Osanai *et al*., 2009). Therefore, the simple and low-cost piles by this method will be suitable to provide cost-effective countermeasures.

In this study, the effects of the underground short piles were examined by simple models of underground section along the failure surface. As the first step of study, a dry silica sand and rigid steel piles were used for the models to make the test conditions simple. The models were sheared under a direct shear condition with constant surcharge, and the shear stress, the displacement and the rotation of the short piles, were observed. Interaction between reinforcements and soils along failure surface is often studied in reinforced soil technology, like Wu *et. al*. (2008). However, they usually use flexible reinforcement like geogrid, while rigid piles are used in this study.

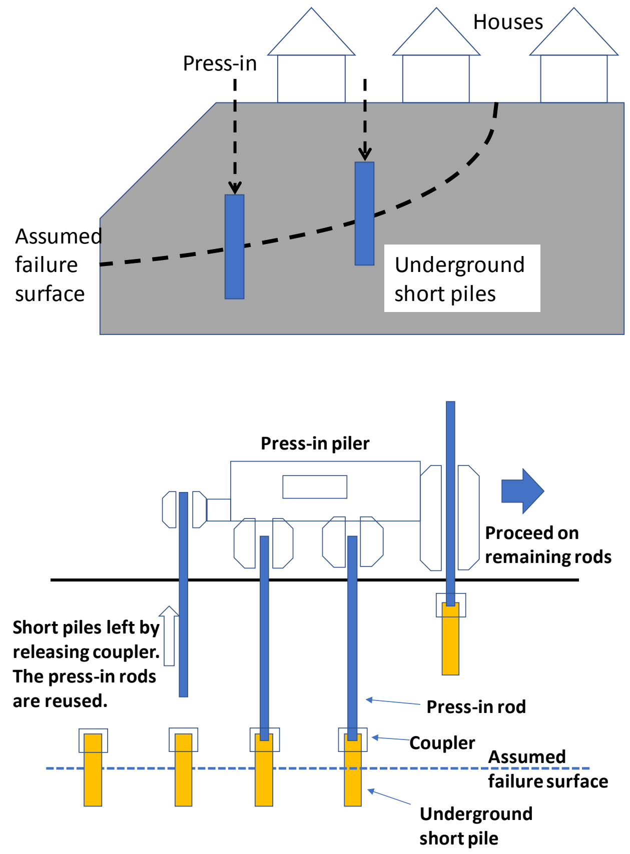


Fig. 1 Concept of underground short piles and their construction procedure

2. Test method

2.1. Model and soil material

Fig. 2 shows the structure of the models, which was sheared in a direct shear condition. The model consisted of a densely compacted (Dr = 85 %) dry Silica Sand No. 7 with specifications shown in Table 1. Its dimensions were 306 mm in the shear direction, 206 mm in width, and 75 mm in height for the upper and lower shear boxes respectively. Constant vertical stress of 15.67 kN/m^2 was applied on the top surface of the model by weight of flat steel plates, while shear load was applied to the upper box by using an air cylinder with the center of load at the height of the shear surface. The shear load was increased in the stress control condition with a constant shear stress rate of 0.84 kN/m^2/min. The relationships between the shear stress and shear displacement were recorded.

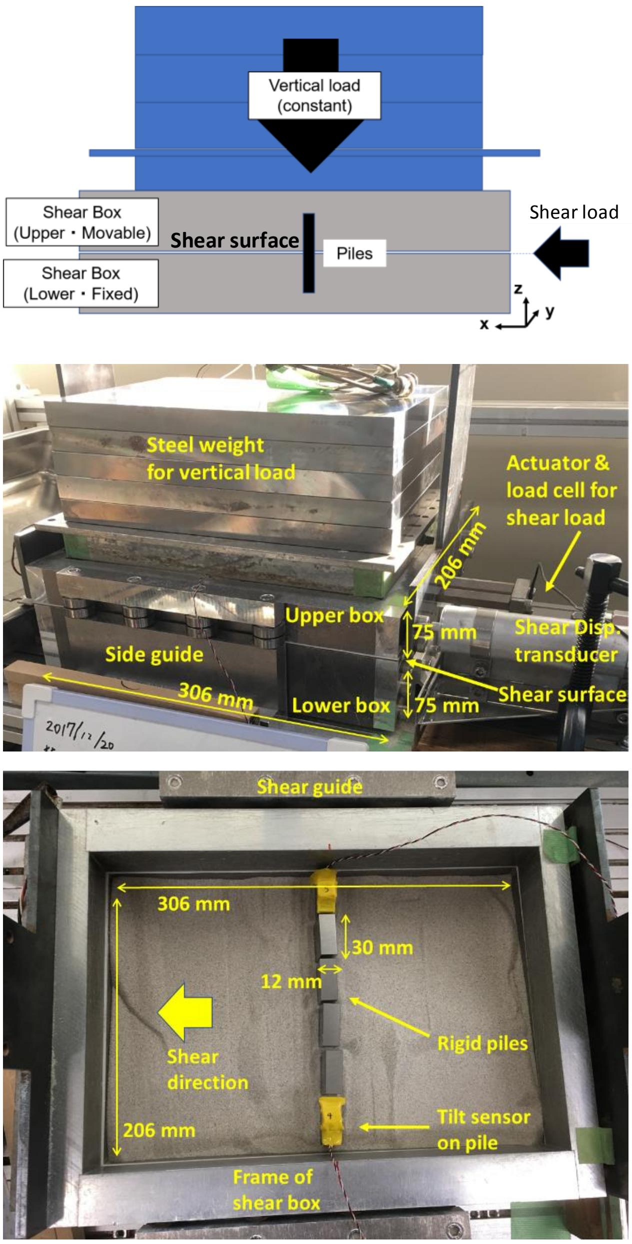


Fig. 2 Model and loading system

Table 1. Specifications of Silica Sand No.7

Dry density	$\rho_d(g/cm^3)$	1.45
Soil particle density	$\rho_s(g/cm^3)$	2.59
Maximum void ratio	e_{max}	0.721
Minimum void ratio	e_{min}	1.152
Particle size	D_{10}(mm)	0.31
	D_{30}(mm)	0.46
	D_{50}(mm)	0.55
	D_{60}(mm)	0.6

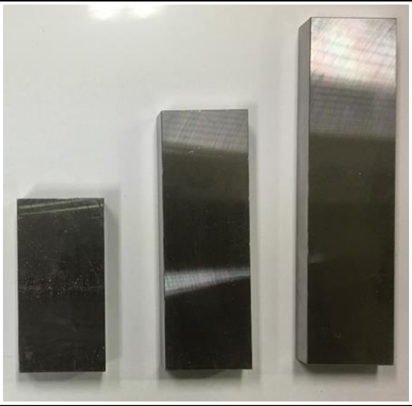
2.2. Rigid piles in the model

Three types of rigid steel plates shown in Table 2 were used to simulate the underground short piles. All of them had a thickness of 12 mm in the shear direction and a width of 30 mm in the orthogonal direction. The lengths of piles in vertical directions varied as 60, 90, and 120 mm. They were arranged along the center line of the model orthogonal to the shear direction as shown in **Fig. 2**.

All of the piles were rigid enough compared to the compacted silica sand, and it could be assumed that the piles would not deform by the shearing. This is to simplify the test conditions, while more flexible sheet piles or steel bars may be used for the piles in practice.

Further, the piles were inserted into the sand after filling the lower shear box with Silica Sand. The direction of the piles was vertical to make the model simple, while it was not consistent with the practical condition. In practice, the pile is vertical while the failure surface is not in the horizontal direction as shown in **Fig. 1**, and the vertical piles are not in the right angle with the failure surface.

Table 2. Steel plates as the underground short piles

Type	B	C	D
Thickness	12 mm		
Width	30 mm		
Length	60 mm	90 mm	120 mm
Image			

3. Test Result

3.1. Effects of pile length

Fig. 3 shows the results from some test cases with various pile lengths. The number of piles was 6 for every case, and the pile was buried so that the center of piles coincided with the height of failure surface.

Fig. 3b compares the peak shear stress for every case. The peak stress with the shortest 60 mm-long piles was similar to that of the case without piles. But, the peak strength increased by 30 % with the longest piles with a length of 120 mm.

Fig. 3b also shows the shear displacement near failure. It is difficult to identify the displacement when the shear stress reached its peak value because the test was conducted under a shear stress control. Therefore, the figure plots the shear displacement observed when the shear stress reached 95 % of its peak value for every case. It is found that the shear displacement near failure increased by the piles. It was increased by around 20 % even in the case with the shortest piles, and by around 80 % with the longest piles.

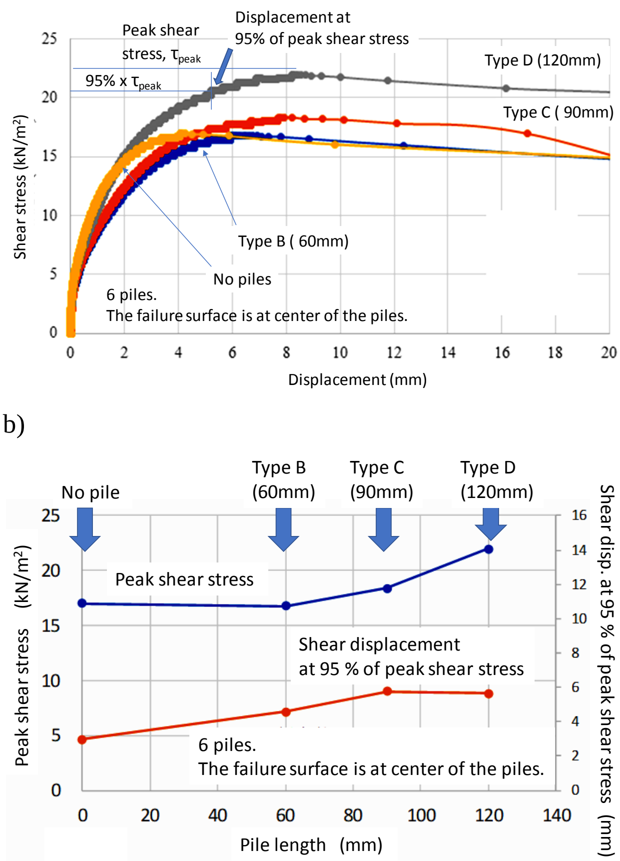


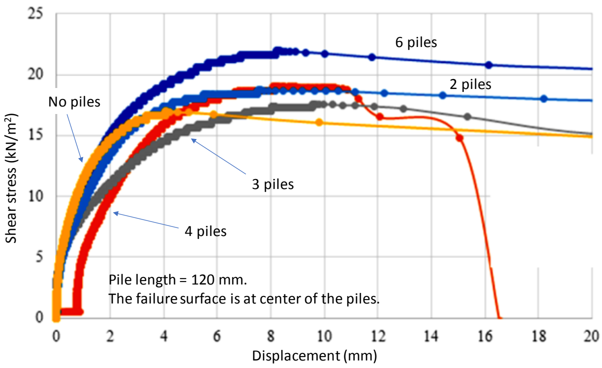
Fig. 3 Shear behavior with various pile length

3.2. Effects of number of piles

Fig. 4 shows the results from some test cases with various numbers of piles. The pile length was 120 mm for every case, and the pile was buried so that the center of piles coincided with the height of failure surface. As the width of every pile was 30 mm and that of sand box was

206 mm, most of the width was covered by the pile in the case with 6 piles, while only 30 % of the width was covered with 2 piles. Again, the peak shear stress and the shear displacement near failure showed larger values with larger number of piles.

a)



b)

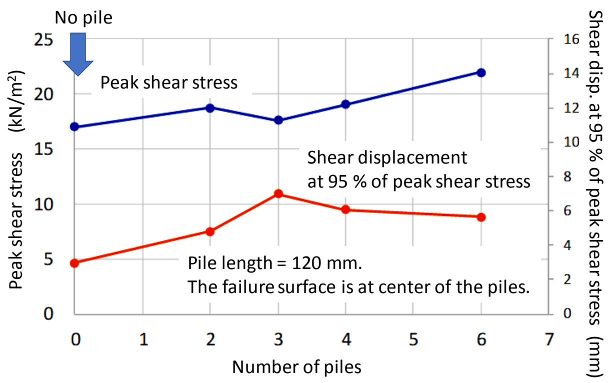
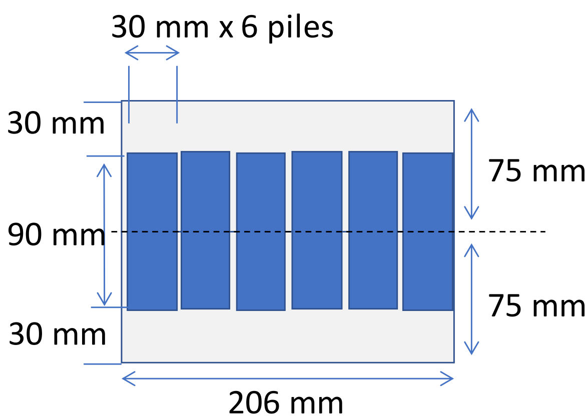


Fig. 4 Shear behavior with various numbers of piles

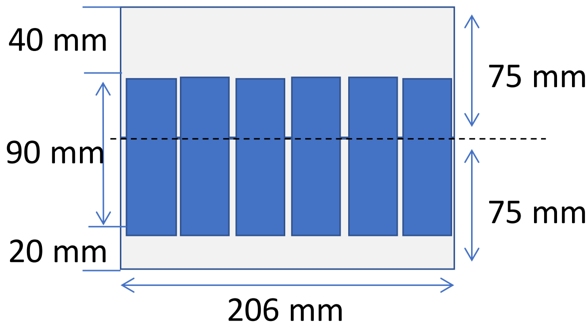
3.3. Effects of vertical position of piles

A series of tests were conducted with various positions of the piles as shown in **Fig. 5**. The pile length was 90 mm, and the number of piles was 6 for every case. In the case with piles at the center position (**Fig. 5a**), the pile was inserted into the sand so that the center of piles coincided with the height of failure surface. As the total height of the sand box is 150 mm, 30 mm-thick sand layers remained over and under the pile respectively. In the cases with piles at lower or upper positions, the piles were at places 10 mm lower or upper than those at the center position respectively (**Fig. 5b&c**). In the case with piles at an alternate position, 3 piles were placed lower and the other 3 piles were placed upper (**Fig. 5d**).

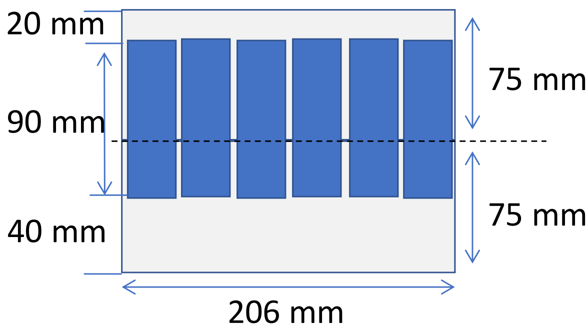
a) Center position



b) Lower position



c) Upper position



d) Alternate position

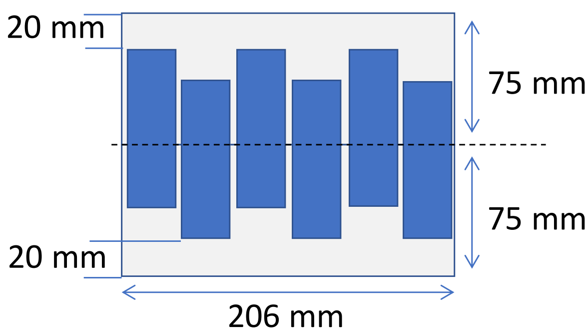
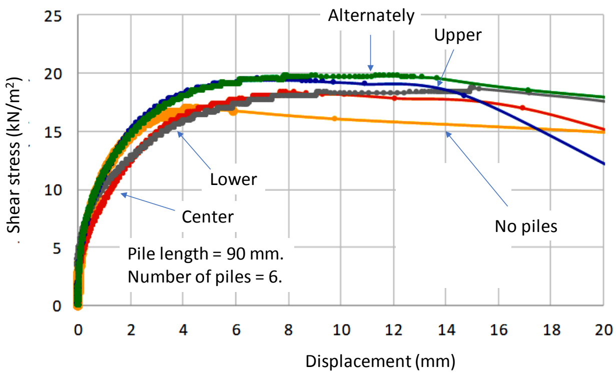


Fig. 5 Various positions of the piles

Fig. 6 shows the results from the test cases with various pile positions. Regardless of the pile positions, the peak shear stress and the shear displacement near the failure showed larger values than those without piles in every case. In addition, there are some differences in the effects of piles according to the pile positions. It seems that the peak shear stress slightly increased when the piles are placed lower or upper, but its mechanism is not clearly understood.

a)



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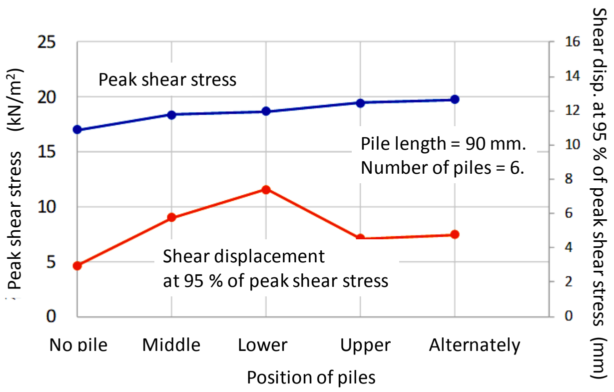


Fig. 6 Result of the pile position comparison

4. Rotation of the piles in the model

In each model test, the rotation of every pile was measured with a small MEMS (Micro Electro Mechanical Systems) tile sensor (SCA100T-D01, Murata) attached on top of the pile (**Fig. 7**). The bending deformation of the model piles is negligible as they are made of thick steel bars and rigid enough compared to the dry sand ground.

Fig. 8 shows typical results with 6 piles with length of 60, 90, and 120 mm at the center position. The tilt sensors were attached to 4 piles among 6 piles, and all of them showed similar trend for every tests. The piles rotated according to the shearing direction, and the rotation angle were nearly proportional to the displacement before the failure occurred. Its ratio was around 0.01 rad per 5 mm of displacement with pile length of 120 mm, 0.013 rad per 5 mm of displacement with a pile length of 90 mm, and 0.015 rad per 5 mm of displacement with a pile length of 60 mm, respectively.

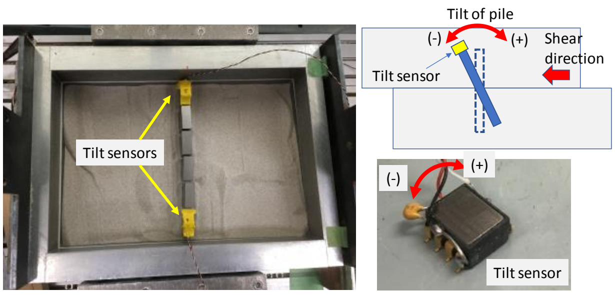
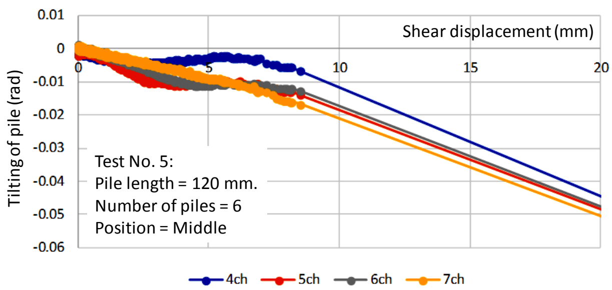


Fig. 7 Tilt sensors on top of piles

a)



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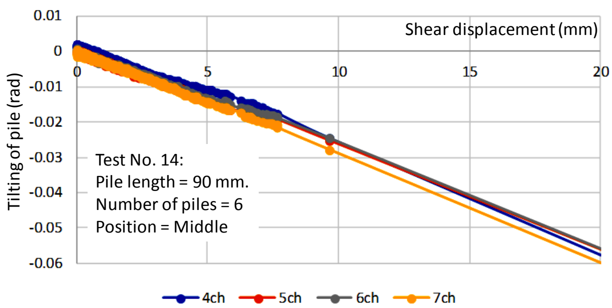

c)

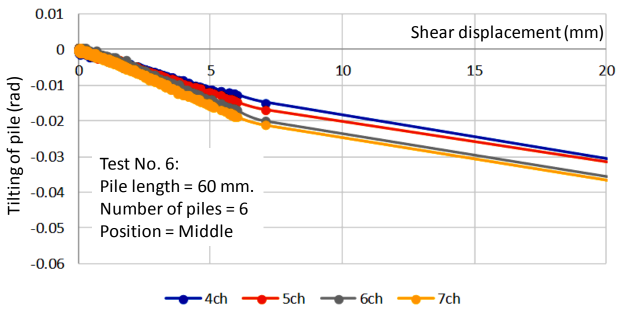

Fig. 8 Tilt angle of piles with length of a) 120 mm, b) 90 mm, and c) 60 mm. (Six piles at center position)

For the case with the 6 piles with a length of 120 mm, most of the cross-section area of the model orthogonal to the shear direction is covered by the piles as shown in **Fig. 9a**. Therefore, it is expected that the pile moved nearly together with the sand. **Fig. 9b** illustrates the shear displacement of the sand and rotation of the piles schematically.

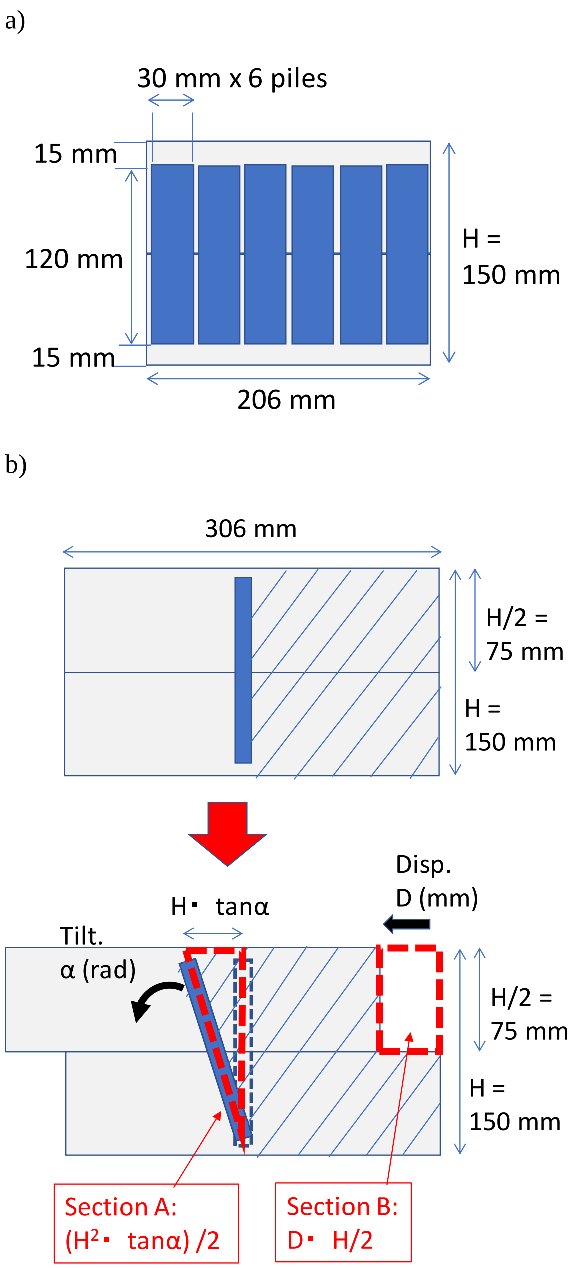

Fig. 9 Consistency of tilt angle of piles with a length of 120 mm, a) cross-section area of the model orthogonal to the shear direction; and b) illustration shear displacement of the sand and rotation of the piles before and after shearing

If the volume change, or dilatancy, of the sand is small enough, the shaded area of the sand in the right side of the piles should be nearly the same before and after shearing. Accordingly, the triangular area (Section A) and the rectangular area (Section B) shown by broken lines in **Fig. 9b** should be similar to each other. As the half height of the sand is $H/2 = 75$ mm, the rectangular area is $D \cdot H/2 = 75 \times 5/2 = 187.5$ mm^2 when the shear displacement $D = 5$mm. Meanwhile, the triangular area is $(H^2 \cdot \tan\alpha)/2 \fallingdotseq (150 \times 150 \times 0.01)/2 = 112.5$ mm^2 when the rotation of the piles is $\alpha = 0.01$ rad, as seen in **Fig. 8a**. Thus, the observed rotation of the piles was roughly consistent with the shear displacement of the sand, although it was somewhat smaller relative to the displacement. One of possible reasons for this difference is that the top surface of the sand was surcharged with a constant load by the steel weight, and vertical displacement of the top boundary may have occurred. **Fig. 8** shows the rotation of piles will be relatively larger in the cases with shorter piles. The interaction between the pile rotation and the shear deformation may be hard to understand, because soil can move over or under the piles, or through the gap between the piles, much more easily than the case with 6 piles with a length of 120 mm.

5. Conclusion

The effects of the underground short piles embedded along the failure surface were examined by simple shear models. The longer and larger number of piles resulted in higher peak shear resistance as well as larger deformation at the peak. It will improve the safety factor and ductility of geo-structures. The pile rotated corresponding to the shear displacement along the failure surface. Further study is needed for its mechanisms.

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