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Visualization of failure pattern of reinforced soil with face bolts on direct shear tests

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ABSTRACT: The objective of this paper is to investigate precise soil-structure interaction behavior on the problem of face bolting method for tunneling using X-ray CT with direct shear test on reinforced sand. First of all, a direct shear apparatus of soil-bolts interaction under X-ray CT is newly developed. After conducting a series of shear test with and without bolts, the precise interaction behavior and failure pattern of reinforced soil are discussed in three dimensions. Here, not only visualization of the behavior but also its quantitative discussion is conducted. Finally, it is confirmed that the proposed test apparatus is useful for clarifying the behavior of soil-structure interaction.

1 INTRODUCTION

In recent years, mountain tunneling method such as NATM (New Austrian Tunneling Method) has been used for tunnel construction even in the urban area. In Japan where land area is small, it is required that tunnel is constructed into unconsolidated ground or low overburden ground. When excavating a tunnel, tunnel face becomes very unstable due to stress release caused by excavation. It is a main issue to maintain the stability in tunnel face during construction. To create the condition for safe construction, it is necessary that tunnel face is reinforced by auxiliary method. Kasama and Mashimo (2003) clarified the effect of typical auxiliary methods such as face bolting, forepoling and vertical pre-reinforcement bolting on the face stability using centrifugal model and distinct element method. It has been concluded from their studies that the length and arrangement of bolts are important factors for stabilization of tunnel face. These results were discussed with the observation of failure mechanism using experimental models of two or quasi-three-dimensional planes. However, failure zone due to tunneling is a behavior in three dimensions and the mechanism of face failure in three dimensions has not been well known yet.

In order to evaluate the mechanism of tunnel face failure, authors developed a system of tunnel pull-out model test system that could be carried out in the system of X-ray CT scanner (Otani et al, 2005) and using this system, failure pattern due to tunneling without reinforcement and with face bolting method were visualized using X-ray CT and as shown in Figure 1, it is observed that face bolting method prevents development of failure zone due to tunneling (Takano et al, 2006).

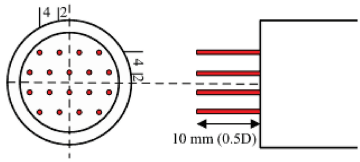
The objective of this study is to investigate precise soil-structure interaction behavior on the problem of face bolts for tunneling using X-ray CT with direct shear test on reinforced sand. Here, a new direct shear test apparatus is developed with the use of X-ray CT scanner and a series of shear test with and without bolts are examined. The specimen is then investigated using X-ray computed tomography (CT) to visualize shear zone in three dimensions. And the influence of reinforcement orientation is visually investigated in three dimensions. Finally, it is concluded that the interaction behavior between soil and bolts can be investigated both qualitatively and quantitatively in three dimensions by the proposed test apparatus.

2 OUTLINE OF TEST

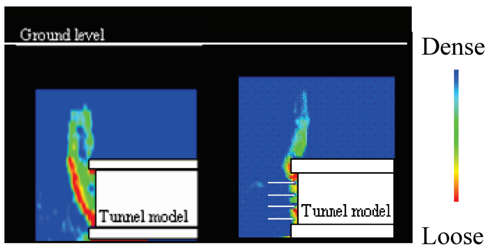
2.1 *Test apparatus*

In this study, a new direct shear apparatus is developed for the use with system of industrial X-ray CT scanner for the purpose of observation on the close interaction behavior in three dimensions. The arrangement of this apparatus is shown in Photo. 1 and its features are described in details with Figure 2. The specifications of this apparatus are summarized as follows:

1) All the operations for this apparatus are conducted remotely using a personal computer from outside the shield room in X-ray CT and the whole loading process was recorded electronically.



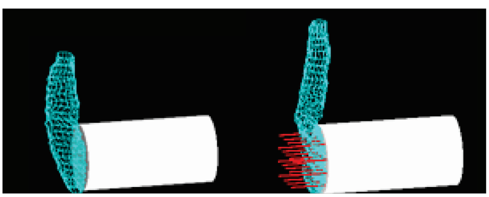
(a) Arrangement of face bolts



2) Without reinforcements

3) With face bolting method

(b) Vertical cross sectional image



(c) Three-dimensional wire frame image of failure zone

Figure 1. Failure pattern due to tunneling without reinforcement and with face bolting method.

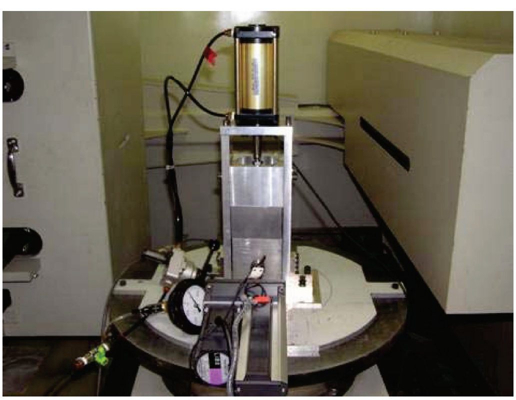


Photo 1. General picture of the sirect shear apparatus.

2) In order to scan the specimen horizontally during direct shear test, there should be no obstacles (e.g., steel bars) around the compression cell because such materials would interfere with X-ray CT imaging.
3) Loading is stopped during scanning operation, which takes about 2.5 min. for one cross sectional image.

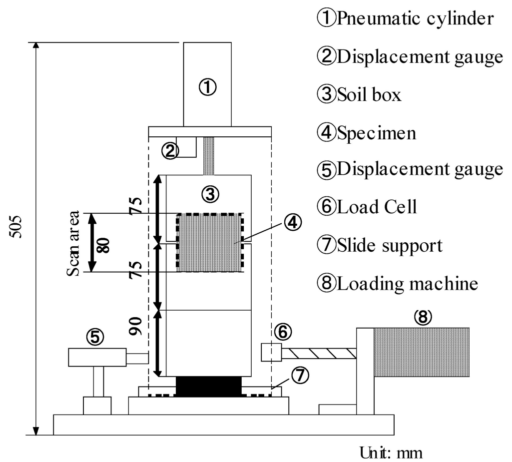


Figure 2. Schematic of the direct shear apparatus.

Table 1. Property of Toyoura sand.

Maximum dry density	1.66 t/m^3
Minimum dry density	1.34 t/m^3
Mean grain size	0.2 mm
Rerative density	85%

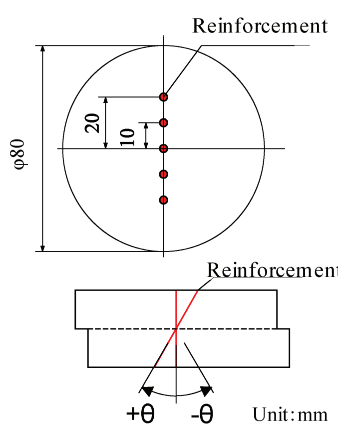


Figure 3. Arrangement of reinforcement.

2.2 *Test condition*

The size of the specimen was 80 mm in diameter and 30 mm in height. The space between upper and lower box was 0.2 mm. In this study, air-dried Toyoura sand was used and a shearing speed of 1.0 mm/sec was applied. Dense specimens with a relative density of Dr = 85% were prepared under vertical pressure of $\sigma = 100$ kPa (constant). Four different specimens (without reinforcement and reinforced by bolts) were examined. Figure 3 shows the arrangement of bolts in the specimen and Table 2 shows orientation of reinforcement. In reinforced specimens, three different reinforcement orientation θ was examined. Face bolts 2 mm diameter and 30 mm long were used as reinforcement. Its surface was made practically rough.

All the specimens were scanned at four different shear displacements which were 1 mm, 2 mm, 5 mm and 8 mm and three dimensional images were reconstructed.

3 TEST RESULT

Figure 4 shows relationship between shear displacement and shear stress. An effect of reinforcement on strength is noticeable. Peak strength and shear displacement at peak increace in order of Case 3, Case 2, and Case 4. The influence of reinforcement orientation θ was analyzed by Jewell (1897), and it was concluded that the reinforcement orientation parallel to the principal tensile strain would give rise to the maximum rate of strength increase. The comparable result is obtained from this test. On the other hand, vertical displacement is the longest in Case 1.

Table 2. Orientation of reinforcement.

	Case 1	Case 2	Case 3	Case 4
Orientation of reinforcement	Without reinforcement	0°	30°	−30°

Vertical cross sectional image of all test cases at four different shear displacements which are 1mm (before peak), 2 mm (peak), 5 mm (after peak) and 8 mm (the end of shear test) are shown in Figure 5. CT image is constructed by the degree of x-ray absorption in the materials. CT images are presented with shaded grey or black color for low density and light gray or white color for high density. Total number of levels on these colors is 256. It is noted that more precise contents about X-ray CT scanner can be obtained by the reference of Otani et al. (2000). It is realized that the low density area can be observed around edge of shear box on images of 1 mm displacement. This area can be considered to be an area of strain localization or shear band after CT scanning. The shear bands develop to center of specimen at 2 mm displacement. At 5 mm of shear displacement, shear strength reach to residual strength and the shear band extends to the whole of the test piece. Finally, at 8 mm of shear displacement, though shear band extends in a perpendicular direction in Case 1 (without reinforcement), it is not remarkable for other cases. It is realized that newly developed shear band can be observed after shear strength reaches to the residual strength and progressive failure occurs in direct shear. When paying attention to area placed between two shear bands in Case 1, density decrease cannot be observed. From this result, it is realized that volumetric strain does not occur in this area. Table 3 shows the amount of maximum vertical displacement and thickness of shear bands. In each test case, maximum volumetric strain and thickness of shear bands is almost the same among all the cases. It is also seen that volumetric strain occurs only in shear band.

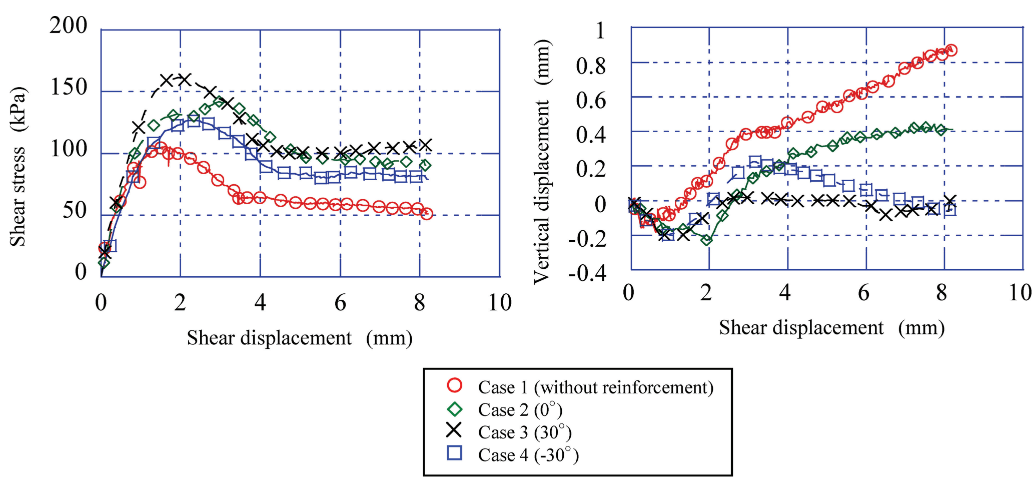


Figure 4. Relationship between shear displacement and shear stress.

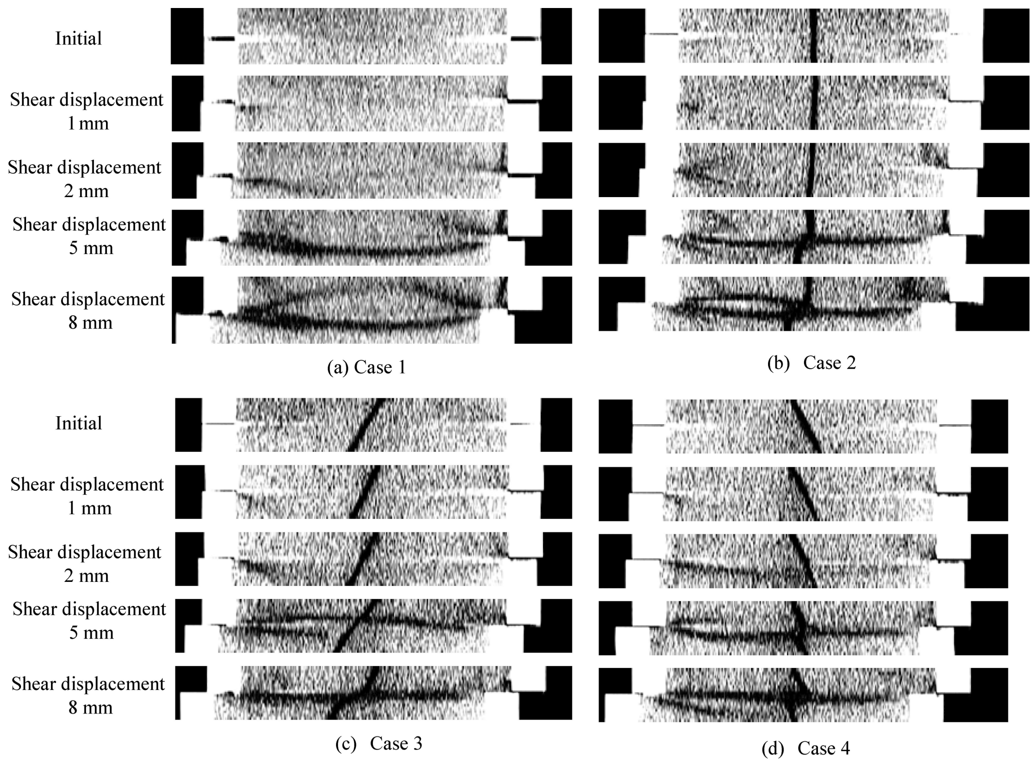


Figure 5. Vertical cross sectional images.

Table 3. Amount of maximum vertical displacement and thickness of shear band.

	Maximum vertical displacement (mm)	Thickness of shear band (mm)
Case 1	0.888	1.24
Case 2	0.441	0.7
Case 3	0.023	0.43
Case 4	0.226	0.39

4 CONCLUSIONS

A new direct shear test apparatus was developed for the use in the system of industrial X-ray CT scanner. Using this apparatus, a series of direct shear tests and CT scanning were conducted. Following conclusions are drawn from this study;

1) The shear band due to direct shearing can be visualized in three dimensions using X-ray CT scanner.
2) The peak shear stress and the shear displacement to reach the peak stress increased for the case of reinforced sand.
3) The progressive failure can be observed from CT image.
4) The maximum volumetric strain and thickness of shear zone is almost the same amount among all the cases.

A newly developed direct shear test apparatus made it possible to evaluate interaction behavior between soil and bolts using an industrial X-ray CT scanner. More quantitative discussion should be required using this apparatus and this should be done in the future study.

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