# Reinforcing effect of face bolts for tunneling -Application of X-ray CT and centrifuge model test-

## Effet de renforcement par boulonnage du front de taille d'un tunnel -Application par tomographie rayons X et essai sur modèle en centrifugeuse-

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ABSTRACT

The purpose of this paper is firstly to simulate the tunnel face failure in laboratory with four cases of model tests by pulling out tunnel model from a sandy ground that are without using auxiliary method nor face bolting and using face bolting with three different lengths of bolts, and secondary, to investigate the behavior of model ground using X-ray computed tomography (CT) scanner to visualize the failure zone in three dimensions. In addition to those results, a series of centrifuge model tests are conducted to confirm the results of X-ray CT test and also to discuss the ground behavior under full scale stress level. Finally, the effect of face bolting method is evaluated based on all the test results.

RÉSUMÉ

Le sujet de ce papier est premièrement de simuler expérimentalement en laboratoire quatre cas de figures de rupture en retirant un modèle de tunnel d'un sol sableux d'abord sans méthode auxilliaire ni boulonnage du front de taille puis avec boulonnage en utilisant 3 longueurs différentes de boulon ; et dans un deuxième temps, d'étudier le comportement d'un sol modèle à l'aide d'un scanner de tomographie rayons X afin de visualiser en trois dimensions les zones de rupture. En complément de ces résultats, une séries de tests en centifugeuse a été menée afin de confirmer les résultats obtenus par tomographie RX et aussi de discuter du comportement à l'échelle complète. Enfin, l'effet de la méthode de boulonnage du front de taille est evalué sur la base de l'ensemble des résultats obtenus.

Keywords :centrifuge model test, face bolting, tunnel, X-ray computed tomography

## 1 INTRODUCTION

When excavating a tunnel, tunnel face becomes unstable due to stress release caused by excavation. In recent years, mountain tunneling method such as NATM (New Austrian Tunneling Method) has been used for tunnel construction even in the urban area because of its cost effectiveness. In such a case, it is more important for the urban area to impose some constrained conditions, such as restrictions of surface settlement and ground water drawn down, compared with those of mountain area because of existing constructions such as buildings, pile foundations and underground pipes around the tunnel face. To create a condition for safe construction without harmful effect of existing constructions, the tunnel face should be reinforced with any kinds of auxiliary methods (i.e. face bolting and fore poling). It is said that the increase of the use of mountain tunneling method to the urban area is due to the development of auxiliary methods. However, there are relatively few studies with respect to the effect of auxiliary methods (Date et al., 2008), so that the issues on the design method for safe tunnel constructions are remained. To observe more precise behavior of the ground to evaluate the mechanism of face failure and the effect of auxiliary methods, it is effective to perform non-destructive test with imaging technique such as computed tomography (Otani et al., 2000). Nagatani et al. (2003) and Takano et al. (2004) developed tunnel pull-out model test system that could be carried out in the system of X-ray CT scanner. These studies made the face failure visualize in three dimensions. As quantitative discussion to the face failure, the volume of failure zone associated with face failure was measured using 3-D image; the results were discussed with effect of overburden ratio, relative density of the model ground and pull-out length on the scale of failure zone.

The purpose of this paper is firstly, to simulate four cases of the failure patterns by pulling out tunnel model from sandy ground that are without using auxiliary method nor face bolting and using face bolting with three different length of bolts and secondly, to investigate the behavior of model ground using X-ray computed tomography (CT) scanner to visualize the failure zone in three-dimensions. In addition to those results, a series of centrifuge model tests are carried to confirm the results of X-ray CT and also to discuss the full scale behavior. Finally, the effect of face bolting method is evaluated based on all the test results.

## 2 TUNNEL MODEL TEST USING X-RAY TOMOGRAPHY

### 2.1 *Test apparatus and procedure*

Figure 1 illustrates the schematic view of the test apparatus. The cylindrical soil tank has an inner diameter of 125 mm with a height of 300 mm. The tunnel model consists of a pipe, which has an outer diameter of 30 mm with an inner diameter of 20 mm. As shown in Fig. 1, the center of the tunnel model is set at a height of 100 mm from the bottom of the cylindrical soil tank, with the tunnel model extruding 20 mm from the tank side. In this experiment, excavation was simulated by pulling out the tunnel core.

Dry Toyoura sand was used in this test, and a relative density of model ground was 80 %. Bolts were installed in front of the tunnel face when the model ground was at the same height as the tunnel face. After preparing the soil in the soil tank, the tank was installed in the apparatus of tunnel pull-out model test and the core part was pulled out from the model ground.

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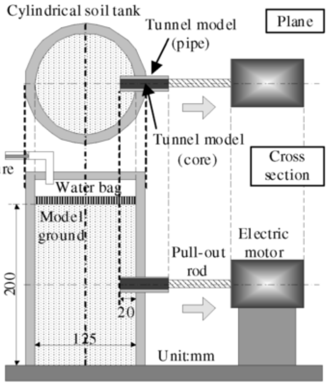



Figure 1. Schematic view of tunnel pull-out model test system

Table 1. Test cases

| Test case | Overburden ratio | Length of face bolt | Relative density (%) |
|---|---|---|---|
| CASE 1 | 2D | - | 80% |
| CASE 2 | | 0.25D | |
| CASE 3 | | 0.5D | |
| CASE 4 | | 1.0D | |

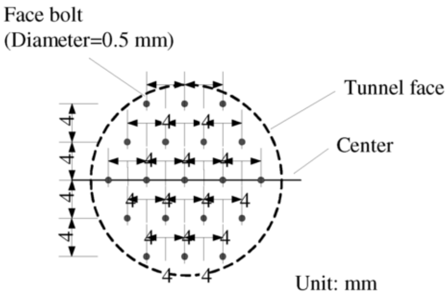



Figure 2. Arrangement of face bolts.

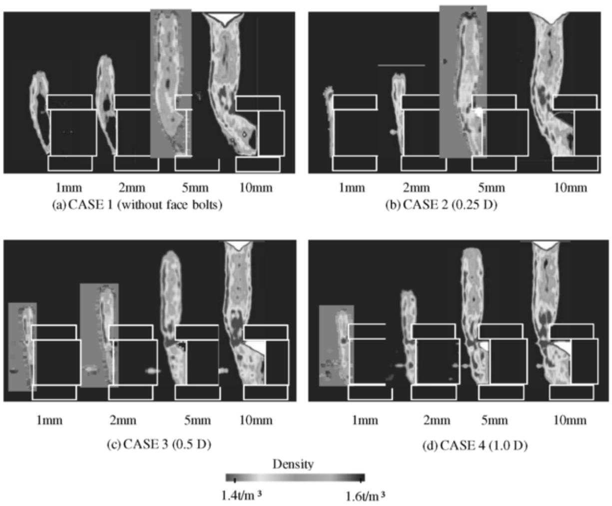



Figure 3. Vertical cross sectional images.

Table 2. Width and depth of settlement of ground for each case at 10 mm pull-out

| Test case | CASE 1 | CASE 2 | CASE 3 | CASE 4 |
|---|---|---|---|---|
| Depth of settlement (mm) | 6.2 | 5.6 | 4.3 | 4.6 |
| Width of settlement (mm) | 18.1 | 17.8 | 12.9 | 12.3 |

The tank was then removed from the apparatus of tunnel pull-out model test and placed on a turntable in an X-ray CT scanner for scanning. To understand the progress of failure zone, the model ground was scanned at pull-out length of 0 mm as initial condition, 1 mm, 2 mm, 5 mm and 10 mm. The model ground was scanned every 1.0 mm from the bottom of tunnel model to the ground surface and totally 70 cross sectional images were obtained. The cross sectional images were analyzed using image processing technique and extracted three dimensional images are also obtained. Test cases are listed in Table 1. In this experiment, the effect of the length of face bolts is discussed. Hence, four different condition of tunnel model were prepared such as the case of without face bolts (herein refer as CASE 1) and placing face bolts with the length of 0.25D (herein refer as CASE 2), 0.5D (herein refer as CASE 3) and 1.0D (herein refer as CASE 4). Here D is diameter of tunnel model of 20 mm. Figure 2 shows the arrangement of face bolts. An overburden ratio at 2.0D and pull-out rate at 0.1 mm/sec was kept constant. The details about application of X-ray computed tomography for geomaterials can be referred in Otani et al. (2000) and Lenoir et al. (2006).

## 2.2 *Test results*

Figure 3 shows the CT image of vertical cross section with the center of tunnel model to the direction of pulling out at the initial condition, 1 mm, 2 mm, 5 mm and 10 mm pull-out lengths, respectively. In CASE 1, there is a low density linear area in front of the tunnel model. This can be considered a shear band due to strain localization and the area enclosed by shear band can be thought a failure zone. Failure zone is developed from the bottom of the tunnel model to the ground surface and shear band is closed due to arching effect of the soil around the crown at 1 mm to 2 mm pull-out lengths. Moreover, there is no density change at the inside failure zone in CASE 1. It is considered that this zone move toward the direction of tunnel inside as a rigid body. As the pull-out length of the tunnel model increases, the failure zone is developed vertically toward the ground surface. The top of the failure zone reaches to the

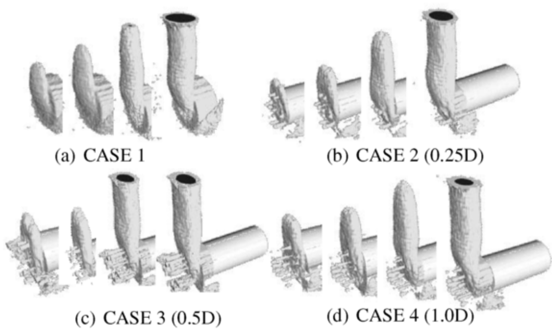



Figure 4. Three-dimensional image of failure zone.

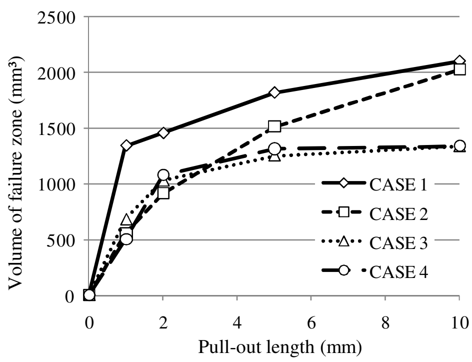



Figure 5. Volume of failure zone

ground surface at 5 mm pull-out length and settlement of the ground surface appears from the center of failure zone. Once failure zone reached to the ground surface, the settlement of ground is enlarged to the vertical direction and as well as horizontal direction. Meanwhile, it can be realized that failure zone is reduced for the cases of installing face bolts such as CASE 2, CASE 3 and CASE 4. The width of failure zone is reduced at the crown even at 5 mm and 10 mm pull-out lengths, and reinforcing effect can be confirmed especially for CASE 3 and CASE 4. In contrast, it can be observed that failure zone is reduced at 2 mm of pull-out length in CASE 2 as well as CASE 3 and CASE 4. However, when pull-out length reaches to 5 mm, the failure width becomes larger than the bolt length and thus, the effect of reinforcement is not produced. Table 2 shows a width and depth for the area of ground settlement for each case at 10 mm pull-out. The width and depth of the settlement is the greatest for CASE 1. In the cases of 0.5D and 1.0D of bolt length, both data are only 70 % of the case of bolts, whereas it is less reinforced effective with 0.25D of bolt length. It is said that the length of face bolts deeply affect to the ground settlement. The reason for constricting settlement by face bolts is that the width of failure zone can be reduced by face bolts at the crown and failure zone developed above the crown can be narrow.

Figure 4 shows three-dimensional extracted images of failure zone reconstructed using a large number of cross sectional images. The volume of the failure zone shown in Fig. 4 is summarized in Fig. 5. From these figures, the volume of failure zone is reduced in the cases with face bolts. However, there is no difference between CASE 3 (0.5D of bolt length) and CASE 4 (1.0D of bolt length). Thus, it may be said that the length of 0.5D is enough for the stability of the tunnel face for the case of large scale of failure. Besides, even if the bolt length is not sufficient, the reinforcing effect can be confirmed for the case of early stage of failure.

Table 3. List of test cases

| Test case | Overburden ratio | Length of face bolt | Material of model ground |
|---|---|---|---|
| CASE 5 | 1D | - | Toyoura sand |
| CASE 6 | | 1.5D | Dr=80% |

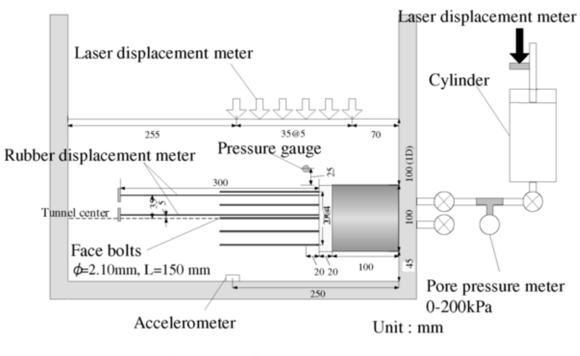



Figure 6. Schematic view of model test system

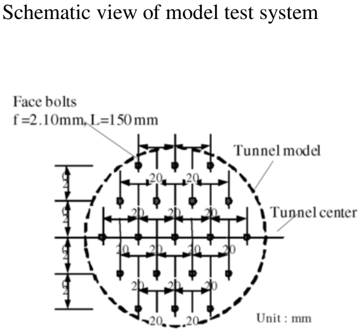
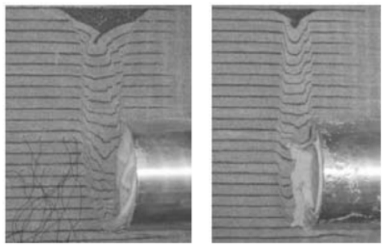



Figure 7. Arrangement of face bolts

## 3 CENTRIFUGE MODEL TEST

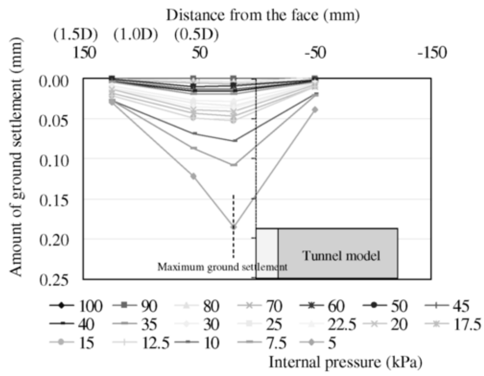
### 3.1 *Outline of the model test*

A series of centrifuge model test were carried out to confirm the results of X-ray CT and also to discuss about transition of the internal pressure of tunnel and failure pattern under full scale of stress level. Table 3 shows the list of test cases. The tunneling was simulated as reducing an internal pressure of rubber cylindrical tube installed at the head of tunnel model. During the tests, ground settlements, internal pressure of tunnel, and earth pressure at the tunnel face were measured by laser displacement gauges and pressure gauges. Rubber displacement gauges were also used to measure the ground displacement at the front of tunnel model. In this series, two types of the tests with and without face bolting were conducted. Figure 6 illustrates the schematic view of the test. From the results of X-ray CT, it has been confirmed that more than 1.0D of the face bolt length is necessary to provide an enough reinforcing effect

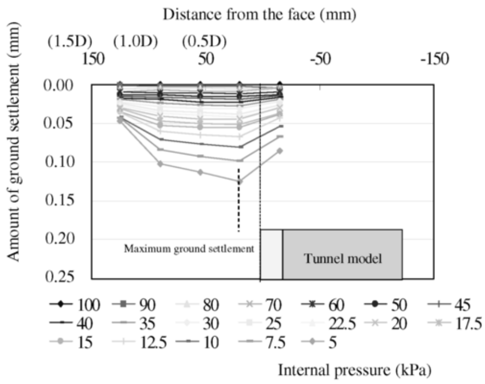


CASE 5 CASE 6

Figure 8. Vertical cross section of ground at tunnel center




(a) CASE 5




(b) CASE 6

Figure 9. Distribution of ground settlement at tunnel center

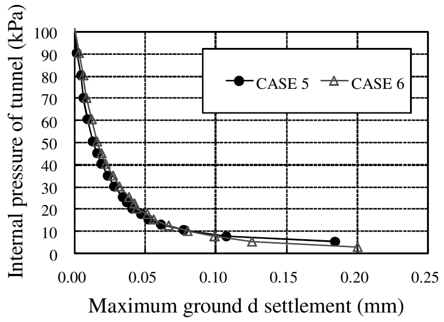
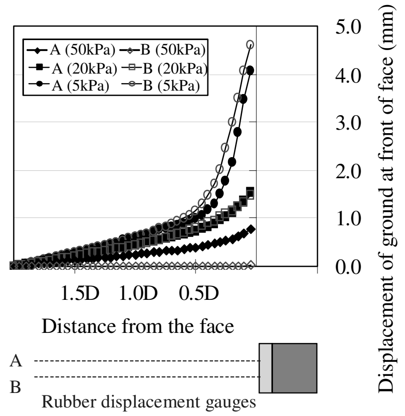
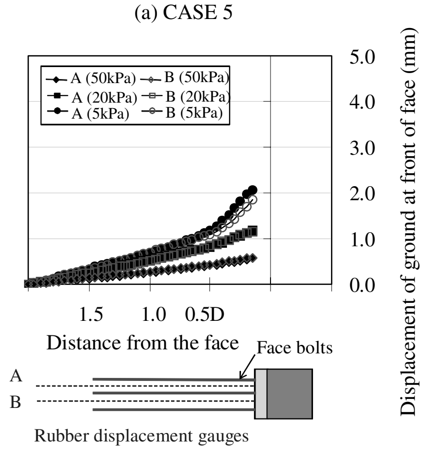



Figure 10. Relationship between internal pressure of tunnel and maximum ground settlement




(a) CASE 5




(b) CASE 6

Figure 11. Displacement of ground around of tunnel face

in sandy ground. Hence, this length was fixed as 1.5D to confirm the reinforcing effect. Figure 7 shows the arrangement of face bolts that was defined from the results of X-ray CT. During preparation of model ground, the layer of colored Toyoura sand was placed in the ground at every 10 mm depths to observe the movement of the soil. In this paper, all the scales of the test results are described as its model size.

### 3.2 *Test results*

The value of internal pressure of tunnel at state of face failure was 4.8 kPa in CASE 5 and 2.6 kPa in CASE 6, respectively. It can be said that this showed the effect of reinforcement due to installing face bolts. Figure 8 shows photos of the cross sections of tunnel center at the end of tests. It is observed that the shear band was developed from the bottom of tunnel model to the ground surface and the ground surface was collapsed. Meantime, the width of failure zone is reduced at tunnel crown in CASE 6. These observations are similar to the results of X-ray CT. It can be said that the results of X-ray CT are reasonable and it is comparable to its behavior under full scale of stress level.

Figure 9 shows distribution of ground settlement at tunnel center. In both cases, the ground settlement increases when the internal pressure was reduced to 5.0 kPa from 7.5 kPa. This sudden development of ground settlement can be considered that the failure zone reaches the ground surface. The maximum settlement is 13.5 mm for CASE 5 and 9.4 mm for CASE 6, respectively. Figure 10 shows a relationship between internal pressure of tunnel and increment of maximum ground settlement. There is no significant difference between both cases until internal pressure reaches the value of 10 kPa. This may be said that the failure zone did not reach the ground surface due to the arching effect. Figure 11 shows the ground displacement in front of tunnel face. The ground displacement measured by gauge A starts increasing from 50 kPa of internal pressure in CASE 5. And also, both of gauges did not show large displacement until the internal pressure reaches the value of 5 kPa. However, at the internal pressure of 5.0 kPa, the face extrusion was much lager in CASE 5 than demonstrated in CASE 6. Thus, the effect of face bolts can be confirmed, especially at the front of tunnel face.

## 4 CONCLUSIONS

In this study, two types of tunnel model test were carried out, which were using X-ray CT and centrifuge model test in order to evaluate the effect of face bolting. In the centrifuge test, it is confirmed that the results of X-ray CT shows reasonable behavior and comparable to its behavior under full scale of stress level. In X-ray CT tests, failure zone could be visualized in the case of with and without face bolts. The reinforcing effect can be confirmed even the case of short length of the bolts for the case of early stage of the failure. And also, if the large scale face failure is occurred, the stability of tunnel face can be expected with 0.5D of the bolt length.

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