Centrifuge Model Test Study on the Behavior of a Tunnel Under the Neighboring Excavation

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Abstract. With the expansion of urban area, the excavations due to the construction of new tunnel cause deformation of the soil, and subsequently affect the behavior and safety level of existing tunnels. In this study, centrifuge model tests were conducted to simulate the underground excavation in the soil where there is a tunnel. The underground excavation is simulated by dissolution of potassium nitrate solid that are buried in the soil in model preparation. The displacement of the soil is measured using an image-based measurement system, and the stress-strain response of the tunnel is measured using the strain gages. The test results show that the horizontal distribution of the soil settlement exhibits an arched shape with the peak at the axis of underground excavation. With increasing elevation, the soil settlement rises first and then stabilizes or even decreases. The tunnel bends towards the excavation side with the largest moment at the excavation axis and have a great effect on the settlement above it. The tunnel has a shielding effect on the upward transfer of the excavation impact and this shielding effect has a certain scope.

Keywords: Soil · Tunnel · Excavation · Centrifuge model test

1 Introduction

There are a lot of inevitable structures near the underground excavation. For example, many subways intersect others. The underground excavation causes new deformation of neighboring soil and structures such as tunnels. It has been indicated that underground excavation has an irreversible effect on the stress and displacement fields of neighboring soil. Therefore, it is significant to explore the influence of underground excavation on the neighboring structures.

A formula was proposed to predict the ground settlement due to stratigraphic loss from experience (Peck 1969). Wei and Yang (2018) proposed a data-driven model to predict the mining-induced ground settlement. Centrifuge modeling is an effective tool for studying the response of soil by producing the same stress level in a small model. Li et al. (2011) conducted a series of centrifuge model tests and analyzed the rules of slope deformation under excavation. Luo et al. (2020) clarified the geogrid reinforcement mechanism on the slope under differential settlement with centrifuge model tests.

Previous studies put their focus on the ground settlement under excavation. The influence of excavation on existing tunnel has not been thoroughly illustrated. The objective of this paper is to investigate the effect of underground excavation on neighboring tunnel and soil using centrifuge model tests.

2   Test Description

2.1   Test Program

The orthogonal excavation under the existing tunnels is the focus of this study. Accordingly, two sets of the model tests are conducted at the 70 g level. In one set, excavation is simulated underneath existing orthogonal tunnel (Fig. 1). The other set is used for comparison where the excavation is simulated at the same place in the soil base without existing tunnel. The response of the soil and tunnel under excavation is analyzed based on the observation of the tests. The soil-tunnel interaction under excavation is investigated based on the comparison of the observations in the two test sets.
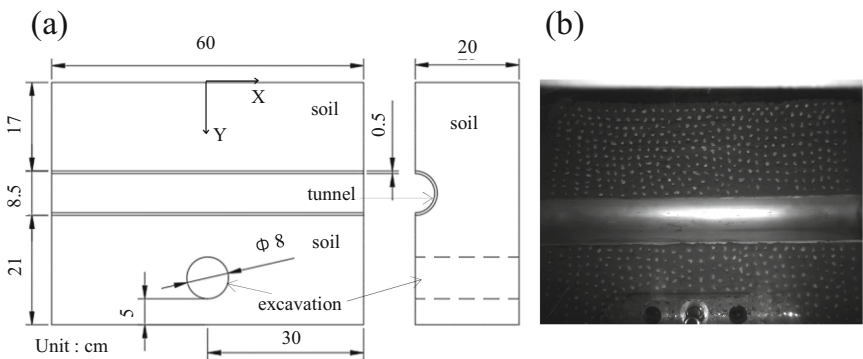

Fig. 1. Schematic view of the model for centrifuge model test. (a) Schematic view; (b) photograph.

2.2   Device

The centrifuge model tests are performed with a centrifuge with a capacity of 50 g-ton and an effective radius of 2 m. The model container is made of aluminum alloy and measures 600 mm × 200 mm × 520 mm from the inside. A plexiglass with a thickness of 40 mm is installed along the length side of the model container. A camera is fixed in front of the model container to capture the response of the model through the plexiglass side.

The soft fire hose filled with the potassium nitrate solid is buried in the soil, connected with a water pipe with a valve. The potassium nitrate is easily soluble in water and pressed tightly, and the diameter of the fire hose is 8 cm. Water is injected into the fire hose during the test, dissolving the potassium nitrate solid, simulating the underground excavation without large-scale construction.

2.3   Model Preparation

A silty clay with a specific gravity of 2.7 is used for the test model. The liquid limit and the plastic limit of the soil are 33.5% and 15.5%, respectively. The optimal moisture content of the soil is 17% and the maximum dry density is 1.93 g/cm^3. For the model preparation, the dry density of the soil is 1.6 g/cm^3, and the moisture content is 17%. The soil is compacted by layers in the model container to the designed dry density. The first seven layers are 6 cm high and the last two are 5 cm high. The total height of the soil base is 52 cm. In this process, the fire hose is placed in the soil for the simulation of excavation.

The tunnel is simulated with an alloy aluminum tube (Fig. 2). The Young's modulus of the alloy aluminum is 72 GPa. The outside radius and the thickness of the alloy aluminum tube are 4.25 cm and 0.5 cm, respectively. The tube is only a half and is attached to the inside of the model according to its symmetry (Fig. 1). To monitor the stress-strain response of the tunnel, 14 strain gages are pasted symmetrically on the tube located 45° on the upper and lower sides (Fig. 2).

The prototype is the excavation with a diameter of 5.6 m at a depth of 25.5 m underground. An existing tunnel with a diameter of 6 m is 11.4 m above the excavation. The side walls of the model container are evenly coated with the silicone oil to reduce friction.

2.4   Test Procedure

This test of each set is divided into three steps. Firstly, the model without the tunnel is put in the centrifuge. The centrifugal acceleration increases from the 1 g sequentially to a multiple of 10 g, and stabilizes at 70 g for 30 min. When the settlement of the soil base is invariable at 70 g, the container is taken out. Secondly, the tunnel is buried in the model and placed in the centrifuge for the test set of the existing tunnel. The centrifugal acceleration is increased slowly to 70 g again. Lastly, when the soil settlement stabilizes at 70 g, the excavation is simulated using the potassium nitrate solution method. The test ends after the soil settlement becomes unchanged.

The strains of the tunnel are measured by the strain gages linked with the data measurement system. A series of the images of the soil and tunnel are captured by the camera during excavation with a rate of 1 frame per second. The images are used to measure the displacement of the whole soil field through a correlation-based analysis algorithm (Zhang et al. 2009). To realize it, a few white particles are placed on the soil behind the plexiglass (Fig. 1b).

According to the similarity law of centrifuge model tests, the depth and displacement measured in the model can be transferred to the prototype by multiplying the g level, namely 70 in this study. The strain is the same at the model and prototype scales. In this paper, all the data is presented at the prototype dimension. A Cartesian coordinate with the x-axis as the central axis of the excavation and the y-axis as the horizon is set up, and the positive directions of x-axis and y-axis are defined as rightward and downward, respectively (Fig. 1a).
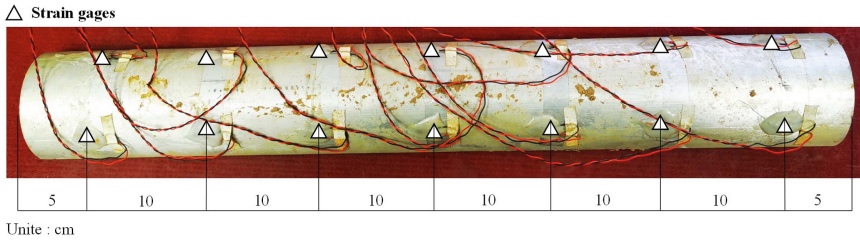
Fig. 2. Photograph of the aluminum tube with stain gages.

3 Observation

The underground excavation causes significant settlement of the soil without obvious failure. Figure 3 shows the distribution of the displacement vector due to the excavation. It can be seen that the settlement is significantly greater than the horizontal displacement. This result indicates that the impact of excavation mainly exhibits the soil settlement.

Comparing with the distribution of the displacement vector (Fig. 3), it can be seen that the tunnel has a significant effect on the soil settlement. The settlement has a distinctly differential distribution below the tunnel. The settlement under the tunnel near the excavation is significantly greater than the one farther away from the exaction. The soil settlement distributes relatively uniformly above the tunnel. The distribution of the settlement has an obvious conical shape, which spreads upwards and around from the excavation.

Figure 4 shows the distribution of soil settlement in horizontal and vertical directions. It should be noted that the results are only presented with the right half due to the symmetry of the model. The soil settlement reaches the peak at the axis of underground excavation and decreases in the horizontal direction with increasing distance from the excavation (Fig. 4a). The vertical distribution of soil settlement exhibits different patterns at different distances from the exaction. From the bottom up, along the axis of the excavation, the settlement increases first, reaches stability and then decreases. When the position is 9 m away from the excavation axis, the settlement increases to a stable level. When the position is far away from the excavation, settlement continues to increase. Within a certain distance from the axis, soil settlement rises first and then stabilizes or even decreases from bottom to top. The farther away it is from the axis, the greater the distance at which the settlement increases.

Figure 5 shows the horizontal and vertical distributions of the soil settlement due to excavation when there is a tunnel. The settlement of the soil above the existing tunnel distributes more uniformly than those under the tunnel. Except for the adjacent area above the tunnel where the soil settlement distributes uniform in horizontal direction, the distribution of the soil settlement exhibits an arched shape with the peak at the axis (Fig. 5a). There is no obvious increase of the settlement on both sides of the tunnel. The settlement increases to a stable level at a vertical direction (Fig. 5b).
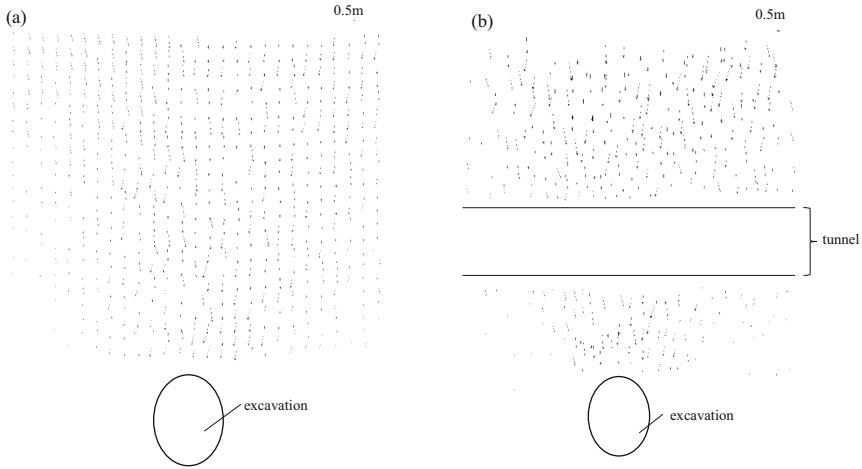
Fig. 3. Distribution of the displacement vector of the soil. (a) without the tunnel, (b) with the tunnel.
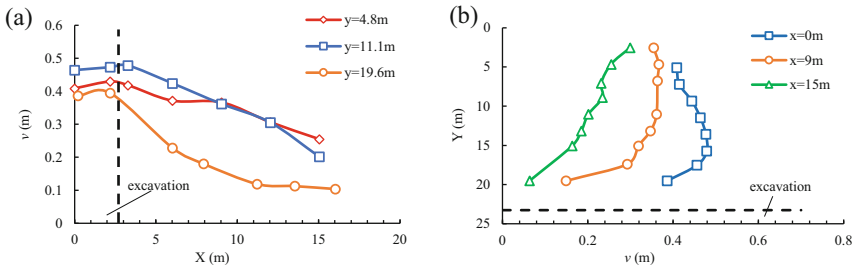

Fig. 4. Distribution of soil settlement (v) without the tunnel. (a) in horizontal direction, (b) in vertical direction.

The strains on the tunnel are measured with the strain gages and calculated to the bending moment based on the continuous beam analysis (Fig. 6). The bending moment is positive when the top point of the tunnel is tensioned. It can be seen that the excavation induces additional bending moment of the tunnel. The moment exhibits the peak at the excavation axis and decreases towards the sides. The tunnel bends towards the side near the excavation. When approaching the excavation location, the support of the lower soil for the tunnel is reduced by the large soil settlement under the tunnel due to excavation, and the tunnel bends downward.

According to the surface settlement and Peck's equation (Peck 1969), the volume loss rates with or without tunnels are calculated to be 42.7% and 49.5%, respectively.
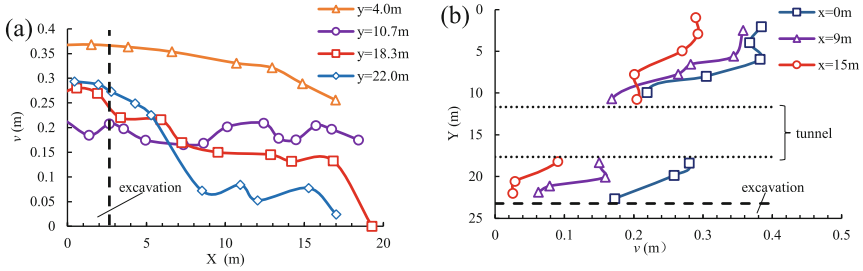
Fig. 5. Distribution of soil settlement (v) with the tunnel. (a) in horizontal direction, (b) in vertical direction.
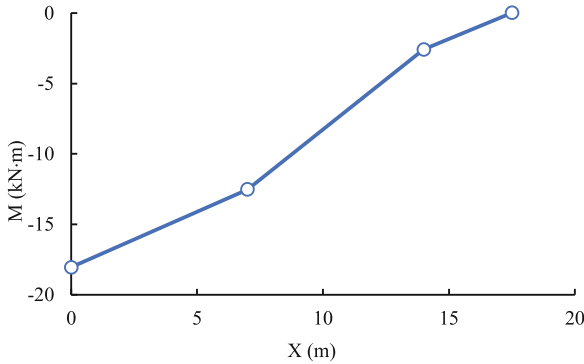

Fig. 6. Horizontal distribution of bending moment increment (M) of the tunnel due to excavation.

4 Soil-Tunnel Interaction

The soil settlements of the two sets have the similar distributions but different values. Figure 7 compares the distribution of soil settlement due to excavation under the condition there is a tunnel or not. It can be seen that the soil settlements of two sets are same within the depth of 5 m in the vertical direction. This result indicates that the tunnel has a small influence on the soil deformation in the zone where the depth is less than 5 m.

The soil settlement is significantly changed by the tunnel near the excavation. Settlement in a certain area above the tunnel is significantly reduced by the tunnel support. In particular, the depth from which the settlement reaches stability in vertical directions is decreased by the tunnel. This result demonstrates that the tunnel takes a shielding effect on the upward transmission of the excavation. To describe the extent of the shielding effect, a shielding index (i) is introduced and described using the following equation:

$$i = \frac{h - h^*}{h}. \tag{1}$$

where h^* and h are the depths where the displacement has just reached stability in the vertical direction in the cases where is a tunnel or not.

Figure 8 shows the horizontal distribution of shielding index of the tunnel. It can be seen that the shielding effect reaches the peak at the excavation axis and decreases rapidly when the distance from the excavation axis is greater than 10 m. This result indicated that the excavation affects the soil deformation within a zone with a distance of 15 m from the excavation in this test.
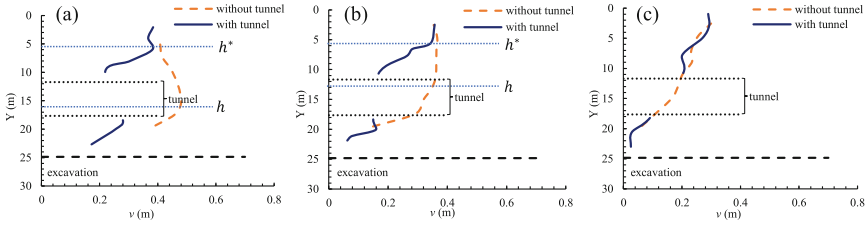

Fig. 7. Vertical distribution of soil settlement under the condition there is a tunnel or not. (a) $x = 0$, (b) $x = 9$ m, (c) $x = 15$ m.
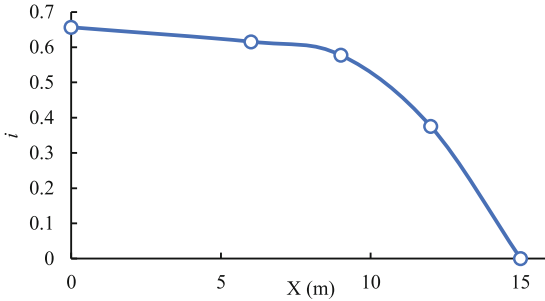

Fig. 8. Horizontal distribution of shielding index of the tunnel.

5   Conclusion

The behavior of the existing tunnel and soil under the excavation of the lower orthogonal tunnel was investigated on the basis of centrifuge model tests. Main conclusions are drawn as follows:

1. The settlement of the soil reaches its peak at the axis of excavation and decreases with increasing distance from the excavation in horizontal direction. The settlement of the soil rises at first and then stabilizes or even decreases with increasing elevation.
2. The tunnel reduces the settlement of the soil within a certain area above it and makes the settlement to distribute more uniformly above the tunnel than under the tunnel.
3. The tunnel bends to the side near the excavation. The bending moment is the greatest at the axis of excavation and decreases with increasing distance from the excavation.
4. The tunnel takes a shielding effect on the upward transmission of the excavation. This effect reaches the peak at the excavation axis and decreases rapidly when the distance from the excavation axis is greater than 10 m.

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