Failure mode of shield excavation face using transparent soil

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ABSTRACT

The stability of the excavation face plays a critical role in the safety of shield tunnel construction, and the failure mode is one of the most important factors. By using transparent soil materials, it is possible to obtain a more real displacement field of the soil without disturbed. This paper used the transparent soil model tests and numerical simulation, two situations of the single tunnel and the crossing existing tunnel were performed to investigate failure mode of the excavation face. The test results indicated that the failure mode of single tunnel is a bulb-like shape with soil arching effect, and the failure mode of crossing existing tunnel is a wedge shape. In addition, comparing the two cases, the surface settlement of the crossing existing tunnel is significantly reduced. This means that the existing tunnels can weaken the surface settlement.

Keywords: transparent soil, failure mode, single tunnel, crossing existing tunnel

1 INTRODUCTION

In order to fully study the failure process of the surrounding soil during the instability of the shield excavation face, it is necessary to clarify the spatial displacement law of the surrounding soil during the instability of the excavation face. However, due to the opacity of the rock and soil materials, the internal environment is restricted. Transparent soil, because of its advantages of observing its internal deformation field, is an excellent material for studying the instability process and failure mode of the excavation face.

The research on transparent soil can be traced back to Mannheimer et al. (1993) used amorphous cinnamon powder and pore fluids matching the refractive index to synthesize transparent slurry for the study of non-newtonian fluid flows. Since then, amorphous silicon powder is synthesized by transparent soil, and the consolidation settlement, seepage and other experimental studies were carried out on geotechnical properties, proves the feasibility of transparent soil as geotechnical test material (Iskander et al. 1994, Sadek et al. 2002). By using transparent soil, optical measurement and digital image technology, the stability and other parameters of shield tunneling were studied (Sun et al. 2011). The combination of transparent soil and numerical simulation is used to study the internal deformation evolution of surrounding rock during construction of shield tunnel in composite formation (Du et al. 2018). The visibility and physical and mechanical properties of the transparent soil prepared by amorphous silicon powder, #15 white oil and n-dodecane were studied (Zhang et al. 2014, Lei et al. 2019).

At present, some achievements have been made for the basic characteristics of transparent soil. However, the use of transparent soil to study the failure mode of shield excavation face is rare, and the study of the failure mode of excavation face instability of crossing existing tunnel is less. In this paper, through the transparent soil model test, the two conditions of the single tunnel and the crossing existing tunnel are used to compare and analyze the failure mode of the excavation face. Furthermore, the numerical simulation of crossing existing tunnel is carried out to further analysis.

2 TRANSPARENT SOIL

Transparent soil refers to the transparent solid-liquid mixture with similar properties to natural soil. Solids (amorphous silicon powder) and liquids (#15 white oil and n-dodecane) are used to simulate natural soil particles and pore water, respectively. Table 1 shows the physical properties of transparent soil.

Amorphous silica powder is a commercial product with particle size of up to μm and density of 0.056 to 0.230 g/cm³ (dry state). The particle size characteristics of amorphous silicon powder in transparent soil were

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measured by LS-POP (6) laser particle size analyzer. The grain-size distribution curves of the amorphous silicon powder selected in this paper are shown in Fig. 1 (Lei et al. 2019). It can be seen that the grain-size of the amorphous silicon powder is mainly concentrated between 4 to 10 μm. N-dodecane (chemical formula C_{12}H_{26}) is a colorless liquid with a melting point of -9.6 °C and a boiling point of 215~217 °C that is insoluble in water.

Table 1. Physical properties of transparent soil.

| Index properties | Value     |
|------------------|-----------|
| Density (g·cm^{-3}) | 1.08      |
| Oil content (%)   | 150       |
| Initial void ratio| 1.224     |
| Compression coefficient (MPa^{-1}) | 0.879     |
| Compression index  | 20.543    |
| Compression modulus (MPa) | 2.531     |
| Springback index   | 0.0006    |

3 TEST APPARATUS AND SCHEMES

3.1 Test apparatus

The test apparatus used in this experiment is shown in Fig. 2, and the geometric similarity ratio with the actual project is 1:120, where each part is:

1. Model box (25cm×25cm×40cm)
2. Excavation face moving device (Φ=5cm)
3. Plexiglass base (40cm×40cm)
4. Slide rail (l=1.5m)
5. Self-balancing optical platform (1.5m × 2m)
6. Laser (200mw, 650nm)
7. Industrial camera (resolution 4896×3264)
8. Support force monitor (0~980N)
9. Laser bracket
10. Camera stand
11. Computer

3.2 Test schemes

Two sets of transparent soil model tests (single tunnel and under the existing tunnel) and a set of numerical simulations (under the existing tunnel) were performed to investigate the failure mode of the excavation face. Specific tests schemes are listed in Table 2.

Table 2. Test schemes.

| Test ID | Tunnel condition | Test method     | Excavation tunnel buried depth ratio |
|---------|------------------|-----------------|-------------------------------------|
| Case 1  | Single tunnel    | Model test      | 3                                   |
| Case 2  | Under the existing tunnel | Model test | 3                                   |
| Case 2  | Under the existing tunnel | Numerical simulation | 3                               |

3.3 Test process

The process of model test are as follows:

1. Fill the configured transparent soil into the model box to a predetermined depth and vacuum to remove the pore gas.
2. Place the mass on the upper surface of the transparent soil to apply pre-consolidation pressure.
3. Turn on the laser to cut the predetermined section of transparent soil.
4. Rotate the excavation face moving device to simulate the instability of excavation face and the industrial camera is used to take pictures.

4 RESULTS AND DISCUSSION

4.1 Single tunnel

Fig. 3 shows the failure mode of excavation face instability of single tunnel from longitudinal and transverse directions. It can be observed that the failure mode of a single tunnel is very obvious. The failure area in front of the shield excavation face develops to a certain height cutoff, showing the soil arching effect and forming a bulb-like failure mode, which is basically consistent with the previous research results (Mair et al. 1979). In addition, it can be observed that the formation area of the soil arch is roughly in the range of 1.5D~2.0D above the top of the tunnel, which is consistent with the range of influence in the actual engineering. Therefore, it can be considered that the test method based on transparent soil can be well
matched with existing achievements and engineering practice.

The surface settlement is larger, about 0.035 m. The surface settlement of crossing existing tunnel is reduced significantly, about 0.005 m. This consequence is caused by the support of the existing tunnel and the difference between the stiffness and the soil.

**4.2 Crossing existing tunnel**

The failure mode of excavation face instability of crossing existing tunnel from longitudinal and transverse directions are provided in Fig. 4. As shown, the failure area in front of the shield excavation reaches the bottom of the existing tunnel, which shows the overall failure mode of the wedge shape, which is related to the change of stress state distribution in the soil caused by the existing tunnel. That is to say, the deformation area of soil is restricted to the space between the front of excavation and the existing tunnel. The specific shape can be divided into two parts, one is an arc that slides along the center point of the bottom of the tunnel, and the other part is a vertical line that is flush with the outside of the existing tunnel.

The surface settlement directly curve above the excavation face caused by the instability of the excavation face is analyzed. The result is shown in Fig. 5. It can be observed that in the case of a single tunnel,
4.3 Numerical simulation

The numerical simulation analysis was carried out using the particle discrete element software PFC3D (version 5.0) which can simulate large deformation. Based on the model test, a numerical model of particle flow is established to simulate the failure process of the excavation face in the existing tunnel construction. The tunnel excavation is simulated by removing the particles inside the tunnel, the lining is simulated by cylindrical wall, and the grouting layer is simulated by parameters of reinforced soil.

The failure mode of excavation face instability of crossing existing tunnel from longitudinal and transverse directions are provided in Fig. 6. The failure mode of excavation face instability of crossing existing tunnel is basically consistent with the result of model test, which expressions a wedge shape and the failure area in front of the shield excavation reaches the bottom of the existing tunnel.

![PF3C5.0](image)

(a) longitudinal

![PF3C5.0](image)

(b) transverse

Fig. 6. The failure mode of excavation face instability of crossing existing tunnel (numerical simulation).

been carried out to investigate two failure modes (single tunnel and crossing existing tunnel) of excavation face instability using transparent soil. The conclusions are as follows:

1) The failure mode of excavation face inside the tunnel can be seen directly by using transparent soil.
2) The failure mode of excavation face instability of single tunnel and crossing existing tunnel are explored by two model test, which are bulb-like shape and wedge shape, respectively.
3) On the basis of the model test, the numerical simulation of the crossing existing tunnel is carried out, and it is found that the results of model test are consistent.

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