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Application of transparent soil model test and DEM simulation in study of tunnel failure mechanism

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ABSTRACT

With fast growing demand for modern transportation, more shallow tunnels are being constructed and planned. Understanding the deformation and failure mechanism of a shallow underground tunnel has been a topic of research. The influences of the surrounding material (rock and soil) strengths and buried depths on the deformation and failure mechanism are investigated through the transparent soil model test technique and PFC^{3D} numerical simulation in this study. It can be observed from model tests that the failure mode of test 1 (relative density of 30%, buried depth of 60 mm) is similar with that of test 2 (relative density of 70%, buried depth of 60 mm), both showing the funnel shape. The difference lies in that the tunnel stability in test 1 is lower. On the other hand, tests 2 and 3 (relative density of 70%, buried depth of 120 mm) are of different failure shapes as the latter displays a chimney shape. PFC^{3D} simulation is carried out to numerically examine the failure modes under different testing conditions. The stress field and the displacement field derived from the numerical results can help to interpret the tunnel failure mechanism. In addition, it is obvious from this study that the Peck formula (1969) is less applicable for the surrounding materials with low strength. Therefore, it should be amended according to the surrounding materials, especially for the granular soils.

1. Introduction

The deformation and failure process of tunnels surrounded by soils has been one of the basic problems in tunneling engineering (Broms and Bennermark, 1967; Peck 1969). Plenty of research has been carried out (Davis et al., 1980; Clough et al., 1983; Lee et al., 2006; Chi et al., 2001; Fang et al., 2011; Adachi et al., 2003; Hamid et al., 2013; Hamid and Bahtiyar, 2014; Zhang and Goh, 2015; Wan et al., 2016; Goh et al., 2017). Among them, model test and numerical analysis are generally regarded as more effective methods, if the field measurements are unavailable.

It is generally accepted that the conventional model test is able to reveal the deformation and failure mechanism. However, a certain number of sensors should be installed for these tests to monitor the inner deformation of surrounding soils around the tunnel. It is unavoidable that the embedment of the rigid sensors of considerable size will affect the mechanics of the surrounding soils through arching effect, thus influencing the instrumentation accuracy. Meanwhile, the inner deformation and the failure pattern of the surrounding soil around the tunnel can't be easily obtained from the traditional model tests. To visualize the interior soil deformation, the transparent soil testing technique was developed (Allersma, 1982). Later some scholars have continuously improved this technology and broaden the geotechnical applications (Iskander et al., 2002; Sadek et al., 2002; Ni et al., 2010; Toiya et al., 2007; Liu, 2009; Liu and Magued, 2010; Ahmed and Iskander, 2011, 2012; Peter et al., 2013; Xiao et al., 2017; Xing et al., 2017).

The finite element method and finite difference method are widely used for numerical analysis of geotechnical problems. However, these two methods are based on the continuum mechanism theory, which can't reflect the discrete characteristics of soil mass and the large deformation caused by tunnel excavation. The particle discrete element method (DEM) is not restrained by deformation, thus it is more applicable in discontinuous medium and capable of simulating large deformation, separation and dielectric cracking. DEM can better capture and display the surrounding soil state, the deformation process as well as the failure mechanism. It was firstly put forward by Cundall (1971); Cundall and Stack (1979) with rapid development and is now widely used in geotechnical engineering (Rothenburg and Bathurst, 1989; Oda and Kazama, 1998; Cai et al., 2007; Ng et al., 2013).

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The transparent soil testing technique is adopted in this study to visualize the deformation process of soils around tunnel induced by excavation. Three transparent soil model tests taking into account different surrounding material strengths and buried depths are designed, from which the deformation process and failure modes are obtained. The stress field obtained from DEM code PFC^{3D} is mainly used to illustrate the influential zones caused by excavation from aspect of stress and also to confirm the results from the model tests. The model test results are validated against the Peck (1969) and it is found that the Peck formula is less applicable for the surrounding materials with low strength and should be amended, especially for the granular soils.

2. Transparent soil model test

2.1. Model test apparatus

The model test system consists of the optical platform, a computer, a CCD high speed industrial cameras, an optical laser, a self-designed plexiglass model tank, and the processing software for PIV digital images. The optical platform is made of ferromagnetic stainless steel with top side of honeycomb support inner core structure, which is of considerable anti-disturbance capacity. The type of the CCD high speed industrial camera is LUMENERA LT425. It is of high resolution of 2048 × 2048 pixel, active area of 11.264 × 11.264 mm, pixel size of 5.5 × 5.5 μm, frame rate of 90 fps at full resolution, and sensitivity of 13.7 DN/(nJ/cm^2). The camera control program is capable of continuously recording the deformation process of the surrounding soil during tunnel excavation. The sheet laser light is of EP532-3W type, the output power is 3 W while the wavelength is 532 nm. The light sheet thickness is less than 1 mm while the light angle is 10–25°. The model groove is made of acrylic plexiglass, with each surface bonded by strong glue. The ribs at the bottom are utilized to restrain the deformation of the model groove. The size of the model groove is 450 mm × 300 mm × 400 mm, with wall thickness of 10 mm. There are two holes of 60 mm diameter at the front and back of the model groove, respectively. The center of each hole is 180 mm from the groove bottom, 195 mm from the side wall. In addition, the outside of the model tunnel is bonded through a round tube of 40 mm long to fix the waterproof film. There are different scale marks on the model slot in accordance with the different testing conditions. The PIV VIEW software is used to post-process the obtained pictures during the test. The accuracy of the adopted PIV non-interference technology is 0.0254 mm. Sadek et al., 2002, Ahmed and Iskander (2011) and Liu (2009) have discussed the accuracy of the technology and thought this accuracy is sufficient for geotechnical model testing. The sketch map of the model test system is shown in Fig. 1.

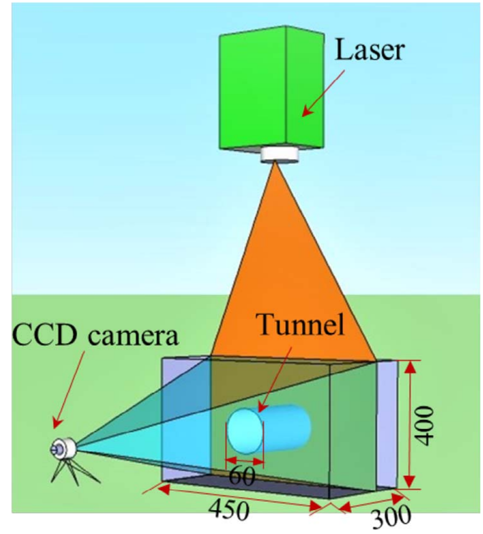

Fig. 1. Sketch map of the transparent soil model testing system.

Fig. 2. TPU film tube.

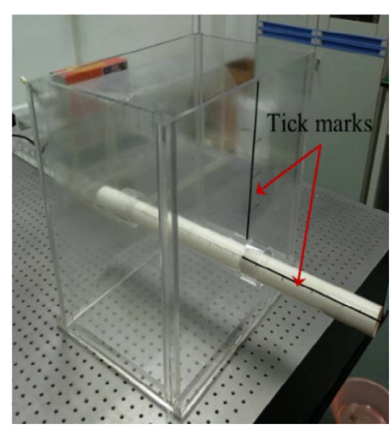

Fig. 3. Model test box and the tunnel extraction model.

2.2. Model test materials

The solid portion of the transparent soil is glass sand with particle size ranging from 0.5 mm to 1.0 mm. Its maximum dry density is 1.274 g/cm^3 while the minimum dry density is 0.907 g/cm^3. The pore fluid consists of NO 15 mineral and n-dodecane with mass ratio of 4:1. The pore fluid refractive index is 1.4585. This transparent soil has the similar physical properties with the natural sand (Kong et al., 2013). The angle of internal friction is between 36 and 39°. The model tunnel is surrounded by a transparent high elastic TPU film tube (as shown in Fig. 2). The tube is mainly adopted to prevent the liquid from flowing outwards along the tunnel model hole during the test. The “extraction method” is adopted to simulate the tunnel excavation (as shown in Fig. 3). The model tunnel is made of an organic glass tube with thickness of 5 mm and diameter of 58 mm. It is wrapped in polyester cloth to reduce the friction effect between the TPU waterproof membrane tube and the organic glass tube. Before test, the model tank should be firstly cleaned for better solution and observation.

Then the solid and fluid compositions are mixed. Firstly, the required amount of glass sand is weighed and ready for use. Next, mix the NO 15 mineral oil and n-dodecane with mass ratio of 4:1 to ensure the refractive index of the mixed liquid match that of the glass sand. The mixed liquid oil is kept in the model tank. Later a certain amount of glass sand is poured into the model tank evenly and slowly to mix with the oil. During mixing, the transparent soil should be stirred with a glass rod slowly to remove the trapped bubbles inside. Stratified compaction method is adopted to ensure that the transparent soil can be paved to the desired density, with a thickness of 10 mm each layer.

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