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Experimental study of the face stability of shield tunnel in sands under seepage condition

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ABSTRACT

Understanding of the failure mechanism and limit support pressure of a shield tunnel face under seepage condition is important in engineering design and construction. Nine physical model tests, i.e. three tests in dry sands, three tests in submerged sands under undrained condition, and three tests under seepage condition were carried out. A rigid plate was set in front of the tunnel face to maintain stability at the initial state. By moving the plate backward from the soil, the displacement and earth pressure curve of the tunnel face was obtained. The earth pressure dropped sharply to a constant value which corresponds to the limit support pressure required to stabilize the tunnel face. The limit pressure was found to increase with the cover-to-diameter ratio in a shallow tunnel, and it turned to be irrelevant to cover-to-diameter ratio in a deep tunnel. The ratio of limit pressure and initial earth pressure decreases with the cover-to-diameter ratio, indicating the effect of soil arching in stabilizing tunnel face stability. Under the same water level condition, the limit pressure of tunnel face with seepage is larger than the one without seepage. The limit support pressure under seepage condition is about 70% of the earth pressure at rest; it is about 50% under undrained condition and is about 15% in dry sand. The flow line around the tunnel face was traced by infused pigment, and the distribution was shown to be irrelevant with water level. The image captured by a HD camera during the test was analyzed by PIV (particle image velocimetry) analysis; the soil particle movements and the distribution of shear strain showed the failure mechanism of tunnel face. The failure mode is a combination of a wedge with slip arc and a prism. Comparing with the failure mode in dry sands and in saturated sands below water table undrained condition, the inclination angle of the wedge block under seepage condition is much smaller.

1. Introduction

Shield tunneling in soft ground area is often under construction below the water table, i.e. cross-river tunnels, subsea tunnels, and urban tunnels in coastal area. In EPB (earth pressure balanced) tunnel or NATM (new Austrian tunneling method) tunnel, seepage will be triggered when the piezometric head at the tunnel face is lower than the hydrostatic head, especially when tunnel passes through saturated sand stratum or soil layer with highly confined aquifer. The destabilizing seepage force has severe effect on the stability of tunnel face (Pan and Dias, 2016). In engineering design and construction, the effect of seepage on the support pressure maintaining face stability, must be considered with caution. Although some theoretical and numerical models (Lee and Nam, 2001; Lee et al., 2003; Perazzelli et al., 2014; Lü et al., 2017a; Lu et al., 2017b; Perazzelli et al., 2017) have been proposed to study the tunnel face stability under seepage condition, the simplification or assumption introduced in them needs experimental validation.

Centrifuge and 1 g physical model tests have been used to study the face stability of shield tunnel (Sterpi and Cividini, 2004; Meguid et al., 2008; Kirsch, 2010; Chen et al., 2013; Min et al., 2015; Budach and Thewes, 2015). The adoption of advanced processing technology, i.e. X-ray CT scanner (Takano et al., 2006) and digital camera recording and image processing (Kirsch, 2010; Idinger et al., 2011), make the failure mechanism of tunnel face be visually shown. The failure zone of tunnel face was shown to be affected by the overburden on ground (Kirsch, 2010). In medium dense sand, the tunnel face shows a combination of prismatic wedge and vertical chimney collapse mode, and the cover-to-diameter ratio has little effect on the limit support pressure when the tunnel is deep enough (Ahmed and Iskander, 2012; Chen et al., 2013). Same failure mode was obtained from large-scale model tests of a large cavern group with large depth (Zhu et al., 2010). Model test of EPB shield tunnel showed that the support pressure at active failure state is linearly proportional to the tunnel diameter but is irrelevant to the

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geometry (Berthoz et al., 2012). The seepage force on the tunnel face was analyzed by model tests under steady groundwater flow condition (Lee et al., 2003). The influence of seepage on the ground reaction curve was studied and the reduction of soil arching was shown (Lee et al., 2006; Shin et al., 2010). The influence of hydraulic pressure on the minimum safety thickness of rock wall of tunnel face was carried out by model tests (Jiang et al., 2017). However, due to the complexity, the seepage flow around tunnel face and its influence on the failure mode and support pressure were scarcely studied by experiments.

To investigate the failure process of shield tunnel face in dry sands, submerged sands under undrained and steady seepage conditions, 9 physical model tests were conducted. The failure process of a tunnel face was modeled by moving a rigid plate, which was used to maintain the initial stability, backward from soil. The displacement-earth pressure curve on the centerline of tunnel was monitored. The results showed that seepage induces a large increase in the limit support pressure (equivalent to the earth pressure at failure state), and the ratio of limit support pressure with initial earth pressure is irrespective of water level. The flow line around the tunnel face under steady seepage condition was traced by the infusion of pigment. The PIV image analysis of the photo taken by HD camera precisely captured the failure process of the tunnel face. The ultimate failure mode is a combination of prismatic wedge and vertical chimney, and the inclination of wedge under seepage is much smaller than those ones under undrained and dry conditions.

2. Physical model tests

2.1. Test setup

The schematic sketch of the physical model test is shown in Fig. 1. The adopted scaling factor for the model and prototype is 1:100; the 150 mm diameter of the model tunnel corresponds to the prototype of 15 m. One needs to be aware that it is hard to replicate all details from the prototype, i.e. the stress level in the model test is much lower than that in the field. The scaling law and size effect should be carefully considered so that reasonable results are ensured. The prototype sand was used in the model test. To minimize the grain size effect, the ratio should satisfy $D/d_{50} > 175$ (D is the tunnel diameter, d_{50} is the mean grain size of the sand) (Kirsch, 2010). To avoid modeling errors caused by scaling law if shear band and dilation behavior occurs, the initial material state of the model tunnel should be loose enough. One side of the model box was made of transparent glass, and the other three sides were made of aluminum plates with thickness 15 mm. The isolated area inside of the model box was used to install controlling system. The inner dimensions of the model box were 1000 mm × 500 mm × 1080 mm (length × width × height). By making use of symmetry, a half tunnel cross section was considered, and the vertical plane of symmetry was placed on the transparent glass side. To keep a constant water level and generate steady seepage, a water circulation system was equipped. The circulation system included two tanks and a pump, one tank was set under the tunnel model to gather the flowed water, and another one was set outside to supply water. The pump kept working to make a constant water level. An infusion apparatus was equipped to trace the water flow; different color pigment was infused into the model tunnel to obtain the flow line.

The support shield was composed of a 300 mm long semi-cylindrical steel shell; the diameter of the shell was 150 mm and the thickness was 5 mm. The soil around the opening of the tunnel was supported by a rigid plate, and the plate was made of a 3 mm semi-circular permeable stone rimmed by an aluminum frame. The rigid plate, which is connected to a linear actuator through a steel rod, was controlled to move backward from the soil. The horizontal displacement of the plate can be measured by a LVDT (linear variable differential transducer) with accuracy of 0.75 μm. An earth pressure transducer was placed on the center of the tunnel face to record the variation of pressure. A HD digital camera was set against the glass wall to record the deformation process during testing. The test program is shown in Table 1. The cover-to-diameter ratio C/D was set as 0.5, 1, and 2 to study the effect of burial depth on tunnel face stability. The water levels H_w in the model tests under undrained and seepage conditions were set as 1D, 2D, and 3D.

2.2. Soil properties

Chinese Fujian standard sand with round to sub-round particle shapes was used in the model tests. The sand composition is 98.23% quartz, 1.21% aluminum oxide, and 0.05% magnetite. The particle size distribution curve is shown in Fig. 2. The physical properties of the

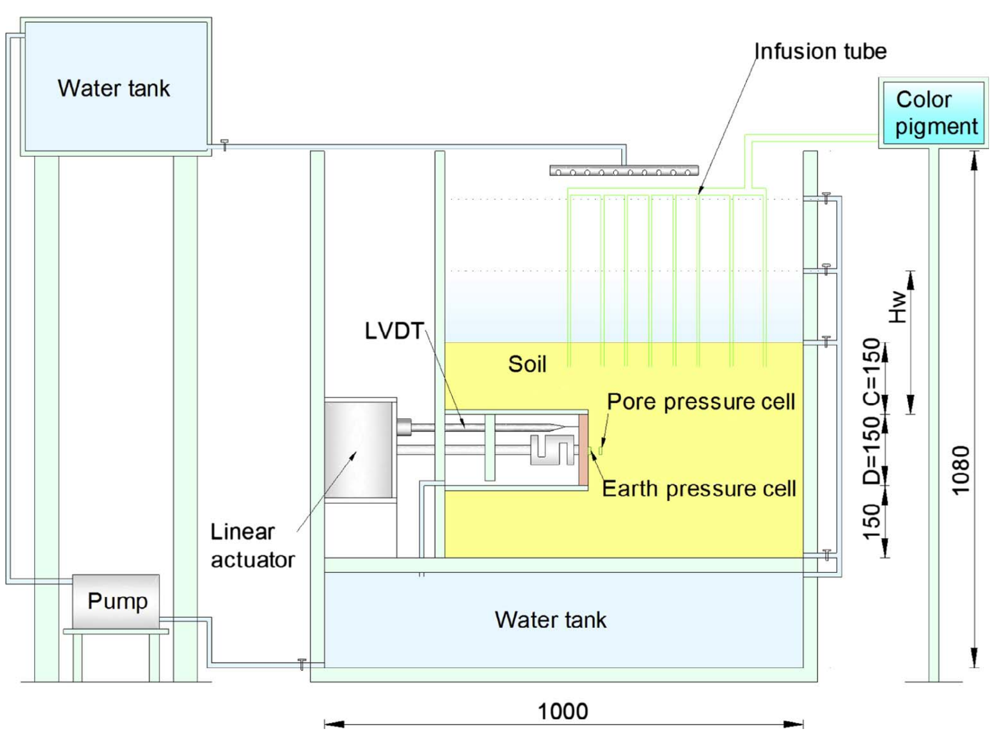

Fig. 1. Schematic sketch of the model test (dimension size: mm).