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Centrifuge investigation into the effect of new shield tunnelling on an existing underlying large-diameter tunnel

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ABSTRACT

A centrifuge model test was carried out to investigate the effect of new shield tunnelling on an existing underlying large-diameter tunnel. Three construction steps of a new shield tunnel were simulated in the test. Soil excavation with ground loss and grouting in each step was simulated by discharge and injection of a dense solution. The vertical displacement and the longitudinal stress of the existing tunnel, as well as the pore water pressure at its spring line, were measured. The vertical displacement and the longitudinal stress of the existing tunnel increase as a result of the excavation of the new shield tunnel. However, the vertical displacement and the longitudinal stress decrease when grouting is injected for the new tunnel. The vertical displacement and the longitudinal stress exhibit an approximately linear change with increases in ground loss ratio and grouting ratio of the new shield tunnel. In the test, the heave zone of the existing tunnel is within 39 m of the axis of the new shield tunnel. The variation in pore water pressure at the spring line of the existing tunnel is low during construction of the new shield tunnel. Grouting is an effective measure to mitigate the responses of the existing tunnel.

1. Introduction

In congested urban areas of Shanghai, more and more subway tunnels and river-crossing tunnels have been constructed to meet the needs of increasing transportation (Shen et al., 2009, 2010, 2014; Wu et al., 2014). Consequently, new tunnels are inevitably constructed across existing tunnels (Klar et al., 2008; Li and Yuan, 2012; Liao et al., 2009; Marshall et al., 2010). In order to maintain services and to ensure the safety of existing tunnels in very soft clays (Chang et al., 2001a, b; Yin et al., 2009, 2010, 2011; Shen et al., 2013a, b), it is necessary to investigate the influence of new tunnelling on adjacent existing tunnels, particularly aging tunnels in a complicated geological environment. There exist many aging river-crossing tunnels in Shanghai. As a typical case, this paper considers a scenario, in which a new subway tunnel is constructed perpendicularly over an existing river-crossing tunnel. The river-crossing tunnel has a diameter of 14.5 m. Fig. 1 illustrates this situation.

In recent decades, field observations and theoretical analyses have been performed to investigate the effects of overlying excavation on existing tunnels (Hu et al., 2003; Huang et al., 2006; Sharma et al., 2001; Zhang et al., 2013). Numerical analyses have also been conducted to estimate the effects of overlying excavation on existing tunnels (Dolezalova, 2001; Jiang and Yin, 2012; Li and Du, 2012a, b; Liu et al., 2009, 2011). However most of these studies did not investigate the effect of overlying tunnelling on existing large-diameter tunnels in detail.

In a geotechnical centrifuge test, the stress state of a model is the same as that in the prototype. Moreover, a geotechnical centrifuge test is highly reliable, controllable and stable. Thus, centrifuge model testing in shield tunnel modelling has developed in recent decades (Meguid et al., 2008; Ng et al., 2013; Nomoto et al., 1999). Centrifuge model testing is a suitable approach, which can not only simulate the interaction between tunnels and soil, but can also be used to carry out quantitative research on relevant parameters, to simulate tunnelling over an existing large-diameter tunnel. However, there is very limited case study into centrifuge

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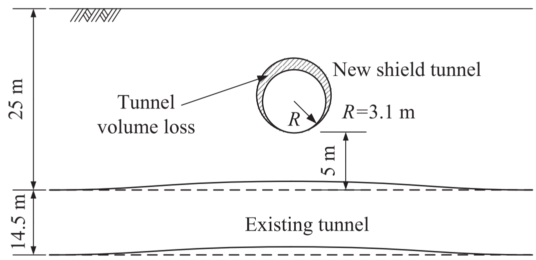

Fig. 1. Schematic illustration of the problem.

testing performed to investigate the responses of existing tunnels due to overlying tunnelling.

In this paper, a centrifuge model test was carried out to investigate the effect of new shield tunnelling on an existing underlying large-diameter tunnel. The construction process of a new shield tunnel, including soil excavation, ground loss, and grouting, was simulated in the test. The vertical displacement and the longitudinal strain of the existing tunnel were measured during the construction process of the new shield tunnel, as well as the pore water pressure at the spring line of the existing tunnel.

2. Centrifuge model test

2.1. Model configuration and materials

The geotechnical centrifuge used in the test is located at Tongji University in China, and has an effective radius of 3 m, a maximum payload of 2 tonnes (at 75 g), and a maximum centrifugal acceleration of 200 g. The geotechnical centrifuge is composed of a power system, a rotational system, a data acquisition system, a control system, and a video surveillance system. The centrifuge can keep running for 24 h. The strong box designed for the centrifuge has an internal plan area of 0.7 m by 0.9 m and an internal height of 0.7 m. The test reported in this paper was carried out at an acceleration level of 100 g. Consequently, the dimensions of the prototype were scaled down by a factor of 0.01, while the stress and strain were scaled by a factor of 1.

The prototype of the existing tunnel referred to the Jungong Road River-crossing Tunnel in Shanghai, which has an external diameter of 14.5 m and an internal diameter of 13.3 m. The maximum longitudinal slope of this tunnel is 4.5%. It passes through about 6 soil layers in the longitudinal direction. The soils around it are mainly soft silty clay. This type of soil has a high water content, low shear strength, high compressibility, and high sensitivity. Therefore, it is important to reduce the disturbance to the surrounding soil of this tunnel when a new tunnel is constructed. In order to avoid leakage of water, low deformation and small displacement of this tunnel are strict requirements, as this tunnel is beneath the Huangpu River and the surrounding soil is in a saturated state. The structure of the new shield tunnel was based on the Shanghai metro tunnels, of which the external and internal diameters are 6.2 m and 5.5 m, respectively.

The layout and the dimensions of the model are presented in Fig. 2, in which the model unit is used. The model represents a prototype where a new shield tunnel is constructed perpendicular to an existing tunnel with a buried depth of 25 m (from the ground surface to the existing tunnel crown). The vertical clearance from the invert of the new shield tunnel to the crown of the existing tunnel is set at 5 m.

The basic characteristic of geotechnical centrifuge testing is that the model can be made using prototype material. The stress state of the model in a centrifuge test is the same as that of the prototype, as long as the centrifugal acceleration is based on the ratio of prototype dimension and model dimension. Therefore, the grey silty clay on site, in which the existing tunnel is mainly situated, was taken to simulate the ground in the centrifuge test. The mechanical and physical properties of the grey silty clay are given in Table 1. The thickness of the existing tunnel lining is 6 mm after scaling down by a factor of 0.01, so the model tunnel cannot be made from concrete. A hollow plexiglass cylinder, with a thickness of 7.5 mm and a Young's modulus of 3 GPa, was used to simulate the existing tunnel. The use of this cylinder ensured that the longitudinal bending stiffness of the existing tunnel model was equivalent to that of the existing tunnel prototype.

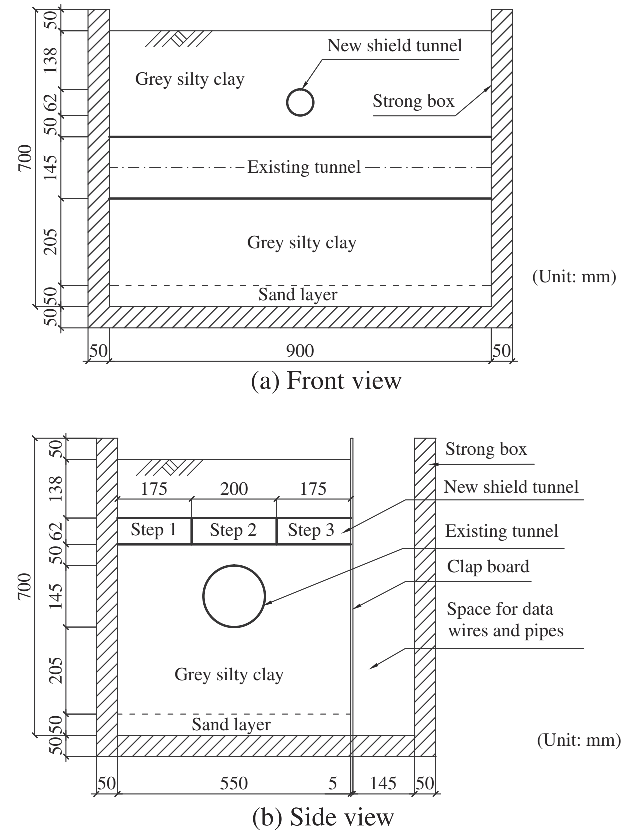

Fig. 2. Configuration of centrifuge model.

Table 1
Soil properties.

Modulus of compressibility (MPa)	3.34
Void ratio	1.2
Water content (%)	44
Unit weight (kN/m^3)	17.8
Cohesion (kPa)	14
Angle of friction (degrees)	19.2
Permeability coefficient (cm/s)	9×10^{-8}

2.2. Data acquisition

The vertical displacement and the longitudinal internal force of the existing tunnel were the main focus of the centrifuge test, since these indexes can perfectly reflect the responses of the existing tunnel due to the overlying shield tunnelling.

Eight displacement transducers, arranged in a line at the crown of the existing tunnel model, were used to measure the vertical displacements of the existing tunnel, and the intervals between