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An improved method to calculate the vertical earth pressure for deep shield tunnel in Shanghai soil layers

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ABSTRACT

Previous studies on field monitoring data indicate that vertical earth pressure would be overestimated by the Terzaghi theory for a deeply buried shield tunnel, which is widely adopted in tunnel design. A kinematic mechanical model was proposed to evaluate its influence on vertical earth pressure and implementation into the finite element program in this paper. To investigate the vertical earth pressure, a numerical study using the commercial software of PLAXIS was conducted on the vertical earth pressure distribution on a single shield tunnel, considering different tunnel diameters and burial depths in sandy and clay layers, such as Shanghai soil strata. Based on finite element model results, the existing problems such as soil displacement around tunnel, earth pressure distribution, collapsed soil mass width and sliding friction in the Terzaghi loosening earth pressure formula for a sand layer were discussed. Then, a feasible calculation method for vertical earth pressure on the tunnel lining was proposed. Through comparisons between calculated results and field measurements, the improved formulas were verified, providing a reference for future designs of deep underground structures in Shanghai Soil Layers.

1. Introduction

Utilization of deep underground space solves the problem regarding shortage of shallow underground space in Shanghai (Ma and Najafi, 2008; Qiao and Peng, 2016; Qiao et al., 2017; Zhao et al., 2016). Overestimation of vertical earth pressure acting on tunnel lining would increase the amount of reinforcement and cross-sectional area of tunnel lining and then project cost would be increased, especially for deeply buried tunnel [H/D (the ratio of tunnel buried depth to tunnel diameter) > 2 referring to Shanghai code DG/TJ08-2033-2008]. Therefore, evaluating earth pressure accurately is very important for a rational design.

The design code of a shield tunnel in China is similar to JSCE (1996), in which the earth pressure acting upon the segment lining is calculated by the overburden pressure or Terzaghi's loosening earth pressure, according to the condition of the stratum and the overburden height only. However, the actual earth pressure cannot be predicted correctly by conventional methods, especially for a deep shield tunnel in Shanghai soft layers. The field measured vertical earth pressure of an interval tunnel of Shanghai Metro Line-2 in a soft clay layer (the buried depth is 14 m and the diameter is 6.2 m) was 204.5 kPa, greater than the full overburden calculation (Jiang and Hou, 2003). The vertical earth pressure measurement of a metro shield tunnel in a sand layer (the buried depth is 34 m, and the diameter is 11.2 m) was only approximately 80% of the Terzaghi theory calculation (Li et al., 2015). Obviously, the current theories underestimate the earth pressure acting on tunnel in clayey soils while overestimate the earth pressure acting on tunnel in sandy soils.

Some researchers have focused on this problem in the last few decades. The field measurements have recently shown that the loads acting on the tunnel lining adopted in the design might be greater than actual loads, particularly in the case of good ground conditions (Koyama et al., 1995; Koyama, 2003). However, there was no detailed analysis for this phenomenon, and no further calculation model was proposed. A new calculation model, modified from the Terzaghi arching model had been proposed by Zhang et al. (2016) to specifically predict the soil pressure acting on the deep burial jacked pipes, providing a reference to calculate the vertical earth pressure acting on the shield tunnel. Further research is needed for deep burial shield tunnel. Based on some experimental studies, various methods of determining radial stresses considering excavation procedure and lining installation have been proposed and discussed (EI-Nahhas et al., 1992; Kim et al., 2006,). However, these methods cannot accurately predict the distribution of the vertical earth pressure acting on the tunnel lining. It is necessary to perform more in-depth investigations on vertical earth pressure for a deep shield tunnel in soft soil layers.

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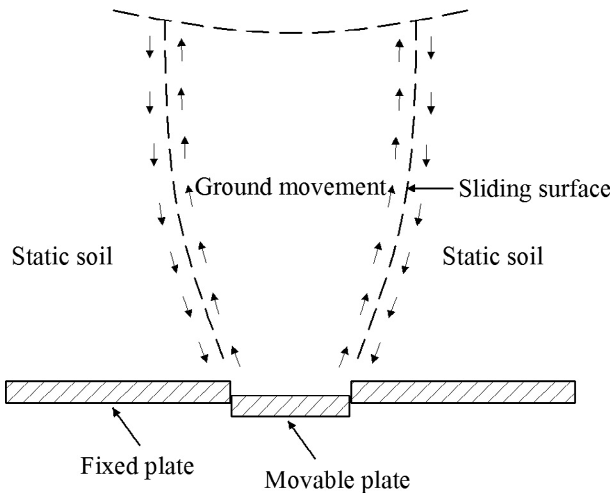

Fig. 1. Schematic diagram of trapdoor tests (Terzaghi, 1936).

In this paper, first, the full overburden theory and Terzaghi theory were described in detail. Second, one kinematic mechanical model (PLAXIS) was proposed for evaluating the vertical earth pressure. Third, to investigate the vertical earth pressure, a series of finite element simulations were conducted on the vertical earth pressure distribution on shield tunnels in different soil layers, considering different diameters and burial depths. Then, based on the finite element method result, the influence of soil type, burial depth and tunnel diameter on the vertical earth pressure distribution was analysed. Subsequently, the assumptions adopted by the Terzaghi theory were discussed, including the width of the collapsed body, the distribution pattern of the vertical earth pressure and the upward friction calculation area (shear band). Finally, a new model to calculate vertical earth pressure was proposed based on improved assumptions, and its applicability was verified. The improved formula proposed in this study can contribute to an improvement in predicting the vertical earth pressure in shield lining design.

2. Outline of vertical earth pressure

The modified usual calculation method (JSCE, 1996) is generally adopted to estimate the earth pressures on the shield tunnel lining in design. The external loading, including earth and groundwater pressures, is considered for use in the above modified calculation method. There are two cases that assume the vertical earth pressure acting on the upper part of the segmental ring. One case is assumed to be a full overburden, and the other consider soil shear strength. For both pressures, a uniform load is assumed. The latter is calculated by the Terzaghi loosening earth pressure theory.

2.1. Full overburden theory

According to the full overburden theory, the vertical earth pressure on tunnel linings is equal to the overburden weight in the range of the tunnel width based on static equilibrium. The formula of full overburden theory can be expressed as follows:

$$P = \sum \gamma_i h_i \tag{1}$$

where P is the vertical earth pressure on the top of the tunnel, γ_i is the soil weight, h_i is the thickness of the soil layer. However, previous studies indicate that the field measured earth pressure on linings is usually less than the full overburden calculation, ignoring stress transfer and the effect of soil arching (Hashimoto et al., 2002; Koyama, 2003; Mashimo and Ishimura, 2003).

2.2. Terzaghi loosening earth pressure theory I

Based on the trapdoor tests (Fig. 1), a loosening earth pressure theory was introduced by Terzaghi (1936), and a calculation model of downward earth pressure on the upper part of a tunnel was proposed. Based on the balance theory of loose medium and the concept of stress transfer, the influence of tunnel diameter and physico-mechanical properties (internal friction angle and cohesion) of soil was considered to calculate the Terzaghi loosening earth pressure. Two assumptions are adopted in the Terzaghi loosening earth pressure theory: (1) the soil is a loose body with a certain adhesive force, which conforms to the Mohr-Coulomb failure criteria; and (2) the shearing bands yield from two bottom corners of a tunnel cross-section along oblique lines, and turn to vertical lines after passing the level of the tunnel crown, ultimately

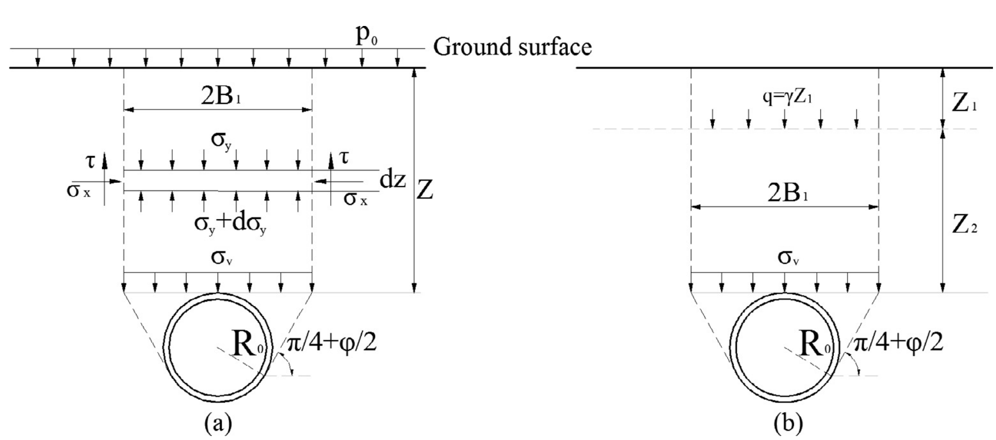

Fig. 2. Schematic diagram of Terzaghi arching models, (a) shearing bands extended to the ground surface (Arching mode I); (b) shearing bands ceased below the ground surface (Arching model II) (revised from Terzaghi (1943)).