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Influence of multi-layered soil formation on shield tunnel lining behavior

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ABSTRACT

The recent development of larger shield-driven tunnels has for consequence that the tunnel face consists more frequently of multi-layered formations. However, most tunnel designs are still currently conducted in the homogeneous soil condition. In this study, a series of 1-g plane model tests and FEM analyses were carried out to investigate the influence of the layered soils in terms of their relative stiffness and thickness on the lining behavior (i.e. inner force and convergence). The numerical results were found to agree reasonably well with the results obtained from the model tests. For multi-layered formation, a linear increase of the relative thickness of the sandy layer could reduce non-linearly the magnitude of both the moment and the convergence. The distributions of the bending moment and of the convergence along the tunnel perimeter were found to be strongly dependent on the relative stiffness of the layered formations. However, the multi-layered condition has little effect on the thrust force under the condition of this test. In view of these results, some discussions on the applicability of the widely used homogenized design model for the multi-layered soil condition are finally presented.

1. Introduction

Although the interest of refined numerical models is nowadays widely recognized, tunnel engineers still prefer for practical purposes to use the simplified model with the assumption of soil homogeneity in a tunnel cross section to design the tunnel lining structure (Duddeck and Erdmann, 1985; ITA, 2004). For most of the geotechnical situations, however, the tunnels always experience the multi-layered conditions where the linings are constrained at least by two different soils (Zhao et al., 2007). It is customary to apply a large factor of safety (FS) in the tunnel design to cover the uncertainty existing in the unsatisfying assumption of the soil homogeneity for multi-layered condition. But the design with a large FS is not always conservative. The inspection data of Shanghai metro tunnels have shown that, although the linings are conservatively designed, e.g. the FS is around 2, there are still quantities of structural defects in operational tunnels (Yuan et al., 2012). Therefore, studying the effects of a multi-layered soil condition on the structural behavior of the tunnel lining appears to be necessary for the assessment of the applicability of the simplified homogeneous assumption.

The investigation of the structural behavior of the tunnel lining is often carried out using the finite element method (FEM) (Arnau and Molins, 2012; Arnau et al., 2012; Bilotta and Russo, 2013). In these FEM analyses, refined models are used to simulate the detailed behavior of the segments and the joints between segments (Blom et al., 1999; Lackner et al., 2002; Winkler et al., 2004). But the surrounding soils are often simplified by a series of Winkler springs rather than by considering a continuous medium and its associated constitutive model due to the limitation of computer powers. However, the difficulties in evaluating a proper spring constant to approximate the behavior of layered soils clearly prevent the direct application of these FEM analyses for cases of multi-layered soils.

Some field data and model test results, although limited, have contributed to the basic understandings of the structural behavior of the tunnel lining in multi-layered conditions. The bending moment of the tunnel lining in layered formations was firstly investigated by Nunes and Meguid (2009) through a series of 1-g model tests. They found that the moment decreases significantly when the depth of the overlying hard layer was closer to the depth of the tunnel crown. However, because the tunnel lining was

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Nomenclature

c	Soil cohesion
C	convergence of the model lining
D	outer diameter of the tunnel lining
EI, EA	bending and compressive stiffness of the PE pipe
E_s	soil compressive modulus
M, N	bending moment and thrust force of the model lining
L_i, L_{eq}	structural behavior in homogeneous layer i, equivalent value for mixed face condition
t_{wall}	wall thickness of model lining
t	thickness of the soil layer in mixed face
ε_{in}, ε_{ex}	bending strain of the PE pipe (in: intrados; ex: extrados)
η	transverse effective stiffness ratio
φ	soil inner friction angle

embedded in a homogeneous soft layer in their studies, it is still not clear for tunnel engineers about the influence of the extreme multi-layered condition, where multi layers contact with each other at the depth between the tunnel crown and the invert (mixed face conditions). Hence, for the purpose of an overall understanding of the lining behavior in multi-layered conditions, this extreme multi-layered condition is thus emphasized in this paper. From here on, this multi-layered mixed face condition is thus referred to as the multi-layered condition.

The field data in Pérez-Romero et al. (2007) and Sousa et al. (2011) indicated that the part of the tunnel lining in contact with expansive or soft clays in multi-layered condition experiences an extremely larger convergence than the rest of the tunnel lining contacting with a stiffer soil in comparison with its convergence. He et al. (2008) and Huang et al. (2011) conducted previously some model tests for a tunnel in a two-layered condition. They found that, in this condition, the lining behaves quite differently from that in a homogeneous soil. However, the detailed effects of layered formations (e.g. stiffness and depth of the layers) were not investigated in the above studies due to the limited tests. By carrying out some three dimensional model tests, Li et al. (2013) have found the tunnel convergences were quite different at different tunnel cross sections due to the effect of the layered formations.

On the basis of the previous studies, we try in this paper to answer the following two questions by conducting a series of 1-g model tests and the corresponding FEM simulations:

- How the layered soil condition affects the structural behavior of the tunnel lining? To be more specific, what is the influence of the relative stiffness and thickness of the different soil layers on the inner force and on the convergence of the tunnel lining?
- Can the assumption of soil homogeneity in a simplified design model be acceptable or not when the tunnel is in a multi-layered soil?

In comparison with the model tests conducted previously by the authors Huang et al. (2011), more scenarios for the layered soil condition are considered in this study, i.e., homogeneous, two-layered and three-layered soil conditions (see in Fig. 1). Some results of the measured inner force (i.e., bending moment and thrust force) and convergence are presented. Although the test results are preferred, the high costs for model tests limit the number of tests. Then, a simplified two dimensional FEM model is proposed and validated by the test results. Parameter analyses are complemented using the validated FEM model to better understand the multi-layered effects on lining structures. Finally, the applicability of the homogenized model for the design of segmental linings in multi-layered soil is discussed. It should be noted that, in agreement with the current practice of the research on the structural behavior of segmental lining, the earth pressure is modeled by external load acting on the wish-in-place segmental lining. In this respect, the "real-life" tunnel excavation and lining installation are not simulated in this paper. The life-time performance of the

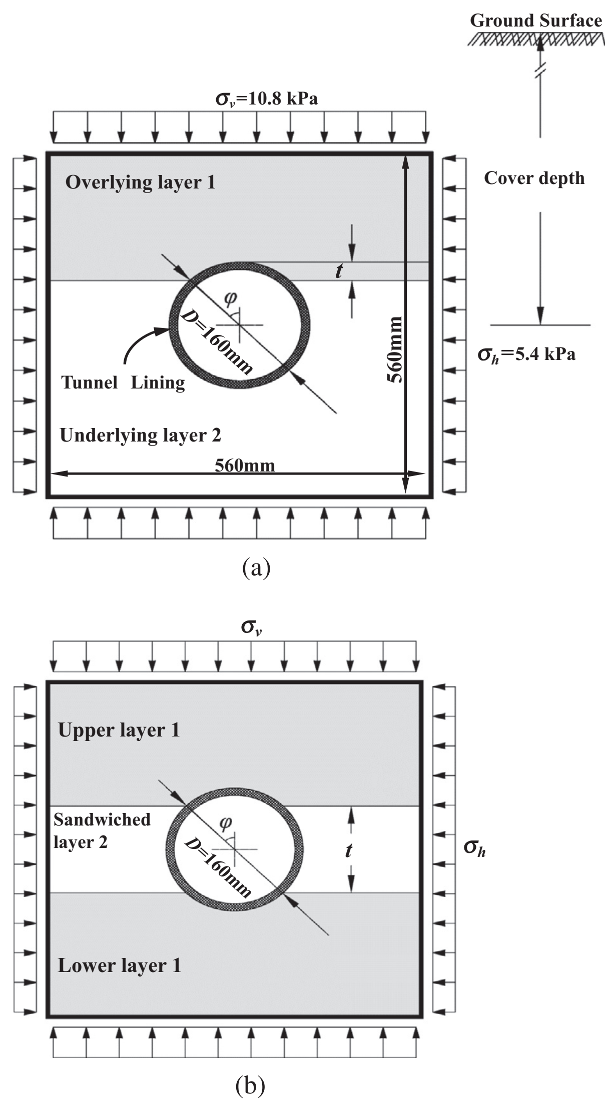

Fig. 1. Multi-layered soil conditions: (a) two-layered formation; (b) three-layered formation.

structures, especially during the operational period, is thus emphasized, whereas the short-term behavior is not considered.

2. Physical modeling

The whole setup of the model test is designed based on the schematic of Wood (1975)'s 2D plane strain model, which is widely used for the structural design of tunnel lining (see in Fig. 1). In the test, the outer diameter of the tunnel lining (hereafter, tunnel