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Tunnel stability and arching effects during tunneling in soft clayey soil

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Abstract

A series of centrifuge model tests and numerical simulations of these tests were carried out to investigate the surface settlement troughs, excess pore water pressure generation, tunnel stability and arching effects that develop during tunneling in soft clayey soil. The two methods were found to provide consistent results of the surface settlement troughs, excess pore water generation, and the overload factors at collapse for both single and parallel tunneling. The arching ratio describes the evolution of the arching effects on the soil mass surrounding tunnels and can be derived from the numerical analysis. The boundaries of the arching zones for both single tunneling and parallel tunneling were determined. In addition, the boundaries of the positive and negative arching zones were also proposed.

Keywords: Arching effect; Tunnel stability; Centrifuge modeling; Numerical modeling

1. Introduction

Tunneling in soft clayey soils has become very popular in recent years because it is one of the best construction methods for building mass rapid transit systems and sewage collection systems in densely populated cities. As the face of a tunnel is advanced, a means of supporting the ground close to the face may be needed; without such support, collapse might occur due to gross plastic deformation of the soil. Moreover, tunneling inevitably induces varying degrees of ground movement towards the tunnel opening and results in detrimental effects on nearby facilities, such as shallow foundations, piles, existing tunnels and other pipeline systems. Taking appropriate measures to protect nearby facilities before excavation is an important part of engineering practice. The prediction of tunneling-induced ground movements during excavation of soft ground tunnel has been carried out using various methods, including empirical methods derived from field observations (Peck, 1969; Clough and Schmidt, 1981) and centrifuge modeling (Mair et al., 1981; Wu and Lee, 2003; Lee et al., 2004), or numerical and analytical methods (Lee and Rowe, 1991).

Terzaghi (1943) explained how stress transfer from yielding parts of a soil mass to adjacent non-yielding parts leads to the formation of an arching zone. This problem has two modes of displacement, depending on whether the trap door is translated into the soil (passive mode) or away from it (active mode). The passive mode can be used for the evaluation of the uplift force of anchors, or of any buried structure that can be idealized as an anchor. The active mode can be used to study the gravitational flow of granular material between vertical walls (the silo problem) or the ground pressure on tunnel liners. Ladanyi and Hoyaux (1969) performed a series of model trap-door tests

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under 1 g conditions in order to check the validity of the classic bin theory. Handy (1983) analyzed soil arching action behind retaining walls, and Wang and Yen (1973) carried out this analysis for slopes. Nakai et al. (1997) performed a series of physical model tests under 1 g conditions and carried out numerical analysis of these tests to investigate the arching effect. They found that the results obtained from the model tests were in good agreement with those obtained from the numerical analysis. Park and Adachi (2002) performed model tests under 1 g conditions to simulate tunneling events in unconsolidated ground with various levels of inclined layers. They found that remarkable non-symmetrical distributions of the earth pressure arose when a tunneling event took place in inclined layers with 60° of inclination. Stone and Newson (2002) presented the results of a series of centrifuge tests designed to investigate the effects of arching on soil–structure interaction. Koutsabeloulis and Griffiths (1989) implemented a finite element method to investigate the trap-door problem. The concept of soil arching was recently adopted in the analysis of the mobilization of resistance from passive pile groups subjected to lateral soil movement (Chen and Martin, 2002).

When tunneling is conducted in the vicinity of existing pile foundations, the axial load transfer mechanism and failure mode on existing piles vary depending on the distance between the existing piles and the new driving tunnel and relative elevation of the piles with respect to the centerline of the tunnel (Lee and Chiang, 2004). These behaviors result from the complicated redistributions of stress around tunnels during tunneling. Hence, the stress distribution in the vicinity of a tunnel or of several tunnels stacked closely in an underground station needs to be established before appropriate protection measures for nearby existing piles can be implemented. By deepening our understanding of the arching effect in various geotechnical problems, we can improve the design of the protection measures required for existing underground structures nearby new tunneling.

Both centrifuge and numerical modeling were used in the study. The stability of a tunnel, the movements of soil mass, the evolution of stress on the soil mass around a tunnel, and the boundaries of the arching zone during tunneling in clayey soils are investigated and discussed. Firstly, a series of centrifuge model tunnel tests was conducted. A finite difference program (FLAC) was then chosen for numerical analysis of the system described by the centrifuge model to provide insight into the arching mechanism and the boundaries of the arching zone during tunneling. Finally, the results from the numerical modeling and the measurements from the centrifuge modeling were compared in order to assess their predictions.

2. Centrifuge and numerical modeling

2.1. Centrifuge modeling

The basic principle of centrifuge modeling is to recreate the stress conditions that are present in full-scale constructions in models of greatly reduced scale. The full-scale system modeled with a centrifuge model (with dimensions N times larger than those of the model if it is tested in an acceleration that is N times earth gravity) is referred to as the prototype. It is intended that the prototype should include all the important characteristics of the field situation of interest. Centrifuge modeling provides an opportunity to study for example the ground responses due to tunneling before and after collapse; collapse is of course not permitted to occur in the field.

This experimental study was undertaken in the geotechnical centrifuge at the National Central University. The NCU centrifuge has a nominal radius of 3 m and is capable of accelerating a 1 tonne model package to 100 g and 0.55 tonne to 200 g. In the single-tunnel model tests, one model tunnel, 60 mm in diameter, was embedded at various depths specified by the cover-to-diameter ratio (C/D). In the parallel-tunnel model tests, two model tunnels (60 mm in diameter) were separated by a specified center-to-center distance (d) (as shown in Fig. 1), and buried at various depths specified by the cover-to-diameter ratio (C/D). All the model tests reported in this study were carried out under a centrifugal acceleration of 100 g in order to model a prototype tunnel with a diameter of 6 m embedded at depths with the tested C/D ratios.

The soil used in the model tests had a plasticity index of 18 and was classified as CL in the Unified Soil Classification System. The soil slurry was remolded at about twice its liquid limit in a mixer and poured into the consolidometer. Consolidation pressure was applied in five stages, with a final pressure of 196 kPa. Further details of the soil bed preparation can be found in Wu and

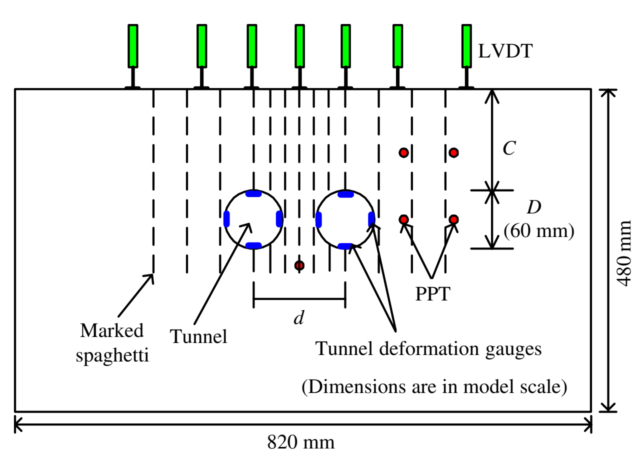

Fig. 1. Setup of test package for two parallel tunnels (model scale).