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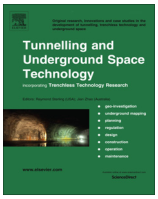

Response analysis of nearby structures to tunneling-induced ground movements in sandy soils

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ABSTRACT

This study examined the effects of tunneling-induced ground movements on the nearby structures in sandy soils considering the soil–structure interactions of different tunnels, structures, ground, and construction conditions. The investigation relates the level of structural distortion and damage to different tunnel field conditions. For this purpose, extensive numerical parametric studies were conducted and the results were compared with some field cases. The discrete element method (DEM) has been used to model structural cracking when the shear and tensile stress exceeds the maximum shear and tensile strength. Two different structures, brick-bearing and brick-infilled frame structures, were considered, and the distortion and cracking induced in the structures was related to different tunnel field conditions. A relationship that correlates the tunnel depth to diameter (Z/D) ratios and ground loss conditions with a level of structural damage with different ground and structure conditions was developed to integrate the study results into a design frame in engineering practice. The relationship developed can be used practically to assess the structural damage in the design stage of tunnel constructions under a range of tunnel field conditions. These results will provide a background for a better understanding of how to control and minimize the damage of the structure to tunneling-induced ground movements in sandy soils under different tunnel, structure, ground, and construction conditions.

1. Introduction

The number of tunnel constructions in congested urban spaces are increasing for many reasons, such as the development of underground transit systems and installing a range of utilities. At the same time, there has been increasing public concern regarding the effects of tunneling-induced ground movements on the adjacent structures. Tunneling-induced ground movement can distort and damage the adjacent structures, causing several problems, such as the loss of property, construction delay, and increase in project cost.

To minimize these problems, it is important to have a reliable damage assessment of the adjacent structures as well as an appropriate protection measure prior to tunnel excavation. Reasonable damage assessments require a better understanding of the complex soil–structure interactions among the tunnel, structure, ground, and construction conditions. A failure to understand these interactions can lead to the implementation of unnecessary protection measures, unnecessary cost and unsatisfactory results.

The response of the adjacent structures to excavation-induced ground movements has been investigated. Notable studies include Breth and Chambosse (1974), Attewell (1977), Boscardin and Cording (1989), Burland (1995), Boone et al. (1999), Finno et al. (2005), Schuster et al. (2009), Son and Yun (2009), Son et al. (2008), and Son and Cording (2005, 2011). Compared to previous studies, the present paper reports the results of a systematic integration of various tunnel conditions into a design frame, which guides the relationship between the different tunnel conditions and structural damage.

In general, a structural response depends on a range of factors including the tunnel and structure conditions as well as the ground and construction conditions. Although field observations are of major importance in assessing the structural response to a nearby tunnel excavation, numerical model tests have the ability to add unique perspectives to an evaluation of the structural response. This study examined the structural response to tunneling-induced ground movements in sandy soils based on extensive numerical model tests. The structural distortion and damage were examined under a controlled variation of the tunnel (tunnel depth and diameter), structure (brick-bearing structure and brick-infilled frame structure), ground (looser and denser soil), and construction (ground loss) conditions. The results are expected to provide a

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background for a better understanding of how to control and minimize the building damage to the nearby structures due to tunneling-induced ground movement in sandy soils under many different field conditions.

2. Tunneling-induced ground movements and structure responses

Tunnel construction in urban areas can cause damage to the adjacent structures due to tunneling-induced ground movements. Ground movement is largely affected by the tunnel condition (depth and diameter), ground condition (loose sand and dense sand) and construction condition (ground loss in a tunnel caused by over excavation, delayed support and grouting installation, support deflection, and face instability, such as raveling or flowing). The ground loss is defined as the volume lost into a tunnel divided by the theoretical tunnel volume. Tunneling-induced ground movements differ from building self-weight-induced settlements in that the former generally have much larger horizontal displacements, which can cause more severe structural damage. Therefore, to assess the structural damage reasonably, it is essential to estimate the horizontal ground movement as well as the vertical ground settlement, where a structure is located.

Peck (1969) assembled empirical information of the tunnel case histories in different types of ground and suggested an error function or normal probability curve for the shape of the settlement trough as follows.

$$S = S_{max} \cdot e^{-\frac{x^2}{2i^2}}$$

where S is the settlement at a distance x from the center of the settlement trough, S_{max} is the settlement at the center of the trough, i is the point of inflection of the curve, and x is the distance from the center of the trough (refer to Fig. 1).

The volume (Vs) of the settlement trough is equal to $2.5 \times i \times S_{\text{max}}$. The points of inflection of the curve are located at a distance, i, on either side of the center line of the trough. The location of the inflection points (i) were determined from the relationship between the tunnel depth (Z) and radius (R), as shown in Fig. 2. Therefore, the ordinate of the normal probability curve can be determined at any distance from the tunnel center line in the transverse direction, provided that the inflection point and maximum settlement can be determined.

The horizontal surface displacement can have a significant effect on the damage to the structures. On the other hand, it has not been commonly measured in the field and there is insufficient field data and information to estimate the horizontal surface displacement profile with the same degree as the settlement profile. Nevertheless, O'Reilly and New (1982) provided an equation to estimate the tunneling-induced horizontal displacements as follows:

$$S_h = S_{max} \cdot 1.65\frac{x}{i} \cdot e^{-\frac{x^2}{2i^2}}$$

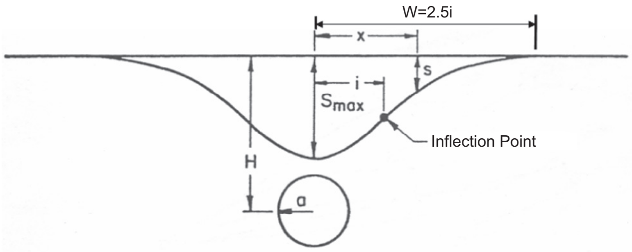

Fig. 1. Error function or normal probability curve to represent a settlement trough above the tunnel (after Peck, 1969).

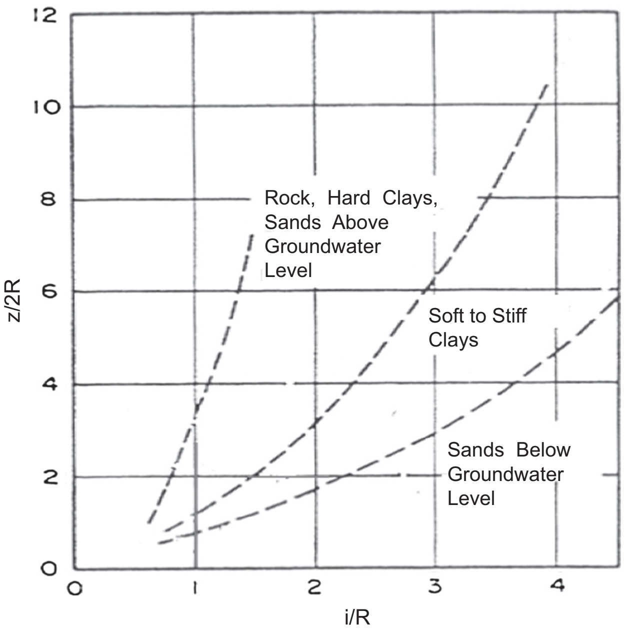

Fig. 2. Relationship among tunnel depth, tunnel radius, and inflection point (after Peck, 1969).

where S_h is the horizontal displacement at a distance x from the tunnel center line, S_{hmax} is the maximum horizontal displacement at the inflection point, and i is the point of inflection of the settlement trough.

The maximum horizontal displacement occurs at the inflection point, and in the Washington D.C Metro, it was one third of the maximum vertical displacement. Cording (1991) reported that the ratio of the maximum horizontal displacement to the maximum vertical displacement varies with the width of the trough and showed that the estimated horizontal displacement at the edge of the settlement profile can be smaller than the real displacement if the equation for estimating the horizontal displacement is used. Field studies by Cording and Hansmire (1975), Attewell (1977), and Cording (1991) revealed the ratios in the range of 0.25–0.4. From the many numerical tests, Son and Yun (2009) also reported that the maximum lateral displacements are approximately 0.35 times the maximum vertical displacements, which are consistent with field observations.

Extensive studies related to ground movements during tunneling in soil have been conducted by many investigators including Attewell (1977), Ward and Pender (1981), Attewell and Yeates (1984), Fujita (1989), and Mair and Taylor (1997).

3. Numerical analysis

The advantages of numerical analysis are that a range of conditions can be considered easily with limited time, cost and space, and reproducible analyses. This characteristic allows examinations of the response of structures to tunneling-induced ground movements under a range of conditions.

The numerical approach used in this study is similar to that of previous studies (Son and Cording, 2011) but is described again briefly. The 2-D Universal Distinct Element Code (UDEC 3.1, 2000) was used to conduct the numerical tests. Each brick was modeled as a separate elastic unit and the brick/mortar contact was modeled using the Coulomb slip model, in which the contact loses strength and a crack is formed when the contact normal stress exceeds the maximum tensile strength of the contact or the contact shear stress exceeds the contact shear strength, which