Tunnelling and Underground Space Technology 56 (2016) 90–104

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

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

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ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 16 November 2015
Accepted 28 January 2016
Available online 16 March 2016

Keywords:
Tunneling
Ground movement
Clay soil
Structural damage
Damage estimation
Engineering practice
Soil–structure interaction

ABSTRACT

This study examined the effects of tunneling-induced short-term ground movements on nearby structures in clay 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 field cases. The discrete element method (DEM) was used to model structural cracking when the shear and tensile stress exceeds the maximum shear and tensile strength. Brick-bearing and brick-infilled frame structures were considered, and the distortion and cracking induced in the structures were related to different tunnel field conditions. A relationship was developed to correlate the ratios of the tunnel depth to the diameter (Z/D) and ground loss conditions with the level of structural damage for different ground and structure conditions. The study results were integrated into a design framework in engineering practice. The relationship developed was compared with observed field cases, and the results indicated that it can be used practically to assess the structural damage in the design stage of tunnel constructions in a range of tunnel field conditions in clay soils. The study results provide a background for better understanding of how to control and minimize the damage of a structure to tunneling-induced ground movements in clay 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 (1980), Boscardin and Cording (1989), Burd et al. (1994), Burland (1995), Potts and Addenbrooke (1997), Boone et al. (1999), Finno et al. (2005), Franzius et al. (2006), Schuster et al. (2009), Son and Cording (2005, 2011), and Son (2015). 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 clay soils.

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 is a companion study of the previous study (Son, 2015) for sand soils and extended the examination to clay soils for the structural response to tunneling-induced ground movements based on extensive numerical model tests and field cases. Structural distortion and damage were examined under controlled

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http://dx.doi.org/10.1016/j.tust.2016.01.032

variation of the tunnel (tunnel depth and diameter), structure (brick-bearing structure and brick-infilled frame structure), ground (soft clay and stiff clay), and construction (ground loss) conditions. All the study results were integrated to provide a structural response in clay soils under various conditions and to develop a design framework to assess building damage directly in clay soils under different conditions. A relationship was developed to correlate the ratios of the tunnel depth to the diameter (Z/D) and ground loss conditions with the level of structural damage under different ground and structure conditions. The results were compared with field cases for clay soils. The study results are expected to provide a background for better understanding of how to control and minimize the building damage to nearby structures due to tunneling-induced ground movement in clay soils under various 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 (soft clay and stiff clay) and construction condition (ground loss in a tunnel caused by over excavation, delayed support and grouting installation, support deflection, and face instability). 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 $2.5 \times i \times S_{max}$. 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.

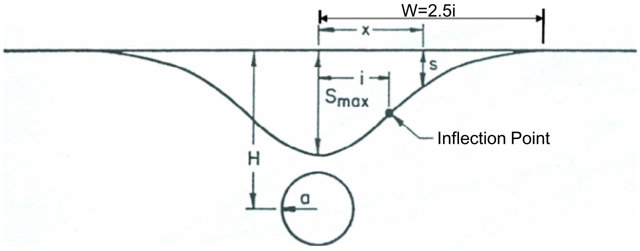

Fig. 1. Error function or normal probability curve to represent a settlement trough above the tunnel (after Peck, 1969).

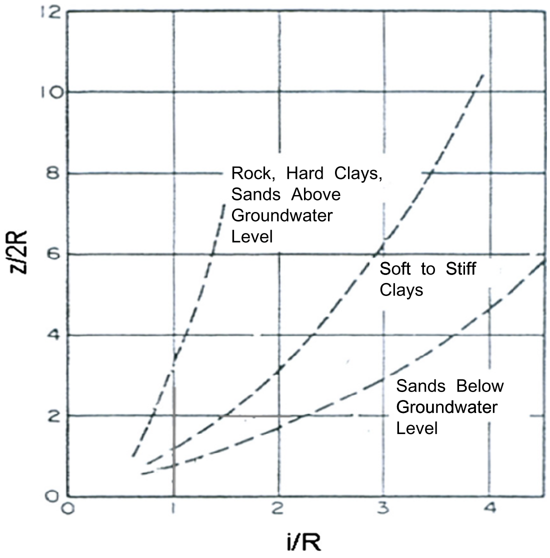

Fig. 2. Relationship among the tunnel depth, tunnel radius and inflection point (after Peck, 1969).

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:

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

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 about 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), Cording (1984), Fujita (1989), Mair and Taylor (1997), Loganathan and Poulos (1998), Chi et al. (2001), Bao et al. (2009), Ahmed and Iskander (2011), Gui and Chen (2013), Pinto and Whittle (2014), and Vu et al. (2015).

3. Numerical analysis

The advantages of numerical analysis are that a range of conditions can be considered easily with limited time, cost and space,