Tunnelling and Underground Space Technology 50 (2015) 499–506

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Effects of cover depth on ground movements induced by shallow tunnelling

Minh Ngan Vu [a,b,*], Wout Broere [a], Johan Bosch [a]

[a] Delft University of Technology, Geo-Engineering Section, Stevinweg 1, 2628 CN Delft, The Netherlands
[b] Hanoi University of Mining and Geology, Faculty of Civil Engineering, Viet Nam

ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form 11 September 2015
Accepted 13 September 2015

Keywords:
Cover-to-diameter ratio
Ground movement
Settlement
Shallow bored tunnel
Soft soil

ABSTRACT

Assessing the impact of underground construction on existing structures in urban areas is an important topic during design. In this paper, the extent of the affected area due to tunnelling is estimated, where existing foundations are influenced based on the investigation of surface and subsurface settlements. The extent of the areas where building deformation exceed allowable settlements is presented, which will provide a preliminary assessment during design on the risk on existing structures, based on allowable settlement u_{max} and slope ω_{max}. A more accurate impact area of shield tunnelling on nearby pile foundations is proposed.

1. Introduction

Shield tunnelling is often used in constructing underground infrastructure in cities due to the ability to limit settlements and damage to existing buildings. However, in an urban environment with soft overburden and buildings on pile foundations such as the North–South Line project in Amsterdam, there is a tendency to design the tunnel well below the surface and below the pile tip level in order to reduce interaction between tunnelling process and piles. This results in deep tunnels and deep station boxes. When the tunnels are located close to the surface and above the pile tip level, this would reduce the required depth of the station boxes and the construction cost. Moreover, other benefits of shallow tunnels are the low operational cost in the long-term and shorter travelling time from the surface to the platforms. Still, the tunnels should be constructed in such a manner that existing buildings are not structurally damaged, which results in a minimum required distance between tunnelling process and existing buildings. In this paper, the extent of the area that is influenced by tunnelling will be investigated in order to determine the limit distance from tunnelling to existing foundations without inducing too large building deformation.

From analysing empirical data of many shield tunnels, Peck (1969) firstly presented the settlement trough on the surface induced by tunnelling in soft soil as a Gaussian distribution. This is also confirmed by other authors (Cording and Hansmire, 1975; Mair et al., 1993; Ahmed and Iskander, 2010). Even though some studies shows that there are some deviations of the Gaussian distribution in some particular cases (Celestino et al., 2000; Jacobsz, 2003; Vorster, 2006; Farrell et al., 2012), the Gaussian curve is still used widely in research and practical design. In this study, the Gaussian curve is used to investigate the ground movement when tunnelling in order to find the effects on existing structures.

Based on the results from centrifuge test and empirical data, Mair et al. (1993) showed that the subsurface settlement profile distributes as the Gaussian curve also. The width of settlement trough at the depth z depends on the depth of the tunnel z_0 and a coefficient K depending on depth. Other studies by Moh et al. (1996), Grant and Taylor (2000) and Jacobsz (2003) based on Mair et al. (1993) proposed a limited change of K in various kinds of soil. Ahmed and Iskander (2010) noted that the equation proposed by Mair et al. (1993) to predict subsurface settlement and horizontal deformation in clay yields acceptable results in sand as well from the observation of the displacement inside transparent soil models.

Assessing the impact of underground construction on existing structures in urban area is important in design. Many studies have

* Corresponding author at: Delft University of Technology, Geo-Engineering Section, Stevinweg 1, 2628 CN Delft, The Netherlands.
E-mail addresses: N.Vuminh@tudelft.nl, vuminhngan@gmail.com (M.N. Vu).

http://dx.doi.org/10.1016/j.tust.2015.09.006
0886-7798/

Table 1
Typical values of maximum building slope and settlement for damage risk assessment (Rankin, 1988).

Risk category	Maximum slope of building	Maximum settlement of building (mm)	Description of risk
1	Less than 1/500	Less than 10	Negligible; superficial damage unlikely
2	1/500–1/200	10–50	Slight; possible superficial damage which is unlikely to have structural significance
3	1/200–1/50	50–75	Moderate; expected superficial damage and possible structural damage to buildings, possible damage to relatively rigid pipelines
4	Greater than 1/50	Greater than 75	High; expected structural damage to buildings. Expected damage to rigid pipelines, possible damage to other pipelines

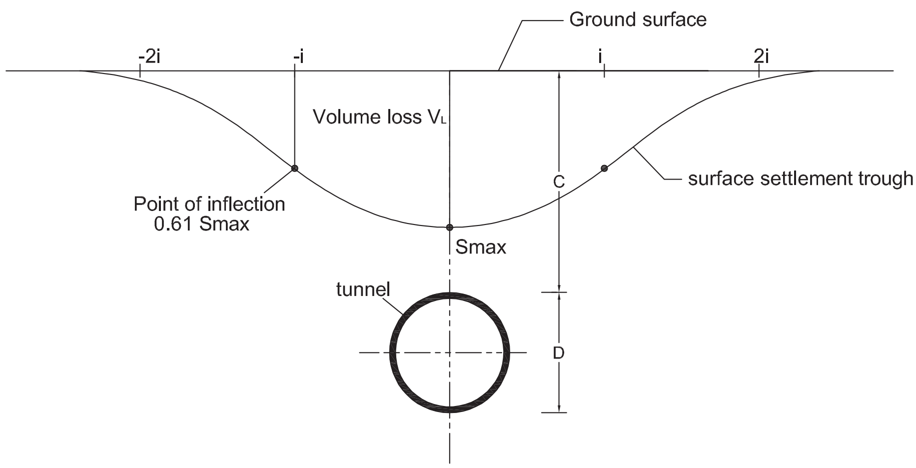

Fig. 1. Transverse settlement trough due to tunnelling (Peck, 1969).

focused on the ground movements around tunnelling and the settlement trough on the surface but research focused on the ground movements that affect nearby buildings for a first assessment the stability of the buildings and the effect of tunnelling near existing deep foundation has only recently gained interest in geotechnical studies. The affected area due to tunnelling should be estimated in order to avoid the impact on the existing foundations. The responses of building due to tunnelling have been investigated by many authors (Rankin, 1988; Boscardin and Cording, 1989; Mair et al., 1996; Franzius, 2004; Netzel, 2009; Giardina, 2013). From these, the Limiting Tensile Strain Method proposed by Boscardin and Cording (1989) has been widely used in design. This method has four steps: predicting the greenfield movement; projection of greenfield ground movement on the building; determination of induced building strains and classification of damage related to strain levels (Franzius, 2004). Table 1 shows the value of maximum slope and settlement for the building with a category damage risk assessment proposed by Rankin (1988).

In this study, the value for category 1 which is the lowest damage category to the building is used, setting the maximum slope of building $\omega_{\max} = 1/500$ and maximum settlement of building $u_{\max} = 10$ mm. These allowable values are also applied in the preliminary assessment in the three stage methodology for the assessment of risk of building damage induced by bored tunnelling indicated in Mair et al. (1996) and Burland et al. (2001). The influence of building stiffness and the difference between sagging and hogging zones of the settlement trough in this risk assessment is not taken into account in this paper. With these conditions in mind, this paper takes a look at the ground movements both at the surface and subsurface when tunnelling in soft soils with deep foundations with the following targets:

- Define the areas where ground movements remain below the acceptable limits for the buildings.
- Estimate the effect of C/D on the extent of this limited ground movement area.

2. Effect of *C*/*D* on surface settlement

The transverse settlement shape of the ground surface shown in Fig. 1 as a Gaussian distribution (Peck, 1969) can be estimated from the maximum settlement $S_{v,\max}$ at the surface directly above the tunnel location and the trough width i as follows:

$$s_v = S_{v,\max} \exp\left(\frac{-x^2}{2i^2}\right) \quad (1)$$

The volume loss can be estimated by:

$$V_s = \sqrt{2\pi} i S_{v,\max} \simeq 2.5 i S_{\max} \quad (2)$$

where V_s is the volume of settlement trough per unit tunnel length.

For a circular tunnel, V_s is often calculated via the volume loss V_L as the percentage of the notional excavated tunnel volume (Mair et al., 1993):

$$V_s = V_L \frac{\pi D^2}{4} \quad (3)$$

The volume loss around tunnel includes loss volumes caused by deformations due to face support, passage of the tunnelling machine and the annular gap grouting (Maidl, 2012). According to Cording and Hansmire (1975), when tunnelling in drained conditions, V_s is less than the volume loss around the tunnel due to dilation and when tunnelling in undrained conditions, V_s equals volume loss around the tunnel. In calculation, V_s is often assumed equal to the volume loss around the tunnel.

The shape of curve is determined by the position of the inflection point i. The width of the settlement trough depends on