Tunnelling and Underground Space Technology 83 (2019) 145–152

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Relating volume loss and greenfield settlement

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ARTICLE INFO

Keywords:
Tunnel
Greenfield settlement
Undrained
Cohesive soil
Volume loss

ABSTRACT

This paper develops a numerical procedure for investigating settlement induced by circular tunnels in soft soils. The numerical procedure aims to simulate the movement and relaxation of the soil around the shield and lining annulus that occurs due to the overcutting and grouting of the tunnel void by a tunnel boring machine. A stress relaxation technique that progressively reduces the tunnel support pressure from a specific amount until a point of failure is detected. For three separate stages before this point of failure, the surface settlement data is exported for analysis. Using a regression of the commonly used Gaussian equation on the settlement data, i_x values can be determined for each case. This is done for a number of geometry and soil stiffness and strength ratios which will cover the most practical range for soft cohesive soils. The results of this study are quite positive, settlement results compare well with previous experimental and observational results. Design charts using dimensionless ratios have therefore been presented.

1. Introduction

Population increases, increased urbanisation, and the rapid development of emerging countries have driven research into the better management of transport services and infrastructure. Tunnels have increasingly become a common solution; with limited scope for changes above ground, better use of the underground space is an effective solution. With the development of tunnel boring machines (TBM's) over the past few decades tunnels can now be produced in increasingly difficult ground conditions, such as very soft ground. In such conditions where the soil mechanics are more critical, responsibility increasingly falls to the geotechnical engineer.

The three primary design criteria of underground tunnels from a geotechnical perspective are: stability during construction, long and short term settlement, and determination of lining structural loading (Peck, 1969; Ward and Pender, 1981; Mair and Taylor, 1997; Mair, 2008). This paper considers the settlement problem. These issues arise in modern tunnel boring machines (TBM's) primarily because of three reasons: the inevitable delay between when the tunnel is bored and when the lining and the grout is installed, the overcutting due to the cutting head being slightly larger diameter than the rest of the TBM to ensure clearance, and some unavoidable local weakening of the soil very near to the excavation. During the construction period, there is always a degree of soil movement.

Surface settlement induced by tunnelling is a complex phenomenon that is dependent on many factors such as soil and groundwater conditions, tunnelling dimensions and construction techniques. Therefore, much modern tunnelling research has been given to better predict the soils response to changes in stress resulting from tunnel construction by determining analytical solutions for these problems. (Rowe et al., 1983; Sagaseta, 1987; Loganathan and Poulos, 1998; Pinto and Whittle, 2013).

However, with the rapid development of computer technology, numerical modelling using finite element or finite difference methods has become the preferred method for geotechnical design and analysis. These models are generally compared to field observations and experimental results for validation. In some cases however, empirical and semi-empirical methods are still applicable, and indeed quite capable. For tunnel settlement in particular, the empirical method is still widely used, due to its suitability and ease of use (Gunn, 1993; Taylor, 1998).

This empirical method for estimating surface settlements generally follow a Gaussian distribution curve, as in Eq. (1). This approach was first suggested by Martos (1958), who observed that it matched settlement patterns of deep excavations remarkably well. For the particular application to tunnels, research by Peck (1969) indicated a close fit with experimental and observational results. This method requires the input of a trough parameter (i_x) which influences the physical width of the profile, and also relates the volume loss and the maximum settlement, as in Eq. (2).

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https://doi.org/10.1016/j.tust.2018.09.041
Received 14 March 2018; Received in revised form 23 August 2018; Accepted 29 September 2018

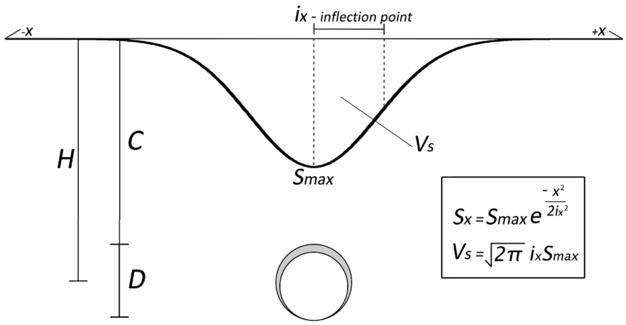

Fig. 1. Typical settlement induced by TBM driven tunnels.

$$S_x = S_{max} e^{-\frac{x^2}{2i_x^2}} \tag{1}$$

$$V_s = \sqrt{2\pi}\, i_x S_{max} \tag{2}$$

In practice, a target volume loss will likely be known (based on experience or client specified); this and the estimated i_x can be used to predict a S_{max}, which can then be used in Eq. (1). This volume loss is commonly given as a percentage of the tunnel cross section area. The volume loss at the surface V_L, is equal to the ground moving into the tunnel in this case, as clay is considered non-dilational.

Fig. 1 shows the nature of this equation: D is the diameter of the tunnel, H is the to-axis tunnel depth, C is the overburden, S_x is the settlement profile at the surface, S_{max} is the maximum vertical settlement, and i_x is the trough width parameter which, physically, is the distance from the tunnel axis to the point of inflection of the curve.

Further examination of this method has been extensive. Centrifuge modelling has been one of the methods used to test its adequacy, with results from Atkinson and Potts (1977), Mair (1979), Mair and Taylor (1997), Taylor (1998), Osman et al (2006). It has also been extensively compared with measurements from constructed tunnels in Attewell and Farmer (1974), Cording and Hansmire (1975), O'Reilly and New (1982), and Rankin (1988), reporting settlement profiles of the shape suggested by a Gaussian equation.

Estimations of the inflection point parameter, i_x have been attempted, the most notably by Clough and Schmidt (1977) in Eq. (3), Mair and Taylor (1997), in Eq. (4), and Lee et al. (1999), in Eq. (5).

$$i_x = 0.5D^{0.2}H^{0.8} \tag{3}$$

$$i_x = 0.75D\left(\frac{C}{D}\right)^{0.8} \tag{4}$$

$$i_x = 0.29\left(\frac{H}{D}\right) + 0.5 \tag{5}$$

However, these only take into account the geometry of the system. Both volume loss and soil strength aren't definable parameters in their study. The most widely used method is the one suggested by O'Reilly and New (1982). Through analysing data collected from tunnels in London, it was suggested that i_x is linearly proportional to the to-axis tunnel depth, H, as in Eq. (6).

$$i_x = kH \tag{6}$$

This equation wouldn't be suitable for very shallow cases ($C/D < 1$), as the diameter would become a more dominant parameter. Nevertheless, this equation involving the coefficient of proportionality (k) allows a degree of flexibility not possible in Eqs. (3)–(5). Commonly assumed values of k range approximately from 0.4 for stiff clays to 0.7 for soft clays (Guglielmetti et al., 2008). However, these haven't been thoroughly defined and studied using dimensionless parameters as well as changing volume loss. The aim of this paper is to study these effects and propose design charts for estimating the k value.

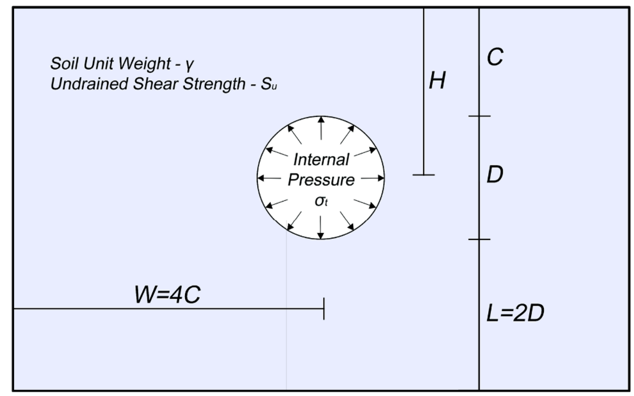

Fig. 2. Problem definition.

2. Problem definition and the modelling procedure

The circular tunnel problem is shown in Fig. 2. In this study, only greenfield settlement has been analyzed. Thus, the surcharge load (σ_s) is set to 0 kPa. The soil is considered as homogenous undrained clay following the Mohr-Coulomb (MC) model. Despite the fact that other soil models, such as modified cam-clay may give a more accurate ground movement simulation, the MC model has the practical advantages. The system will be described in terms of dimensionless ratios: C/D, $\gamma D/s_u$, and E/s_u.

This paper will study the following parametric range: C/D = 1–5, $\gamma D/s_u$ = 1.5–6, and E/s_u = 100–800. Using this approach, the results can be studied methodically, and practical design charts employing these ratios can be produced that should cover a practical range.

The problem is modelled using 2D plane strain conditions in *FLAC* (Itasca, 2003). Despite the fact that tunnelling is a three-dimensional activity, transverse settlement under greenfield conditions can be modelled quite accurately with this simplification (Ghaboussi et al., 1978).

3D numerical programing is much more complex requiring more parameters which sometimes can be difficult to determine in practice. Three-dimensional analysis is also much more time consuming and computationally demanding. For simplicity, the tunnel can be reasonably considered to be very long and at a consistent depth. It is the focus of this paper to study 2D transverse surface settlement.

With the development of powerful computers over the last two decades, numerical modelling has proceeded to become a dominant technique for problem resolution. The finite difference method is one such technique that has been successfully used in the past for modelling tunnels using shear strength reduction method (Shiau et al., 2017), and it has again been used in this study with a pressure relaxation method (Panet and Guenot, 1983) developed with the built-in program language, *FLACish (FISH)*.

After defining boundary conditions, soil properties and tunnel geometry, the developed model slowly reduces the internal supporting pressure from the at-rest pressure, at each relaxation step. In this study, the model was set to fully relax from this initial amount in 1% increments. At each of these relaxation steps, the surface settlement data is recorded.

A typical finite difference mesh of the problem in this study is shown in Fig. 3. The boundary conditions shown in the figure are important as they ensure that the entire soil mass is modelled accurately despite using a finite mesh. It should be noted that the soil domain size for each of the cases was chosen so that the failure zone of the soil body is placed well within the domain. Using Fig. 2, L = 1.5D and W = 4C are adopted in all analyses of the paper.

The internal pressure σ_t, is reduced by multiplying the at-rest pressure, where no movement occurs, by a reduction factor which is based on the number and range of relaxation steps. At each subsequent