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Non-linear description of ground settlement over twin tunnels in soil

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ABSTRACT

Tunneling inevitably leads to ground settlement. The ground settlement trough over a single tunnel is well described by the generally accepted Peck's formula. A new model of settlement trough is proposed by extending Peck's formula to the case of horizontally aligned twin tunnels, which is a widely used tunnel configuration in urban metro projects. The feasibility of the new model is demonstrated through exploration of a large amount of ground settlement data accumulated from a metro tunnel project in China. Two numerical methods are implemented in the data exploration process to solve the problem of non-linear curve-fitting and estimation of model parameters. The Levenberg–Marquardt method is shown to be more suitable than the Nelder–Mead method. Based on the new model of settlement trough, a new method for calculating ground loss over twin tunnels is also proposed. The concluded empirical value of the ratio of ground loss is considered to provide an excellent reference for similar urban railway projects in the future.

1. Introduction

With the rapid development of urbanization in China, exploitation and utilization of the underground space is becoming an effective way to expand city capacity and functionality. Tunneling has become a preferred construction method for transportation and underground utility systems. The construction of a tunnel inevitably affects existing ground stresses and hydro-geological conditions, which in turn leads to ground settlement (ITA, 2007). With so many tunnels being built, large settlement occurs on the ground surface, which could endanger the safety of near-by structures as well as the tunnel itself. Consequently, it is important to have a comprehensive understanding of the tunneling induced ground settlement. Settlement trough and ground loss are 2 research topics that deserve most attention.

1.1. Settlement trough

In engineering practice, the ground settlement is often described by empirical formulas based upon field instrumentation. It is generally assumed that the surface settlement trough can be approximated by the Gaussian curve (Peck, 1969)

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

In the equation, S is ground settlement, $S_{\max}$ is the maximum settlement above the tunnel centerline, x is the horizontal distance from the tunnel centerline in the transverse direction, and i is the distance from the tunnel centerline to the inflexion point of the curve and is called settlement trough width, which determines the shape of the curve, as shown in Fig. 1.

Peck's formula has become a generally accepted model of demonstrating settlement trough over single tunnel (Attewell and Hurrell, 1985; O'Reilly and New, 1982; Rankin, 1988). The trough width i deserves much attention (Attewell and Woodman, 1982; Clough and Schmidt, 1981; Mair and Taylor, 1997) and it has some relation with ground loss.

1.2. Ground loss

An important application of settlement trough is estimating the ground loss. Ground loss is defined as the volume of surface settlement trough per unit length of tunnel (Loganathan and Poulos, 1998). There is a strong correlation between ground loss and safety risk, because the larger the ground subsidence, the greater the nearby structures are affected. The ground loss is highly dependent on soil and water conditions, and even more on construction details (Bobet, 2001). Although some analytical solutions for estimating ground loss have been presented (Chi et al., 2001; Park, 2005), it still heavily relies on empirical factors and past experience (Attewell et al., 1986; Macklin, 1999). However, according to the definition of ground loss and the model of

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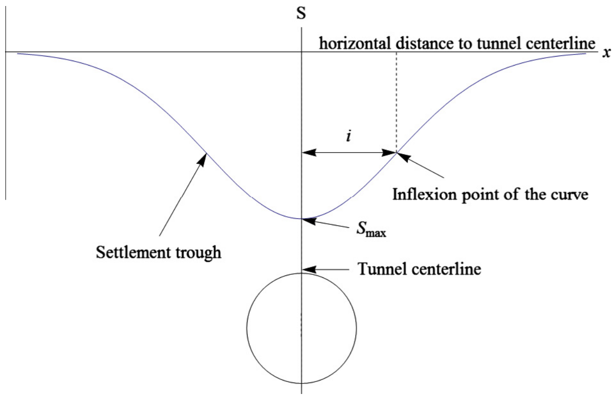

Fig. 1. Ground settlement trough induced by a single tunnel.

settlement trough (as shown in Eq. (1)), it is much easier to calculate ground loss (V_l) after settlement occurs, as shown below,

$$V_l = \int_{-\infty}^{\infty} S_{\max} \exp\left(-\frac{x^2}{2i^2}\right) dx = \sqrt{2\pi} i S_{\max} \quad (2)$$

The key premise of Eq. (2) is to estimate the parameters (i.e. S_{max} and i) in Peck's formula, and this is usually done by curve-fitting with large amount of instrumentation data. The instrumentation data on site is considered as the best 'text book' for evaluation ground settlement.

However, in engineering practice, twin-tunnel is the most used configuration in urban railway projects, especially in a horizontally aligned layout which causes lowest ground settlement (Chehade and Shahrour, 2008; Suwansawat, 2004), and Peck's formula could not be directly applied to the case of twin tunnels, because it was derived for a single tunnel. How can we describe the ground settlement trough over twin tunnels?

1.3. Motivation

Yang and Wang (2011) proposed a simplified stochastic medium method to calculate the ground settlement of twin tunnels by superposing settlement induced by two identical tunnels. They obtained a settlement trough which is symmetric with respect to the mid-point between two tunnels. However, their model hypothesis is too idealistic and the symmetrically shaped settlement trough does not conform to real-life situations (Yoo and Kim, 2008). As a matter of fact, a skewed settlement trough is widely observed in engineering practice (Ercelebi et al., 2011; Mahmutoglu, 2011), because the two tunnels are not excavated simultaneously but in sequence, and the following tunnel would generate significantly greater ground settlement than the preceding one (Chen et al., 2012). The asymmetric settlement trough occurs as a result of interactions between twin tunnels (Mirhabibi and Soroush, 2012). The interaction is influenced by a series of factors including disturbance of the primary state of stresses, the soil movement toward to the tunnel opening, the stress relief induced by the excavation of the preceding tunnel, etc. Some research tried to investigate the complicated mechanism.

2D or 3D finite element (FE) analyses (Karakus, 2007) are popular numerical methods to investigate the pattern of ground settlement trough. However, setting up a realistic model that precisely describe the soil behavior is rather difficult (Karakus and Fowell, 2005). Artificial intelligence methods are emerging methods (Kim et al., 2001; Neaupane and Adhikari, 2006; Santos and Celestino, 2008), but it requires obtaining almost all the parameters that might be related with the ground settlement, which is also very difficult (Suwansawat and Einstein, 2006). In contrast, summative evaluation by curve fitting to ground settlement data is a very pragmatic method, and some research has proved that Peck's formula is more superior in estimating the ground settlement trough than that of the cumbersome numerical analysis, especially in the case of twin tunnels (Chen et al., 2012).

Suwansawat and Einstein (2007) proposed a 2-step curve fitting method. First, when the preceding tunnel just passed through, the ground settlement was fitted by Peck's formula, which was referred to as the settlement trough induced by the preceding tunnel. Then, when the following tunnel passed through, the additional settlement was obtained by subtracting the formal part of settlement from the final settlement, and the additional settlement was fitted by Peck's formula again. Finally, the two fitted curves were superposed to present the overall ground settlement trough.

The 2-step curve fitting method is a little bit cumbersome and implies a hypothesis that the additional settlement is only induced by the following tunnel but is not relevant with the preceding tunnel. This hypothesis deviates from the actual situation because it eliminates the interaction between two tunnels (Afifipour et al., 2011; Yamamoto et al., 2013) and may lead to non-optimal fitting results, and the ground settlement induced by twin tunnels is usually found to be larger than estimated using the principle of superposition (Ou et al., 1998). As a result, a reasonable model to describe the settlement trough over twin tunnels is still in need.

2. Ground settlement trough over twin tunnels

According to Suwansawat and Einstein (2007) and Chen et al. (2012), the Gaussian curve may not only be applicable to describe the ground settlement induced by the preceding tunnel, but also to describe the additional settlements induced by the following tunnel. As a result, it is reasonable to apply the Eq. (1) to each tunnel and propose a double Gaussian model to describe the overall ground settlement trough, as shown in Eq. (3).

$$S = s_1 \exp(a_1 x^2) + s_2 \exp[a_2 (x-u)^2] \quad (3)$$

In Eq. (3), S is the overall ground settlement. s_1 and s_2 can be considered as the maximum ground disturbance induced by northbound tunnel and southbound tunnel respectively, x is the horizontal distance from the northbound tunnel centerline in the transverse direction, a_1 and a_2 are the shape parameters of the settlement trough, u is the distance between two tunnels. A typical ground settlement trough over twin tunnels is shown in Fig. 2.

One of the differences between Suwansawat and Einstein (2007) and this paper is the sequence of data processing. The

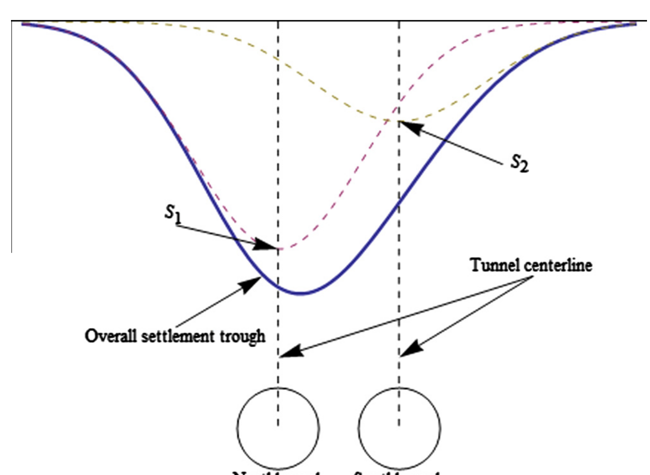

Fig. 2. A typical ground settlement trough over twin tunnels.