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Embankment responses to shield tunnelling considering soil-structure interaction: case studies in Hangzhou soft ground

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ABSTRACT

As more and more under-river tunnels are constructed in urban areas, the deformations and potential damage of existing embankments due to tunnelling have become a major concern. This problem is complex because not only does tunnelling affect the existing embankments, but their presence also alters tunnelling-induced ground movements. An analytical method, which takes account of the effects of the embankment's self-weight, the property of the soil-embankment interface, and the embankment's bending and axial stiffness, is put forward to estimate the embankment's deflections and horizontal strains due to tunnelling. Subsequently, a procedure is proposed to identify the embankment's damage level based on its calculated maximum tensile strain. In the end, case studies of three embankments in Hangzhou soft ground are conducted to examine and validate the analytical method and the damage identification procedure. Further parametric studies show that the embankment's bending stiffness has a significant effect on its deflections and damage level, while the influence of self-weight is mild.

1. Introduction

Building damage resulting from tunnelling-induced ground movements is a complex soil-structure interaction problem. As more and more tunnels are constructed in urban areas, this issue has increasingly received greater attention than in the past.

The limiting tensile strain method (referred to as the LTSM hereinafter), which was derived on the beam theory and the empiricism gained from field observations, is commonly adopted in practice to evaluate a building's settlement-related damage (Burland and wroth, 1974; Boscardin and Cording, 1989). Its basic principle is that a building's damage relies on its tensile strains generated by ground movements. However, as the building is assumed to be infinitely flexible, its deformations, in terms of both vertical deflections and horizontal extensions, are anticipated to be equal to that of the greenfield. This assumption is generally conservative as it ignores the building's ability to resist deformations (Farrell et al., 2014; Franza and DeJong, 2019).

Potts and Addenbrooke (1997) studied the influences of the stiffness of both the building and the subsoil on the building's responses and incorporated the effects of soil-structure interaction into the LTSM. Later, more building features, such as the building weight and the nature of the soil-structure interface (Franzius, 2004; Franzius et al., 2004, 2006; Ritter et al., 2017), were taken into account. Besides, many elaborate numerical simulations have been conducted to investigate the effects of soil-structure interaction (Bloodworth, 2002; Deck et al., 2003; Mroueh and Shahrour, 2003; Netzel, 2009; Selby, 1999; Son and Cording, 2005, 2006, 2007, 2008, 2011).

Numerical simulations considering a variety of influencing factors have been widely employed for final evaluations. By comparison, analytical methods, by virtue of their simplicity, are more suitable for preliminary assessments. Deck and Singh (2012) developed an analytical model involving soil-structure interaction to predict tunnelling-induced building deflections, in which the ground and the building were idealized as a Winkler model and an elastic beam, respectively. Boone (1996) presented a concept for a first-order evaluation of building damage resulting from differential ground settlements. Finno et al. (2005) formulated closed-form equations to relate a building's bending and shear stiffness to its normalized deflection ratios by using a laminate beam method. Schuster et al. (2009) presented a simplified model that incorporates the building's angular distortion and lateral strain for evaluating its damage potential due to a braced excavation.

Dimmock and Mair (2008) observed the progressive responses of several two-three storey buildings to bored tunnelling in London. In

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general, field observations provide an intuitive way of evaluating a building's responses to tunnelling (Burland et al., 2001; Sun et al., 2012; Sirivachiraporn and Phienwej, 2012; Vahdatirad et al., 2010). Besides, laboratory model tests were performed in controlled environments to validate the computational models and facilitate a deep insight into the factors governing the structural responses (Giardina et al., 2012). Furthermore, a variety of staged approaches have been put forward for damage evaluation based on findings from numerical, analytical and experimental methods (Cording et al., 2010; Devriendt, 2010; Torp-Petersen and Black, 2001).

All across the world, more and more under-water tunnels are constructed using the shield tunnelling method to cross rivers in urban areas. Embankments are important infrastructures to protect neighboring residents from floods and tides. Therefore, one particular concern in the construction of under-water shield-driven tunnels is the damage potential of the embankments resulting from shield tunnelling. Over the last decades, numerous studies have been conducted on soil-structure interaction problems related to masonry and reinforced concrete buildings and underground facilities (piles and pipelines for instance). However, sparse attention has been paid to the responses of embankments to tunnelling.

This paper presents an analytical method to assess the deformations and damage of an embankment induced by shield tunnelling. The effects of soil-structure interactions are elaborated in terms of the embankment's self-weight, its bending and axial stiffness, and the property of the soil-embankment interface. The analytical method is validated by field observations from three case histories in Hangzhou soft ground.

2. Analytical model

In this section, an analytical method is employed to estimate an embankment's deformations (both vertical deflections and horizontal strains) due to tunnelling-induced ground movements.

2.1. Effect of the embankment's self-weight

Numerical simulations have been conducted to investigate the influence of a building's self-weight on its deformations due to tunnelling. The two-dimensional analysis conducted by Liu et al. (2001) found that an increase of the façade weight tends to increase the damage level owing to larger generated horizontal strains. Numerical parametric studies carried out by Franzius et al. (2004) yielded that the modification factors relating the deflection ratios and horizontal strains of a building to that of a greenfield increase with an increase of the building's self-weight. Three-dimensional numerical simulations executed by Bloodworth (2002) also discovered that the increase of a building's self-weight is anticipated to increase its settlements and damage level.

Herein, the modification to tunnelling-induced ground settlements due to an embankment's self-weight is formulated by introducing a virtual overburden that can generate additional stresses in the subsoil which are approximately equivalent to that generated by the embankment's self-weight. Subsequently, the ground settlements at the level of the soil-embankment interface can be estimated by using the well-established formulas for tunnelling-induced subsurface settlements (Mair et al., 1993; Marshall et al., 2012). This procedure, referred to as the virtual overburden method herein, is to be illustrated by an example below.

Fig. 1(a) depicts that a tunnel is to be constructed beneath an existing embankment. It is assumed that the tunnel's alignment is perpendicular to the embankment's longitudinal direction and the tunnel's overburden C is 14 m high at the greenfield.

The unit weight of the embankment r_e and the subsoil r_s is assumed to be 21 kN·m^{-3} and 19 kN·m^{-3}, respectively. Subsequently, the additional soil stresses in the subgrade can be calculated by regarding the embankment's self-weight as a surcharge. Fig. 2(a) presents the calculated additional vertical soil stresses with depth beneath the

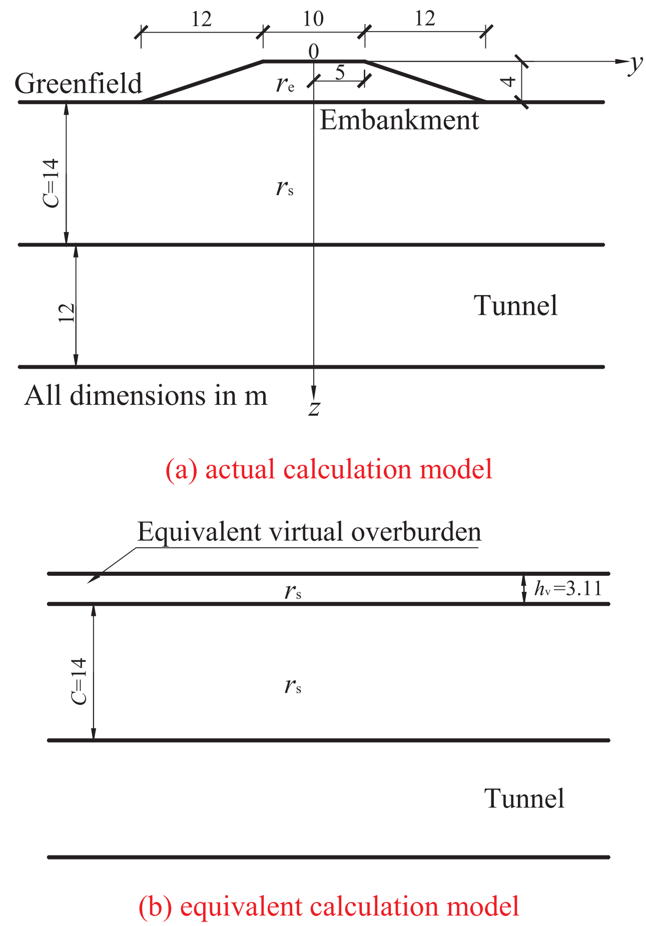

Fig. 1. Sketch of tunnelling beneath an embankment and the equivalent virtual overburden.

embankment's longitudinal axis (where $y = 0$). Moreover, for embankments with other different geometrical shapes, additional vertical soil stresses can also be figured out by using available solutions for distributed loading or by an integration of the Boussinesq solution (Poulos and Davis, 1974). The superposition method could be applied when the embankment's geometrical shape is complicated.

Extensive field observations have proven that tunnelling-induced greenfield settlement troughs transverse to the tunnel axis at both surface and subsurface can be well described by the Gaussian function as (Marshall et al., 2012; O'reilly and New, 1982; Peck, 1969)

$$s(x, z) = \frac{\pi R^2 V_l}{\sqrt{2\pi} K (z_0 - z)} \exp\left[-\frac{x^2}{2K^2(z_0 - z)^2}\right] \tag{1}$$

where x is the horizontal distance from the tunnel axis; z_0 and z are the depth of the tunnel axis and the subsurface under consideration, respectively; $s(x, z)$ is the ground settlement at the coordinate (x, z); R is the tunnel radius; V_l is the volume loss; and K is the trough width parameter at depth z.

As indicated by Eq. (1), the transverse settlement trough varies with depth. This variation is most likely dominated by the soil's property and initial stresses. To determine the transverse greenfield settlements at a depth of the soil-embankment interface at $y = 0$, a virtual overburden that can generate additional vertical soil stresses in the subgrade as depicted by Line 2 in Fig. 2(b) is introduced. The virtual overburden is assumed to be the same in nature as the embankment's subsoil. In Fig. 2, Line 1 and Line 2 present the additional vertical soil stresses induced by the embankment's self-weight and its corresponding virtual overburden, respectively; and A_1 and A_2 are the areas enveloped by Line 1 and Line 2 within the depth of the tunnel's overburden,