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Mixed empirical-numerical method for investigating tunnelling effects on structures

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ABSTRACT

The assessment of potential for building damage due to ground displacements caused by tunnelling is a global issue being faced by engineers. There is a two-way interaction between tunnelling and existing buildings; tunnel construction affects a building by inducing displacements in the soil underlying its foundation, and buildings influence tunnelling induced displacements via their weight and stiffness. Numerical analyses are widely used to investigate tunnelling and its impact on structures, however numerically predicted ground displacements are generally wider and shallower than those observed in practice. This paper presents a two-stage mixed empirical-numerical technique to estimate the effect of building stiffness on ground displacements due to tunnelling. In the first stage, greenfield soil displacements are applied to the soil model and the nodal reaction forces are recorded. In the second stage, the effect of tunnelling on a structure is evaluated by applying the recorded nodal reactions to an undeformed mesh. Results from conventional numerical analyses of the problem are compared against those obtained using the mixed empirical-numerical approach. Results demonstrate the importance of imposing realistic inputs of greenfield displacements when evaluating structural response to tunnelling.

1. Introduction

As cities grow and urban infrastructure systems expand, the need for tunnels increases. Tunnel construction inevitably leads to the potential for ground displacements and damage to existing buildings and infrastructure. This paper focuses on the problem of how to evaluate tunnelling-induced movements within buildings. There have been many investigations of the effect of tunnelling on buildings. These studies include the influence of ground movements induced by tunnelling on both surface and subsurface structures. The interaction between a newly constructed tunnel and an existing building is a two-way relationship. The constructed tunnel affects the building by creating displacements in the soil underlying its foundation, and the existence of the building influences resulting soil movements. The effect of structural stiffness (Mair and Taylor, 1997; Franzius et al., 2006; Dimmock and Mair, 2008; Maleki et al., 2011; Farrell et al., 2014; Franza and DeJong, 2017) and building weight (Franzius et al., 2004; Giardina et al., 2015; Bilotta et al., 2017) have been shown to have an effect on the resulting ground movements.

Researchers have proposed several approaches to account for the effect of building stiffness in tunnel-structure interaction problems. Potts and Addenbrooke (1997) proposed a method based on the relative stiffness of a building compared to the underlying soil. They used 2D finite element (FE) analyses and considered several influential parameters of both the soil and the structure, such as material elastic moduli, building length, and cross sectional moment of inertia. This approach was extended by Franzius et al. (2006) who investigated the effect of structural stiffness on ground displacements in a 3D environment. The relative stiffness method was further examined by researchers and new approaches have been proposed, some of which included the effect of building weight (Goh and Mair, 2014; Mair, 2013; Giardina et al., 2015).

In the analysis of Potts and Addenbrooke (1997) and Franzius et al. (2006), the effect of tunnelling on ground displacements was simulated within the FE model. The numerical simulation of a tunnel is an effective method for estimating tunnelling effects on buildings, however, FE methods generally predict a wider and shallower greenfield settlement trough than observed in practice (Mair et al., 1982; Augarde, 1997; Franzius et al., 2005, 2006; Jurecic et al., 2013). This issue can be overcome by the use of sophisticated soil constitutive models (Addenbrooke et al., 1997), however the input parameters for these models are generally not readily available. A wider/shallower input of greenfield displacements can affect the results of a soil-structure interaction analysis in two ways. First, for a given settlement trough

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shape, a smaller maximum settlement produces less distortions and therefore less damage to a building. Second, the width of the settlement trough can alter the response of the building; a building affected along its entire length will show less resistance to deformation compared to the same building subjected to ground displacements along part of its length. This feature, which relates to the effective end-fixity of the building, can be demonstrated using a beam analogy (Haji et al., 2018). A relatively long building extending further outside the ground displacement zone can be thought of like a beam with a relatively stiff support that constrains the rotation of the beam (similar to a fixed ended beam), whereas a shorter building behaves like a beam with a more flexible support that allows a degree of rotation (similar to a simply supported beam).

The aim of this paper is to describe the use of a two-stage mixed empirical-numerical (E-N) method to estimate the effect of the stiffness of a weightless building on ground displacements caused by tunnelling. In this method, realistic greenfield ground displacements, obtained from empirical or analytical relationships, are used as an input in a numerical analysis in order to determine the nodal reaction forces within the numerical mesh required to obtain the greenfield displacements (stage 1). The tunnel-building interaction is then solved in stage 2 by including the building within the model and applying the greenfield nodal reaction forces to the mesh. The applied numerical analysis adopts simple linear elastic constitutive soil behaviour; the effects of building weight on the tunnelling-induced response is therefore not considered in the analysis.

The paper begins with an overview of the relative stiffness approach, followed by a description of the adopted numerical analyses, including 'conventional' numerical analyses (in which the tunnelling process is simulated) and mixed E-N analyses. The purpose of the 'conventional' numerical analysis is to provide results for comparison which might be obtained by a practising engineer considering this problem, using reasonably standard numerical modelling methods. Results from the two numerical analyses are compared and the importance of having an accurate input of greenfield displacements in evaluating structural distortions is demonstrated.

2. Relative stiffness approach

Potts and Addenbrooke (1997) estimated the stiffness effect of a weightless structure on tunnelling induced ground movements in London clay. Based on 2D numerical analyses, they represented the building as an elastic beam and proposed two relationships to estimate the relative bending and axial stiffness of the soil and the structure:

$$\rho^* = \frac{E_b I_b}{E_s (L_{bldg}/2)^4}; \quad \alpha^* = \frac{E_b A_b}{E_s (L_{bldg}/2)} \tag{1}$$

where ρ^* is the relative bending stiffness, α^* is the relative axial stiffness, E_b and E_s are the elastic moduli of the equivalent beam and the soil, respectively, I_b is the cross sectional moment of inertia of the equivalent beam, A_b is the cross-sectional area, and L_{bldg} is the length of the building perpendicular to the tunnel direction. For their plane strain problem, α^* is dimensionless but ρ^* has dimensions of m^{-1}.

Potts and Addenbrooke (1997) calculated the moment of inertia of the structure from that of each slab by employing the parallel axis theorem, with the centreline located in the middle of the building. An equivalent beam was then used to represent the building, which was designed such that it had a similar bending or axial stiffness as the building. Building damage parameters were proposed, referred to as the sagging and hogging deflection ratios (DR_{sag}, DR_{hog}), and compressive and tensile horizontal strains induced in the building (ε_{hc} and ε_{ht}), as shown in Fig. 1. Subscripts *bldg* and *gf* refer to *building* and *greenfield*, respectively. The inflection point, *i*, of the settlement trough separates the zones of sagging and hogging. Strains were obtained directly from the output of the FE analyses at the neutral axis of the beam in order to eliminate bending effects. Potts and Addenbrooke (1997) suggested the following modification factors to relate the deflection ratios (Eq. (2)) and maximum horizontal strains (Eq. (3)) to the corresponding finite element greenfield situations:

$$M^{DR_{sag}} = \frac{DR_{sag,bldg}}{DR_{sag,gf}}; \quad M^{DR_{hog}} = \frac{DR_{hog,bldg}}{DR_{hog,gf}} \tag{2}$$

$$M^{\varepsilon_{hc}} = \frac{\varepsilon_{hc,bldg}}{\varepsilon_{hc,gf}}; \quad M^{\varepsilon_{ht}} = \frac{\varepsilon_{ht,bldg}}{\varepsilon_{ht,gf}} \tag{3}$$

where ε_h is maximum horizontal strain and the subscripts *c* and *t* denote compressive and tensile, respectively. The greenfield values relate to that portion of the greenfield settlement curve lying beneath the building.

Franzius et al. (2006) extended the relationships proposed by Potts and Addenbrooke (1997) to 3D (i.e. including the effect of building width) and also considered the effect of tunnel depth in a more explicit fashion. They used the same principles for estimating building stiffness and represented the building by shell elements (rather than an actual 3D building). They suggested the following expressions for calculating bending and axial modification factors:

$$\rho^*_{mod} = \frac{E_b I_b}{E_s z_t L^2_{bldg} B_{bldg}}; \quad \alpha^*_{mod} = \frac{E_b A_b}{E_s L_{bldg} B_{bldg}} \tag{4}$$

where ρ^*_{mod} is the modified relative bending stiffness, α^*_{mod} is the modified relative axial stiffness, z_t is the tunnel depth and B_{bldg} is the building width parallel to the tunnel direction. It was shown that explicitly including tunnel depth in the relationship for ρ^*_{mod} provided a more realistic representation of bending response; this was not the case for the axial response described by α^*_{mod}.

Goh and Mair (2011) and Mair (2013) also proposed definitions of relative bending stiffness and design charts which were independent of tunnel-building eccentricity (whereas the previously adopted methods varied with eccentricity). Their methodology separates the building into sagging and hogging zones and estimates the relative bending stiffness independently for each part. This paper, however, adopts the methodology of Franzius et al. (2006) (Eq. (4)). Each method has its own advantages and limitations, however it was felt that treatment of the building as a single entity (as in the Franzius et al. (2006) method) was more logical for the analyses considered in this paper since the fixity condition of the building ends (which is misrepresented by splitting the building into parts) plays an important role.

3. Mixed empirical-numerical approach (mixed E-N)

To address the issues related to poor prediction of tunnelling induced settlement trough shape using numerical methods, yet still take advantage of the capabilities of numerical modelling for soil-structure interaction analysis, several authors have incorporated an empirical or analytical greenfield input into numerical analyses. Selby (1999) applied tunnelling induced ground surface movements to a finite element numerical model using Gaussian equations to estimate tunnelling effects on structures. Klar and Marshall (2008) applied Gaussian ground movements to all nodes of a finite difference numerical model in order to estimate tunnelling effects on pipelines. Wang et al. (2011) used a semi empirical method to investigate tunnelling effects on buried pipelines. The method of Selby (1999) and Klar and Marshall (2008) incorporated a two-stage analysis in which displacements are applied to the model in the first stage, and the reaction forces required to create the prescribed displacements are applied to the model in the second stage, after the structure is added to the model. In this way, the tunnelling process is not simulated directly in the numerical model, yet the soil-structure interactions caused by the greenfield input are simulated.

In the methodology presented in this paper, the two-stage analysis approach was adopted. The method is referred to as the mixed empirical-numerical (mixed E-N) method because an empirical/semi-