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Finite element analysis of tunnel–soil–pile interaction using displacement controlled model

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Abstract

Significant additional loads could be induced in pile foundations adjacent to new tunnels. Accurate prediction of magnitude and shape of the ground displacements, which define curvature changes, is crucial for the computation of tunnelling induced bending and axial stresses in pile foundations. The finite element simulation of tunnelling by removing forces corresponding to initial stress-state, tend to predict incorrect shape of ground displacement profiles, hence incorrect forces in pile foundations adjacent to tunnels. To overcome this difficulty, this paper describes the development and application of a simple and useful displacement controlled model (DCM) to predict the effects of tunnel excavation on adjacent pile foundations. The DCM simulates tunnelling by applying displacements to the tunnel boundary. A method to determine magnitude and direction of tunnel boundary displacements, based on convergence patterns observed in field and centrifuge test results, is proposed. Back analyses of numerous greenfield tunnel case histories using the DCM indicate good agreement between computed displacement profiles and field/test data. The suitability of the DCM in modelling tunnel–soil–pile interaction problems is demonstrated through back analysis of a centrifuge test and a field case study.

Keywords: Tunnelling; Pile foundation; Displacement profiles; Bending moment; Axial force

1. Introduction

Ground movements due to tunnelling activity can be reasonably well predicted using empirical methods (Peck, 1969; Attewell and Woodman, 1982), or quasi-analytical solutions (Loganathan and Poulos, 1998). The applicability of these solutions is limited to tunnelling in greenfield sites only and may not be suitable to analyse the effects of tunnelling in densely built-up areas with existing structures, where tunnel–soil–structure interaction plays an important role. Recent studies on the modelling of tunnel–soil–building interaction (Potts and Addenbrooke, 1997; Burd et al., 2000) show significant differences between settlements that would have been obtained at greenfield sites and at sites with the structure in place. Such complex interaction can be simulated using the finite element (FE) method, in theory. However, it is well known that commonly used finite element modelling techniques, henceforth called force controlled models (FCM), which simulate tunnelling by removing nodal forces corresponding to the initial soil stress-state predicts incorrect shape of displacement profiles (Simpson et al., 1979; Dasari, 1996; Leca, 1996; Stallebrass et al., 1996). The predicted settlement profiles tend to be shallower and wider than field observations, i.e. near field movements are under predicted while far field movements are over predicted. This shortcoming can be partly improved by using advanced soil constitutive models, Lee and Rowe (1989), Simpson (1992), Gunn (1993), Bolton et al. (1994), Stallebrass et al. (1994), Dasari et al. (1996), Addenbrooke et al. (1997). As reported by Stallebrass

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et al. (1996) and Addenbrooke et al. (1997) for plane strain modelling, and for three dimensional NATM tunnelling studies by Dasari et al. (1996), the use of advanced soil models has only resulted in limited success, especially with shape, as far field displacements were consistently over predicted. Addenbrooke et al. (1997) also reported that, in order to match ground displacement due to tunnelling, unrealistic material anisotropy needs to be assumed.

The shape of ground displacement profiles, which determines the degree of curvature, is a critical factor in obtaining realistic bending moments in piles adjacent to new tunnels. The limitation of the FCM in predicting the correct shape of surface and subsurface displacement profiles makes it unsuitable for the analysis of tunnel–soil–pile interaction problems. Analytical solutions (Loganathan and Poulos, 1998; Park, 2004) have been proposed to overcome this issue. The analytical solutions assume linear elasticity and do not take the soil non-linearity into account. Therefore, there is a need for an alternative simple FE modelling technique for modelling the effects of tunnelling.

The first part of the paper presents details of the Displacement Controlled Model (DCM), which can predict both realistic soil displacement magnitude and more importantly the correct shape of ground displacement profiles due to tunnelling. In the DCM, nodes on the tunnel boundary are "pulled", to simulate the effects of stress relief, to a predetermined final configuration depending on tunnel cover (distance between ground surface and tunnel crown) to diameter ratio (C/D_t) and anticipated volume loss. The applied displacements in the DCM are computed based on observations of convergence patterns around tunnels from centrifuge tests and field cases. The model has been verified by back analysing many centrifuge and field tunnel case studies. The potential of the DCM has been explored by back analysing a tunnel–soil–pile interaction centrifuge test. The DCM has also been used to back analyse a field case study to determine induced axial force and bending moment in a pre-existing instrumented pile due to excavation of twin tunnels.

2. Displacement controlled model

Tunnelling in finite element models is usually simulated by applying forces corresponding to a fraction of the initial stress-state, to the nodes on the tunnel boundary. These models hitherto will be referred to as the force controlled models (FCM). When the FCMs are used to simulate tunnelling, in plane strain or in 3D conditions, they commonly result in wider surface settlement troughs accompanied with higher far field settlements than field or centrifuge test data. The reason for such prediction lies in the resultant deformation mechanism of the excavated tunnel boundary. It has been observed that the FCM tend to result in higher than measured invert displacements (Dasari et al., 1996; Stallebrass et al., 1996; Leca, 1996). This excess invert heave provides an avenue for soil below the tunnel spring line to experience higher movements. These higher movements cause soil in the far field to be drawn towards the region below the tunnel spring line to satisfy volumetric constancy as shown in Fig. 1. This results in excessive far field settlements, and for a given volume loss, maximum surface settlement (S_{max}) would be small. The predicted settlement profiles would be shallower and wider than the field or test measurement. Although displacement patterns can be improved using advanced soil models or by other means, there is a need for a simple approach to predict tunnelling induced ground movements as discussed in the introduction.

The key for a different approach lies in the displacement convergence pattern around a deforming tunnel boundary. Upon excavation, soil around the unsupported tunnel converges inwards in a radial fashion towards a point on the tunnel vertical line of symmetry. Previously, this pattern of convergence has been ideally assumed to be uniform in the analytical solutions proposed by Sagaseta (1987) as a means of simplifying mathematical derivations. However, it is expected that the tunnel convergence is highly non-uniform with more crown settlement and less invert heave. Fig. 2 shows displacement vector plots of soil deformation around the excavated tunnel for plane strain centrifuge experiments conducted by Mair (1979). The displacement vectors in the tests clearly show large crown settlement with very little invert heave. Centrifuge tests by Hagiwara et al. (1999) and field measurements at the Heathrow trial tunnel by Deane and Bassett (1995) also show that the area close to tunnel invert experienced very little movement compared to the crown. The above observations lead to the first assumption in the displacement controlled model (DCM) that convergence is non-uniform. Loganathan and Poulos (1998) and Park (2004) reported that such non-uniform convergence profiles lead to realistic predictions of ground displacements due to tunnelling.

The second assumption for the DCM is that deformed tunnel shape is similar to the original excavated shape. Such an assumption is justified as deformations are usually small compared to tunnel size under working conditions. The third assumption for the DCM is that there exists a single point on the tunnel vertical line of symmetry to which all nodes on the excavated tunnel boundary converge to. There have been numerous studies, which propose that soil displacement vectors of the excavated tunnel boundary converge to the tunnel centre (Attewell et al., 1978; O'Reilly and New, 1982), 0.175/0.325 z_o below tunnel axis level (Taylor, 1995) or towards a point on the tunnel invert (Deane and Bassett, 1995). The latter is proposed based on field data while the former two are derived based on the following well established empirical relations:

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

$$i = K(z_o - z) \tag{2}$$

$$S_h = \frac{x}{z_o} S \tag{3}$$