Analysis of effects of tunnelling on single piles

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ABSTRACT: This paper describes an efficient and practical method of analysis to predict some important effects of tunnelling on pile foundations. The method involves a combination of the finite and boundary element methods (FAB), with free-field ground movements predicted by the finite element method and the response of an embedded pile to these ground movements predicted by the boundary element method. A summary of the theory behind the proposed method, verification of the method and demonstration of its computational advantages and applicability are described. Predictions of the proposed method are presented for horizontal components of ground and pile displacements. Good agreement of these predictions with field observations has been obtained for a number of different cases, providing confidence in the utility of the method.

1 INTRODUCTION

One of the main concerns that arise from tunnelling in an urban setting is the effect of the induced ground movements on surrounding structural foundations. The foundation types considered in this paper are pile foundations, which are commonly used to support high rise buildings in many major cities.

The reported studies of tunnelling-induced ground movements have concentrated on the issue of surface settlements (e.g., Rowe and Kack, 1983; Attwell *et al.*, 1986; Gunn, 1993; Addenbrooke *et al.*, 1997; Mair, 1993; Mair *et al.*, 1993; Mair and Taylor, 1997; Grant and Taylor, 2000; McNamara *et al.*, 2003). Horizontal ground movements induced by tunnelling have only recently been addressed in any detail and field measurements of these movements, particularly from the ground surface to tunnel level, are reasonably rare.

In contrast, several prediction methods have been suggested for tunnelling-induced ground movements, ranging from those that are empirical (e.g., Peck, 1969), to completely analytical (e.g., Sagaseta, 1987; Mindlin, 1940; Verruijt and Booker, 1996), and including those that are semi-analytical (e.g., Loganathan, 1998) and purely numerical (e.g., Mhroueh and Shahrour, 2002).

There appear to be no published solutions for the influence of tunnel construction on the behaviour of pile groups, other than those by Chen *et al.* (1999, 2000) and Mroueh and Shahrour (2002). It would appear that only Mroueh and Shahrour (2002) have attempted to address fully the three-dimensional nature of this problem.

There is a need to understand better the interaction between tunnelling operations and existing pile foundations and to develop an efficient, yet rigorous, method for predicting the influence of tunnelling on existing single piles and pile groups. The aim of this paper is to demonstrate a method of analysis that can overcome the need for a full 3-D numerical analysis for every scenario in a tunnelling project. To achieve this, a summary of the method proposed by Surjadinata *et al.* (2004) is presented, followed by comparisons of the predictions of the proposed method with published solutions and field measurements. Attention is restricted to single pile foundations and the movement of the ground and the pile in a plane perpendicular to the tunnel's axis.

2 OVERVIEW OF PROPOSED METHOD

The finite element (FE) method has become virtually a standard analytical tool for practicing engineers to carry out analyses of tunnelling problems. However, the cost may be very high if a conventional 3-D FE analysis is conducted for each and every possible scenario of interest. If non-linear behaviour of the soil surrounding the tunnel and complicated construction sequences are to be taken into account the cost may become prohibitively high.

By combining finite element predictions of tunnelling-induced free-field ground movements (i.e., predictions from a model without any pile) with a separate boundary element analysis of a single pile foundation or a pile group, a large number of cases can be analysed efficiently. Chen *et al.* (1999, 2000) previously demonstrated the efficacy of this type of approach, but the ground movements input to their boundary element analysis were empirically derived.

In the method proposed here, for relatively uniform ground conditions only a single 3-D FE analysis is required for each tunnel configuration, independent of the multitude of configurations of pile foundations that may be of interest. This method, described previously in detail by Surjadinata *et al.* (2004) and designated as FAB (combined finite and boundary element method), therefore has the potential to generate economical predictions for a very large number of cases of practical interest, enabling practicing engineers to investigate many more cases than are viable at present by conventional 3-D FE analyses.

3 ESTIMATION OF SOIL MOVEMENTS

The first step in the analysis of tunnel-pile interaction is to predict the free-field soil displacements induced by a tunnelling operation. As a first approximation this prediction can be achieved using a linear elastic 3-D finite element analysis. However, more sophisticated models of soil response could also be used with this approach. In this paper, the AFENA finite element package (Carter and Balaam, 1995) was used for this purpose. Since the linear elastic finite element method is well known, it will not be discussed here. The finite element model does not include a pile adjacent to the tunnel, but rather it estimates the soil displacements due to tunnelling without the pile in place. A typical finite element mesh includes from 2,000 to 4,000 twenty node isoparametric hexahedral elements.

Simulation of tunnel excavation can be achieved in at least two ways. In the first, each excavation stage is simulated by removal of elements from the finite element mesh to create the appropriate increment of tunnel void. Removal of these elements implies their stiffness no longer contributes to the global stiffness of the soil. Appropriate force increments are then applied to the new tunnel boundary to simulate complete removal of stress from the surfaces created by excavation. Thereafter in the incremental analysis this surface remains stress free. It should be noted that the number of steps used to excavate does not affect the results in a linear elastic body (Brown and Booker, 1985). In the second way, it is possible to simulate excavation of the tunnel by specifying the displacements of the tunnel boundary corresponding to a pre-defined ground loss. The ground loss is defined as the reduction of tunnel volume, as a percentage of the initial excavated volume.

For the calculations presented in this paper the second of these methods was used, i.e., a pre-defined ground loss value was specified in the finite element model. Ground loss values quoted for the test cases described below correspond to the value when plane strain conditions are achieved (usually corresponding to the end-of-excavation condition). Since the free-field soil movements are eventually used as the sole input to the boundary element analysis of a single pile, it is crucial to ensure a reliable prediction of these movements. To check this, two well documented case histories are considered, and the finite element predictions of ground displacements are compared with field measurements. In both these comparisons, it was ensured that the ground loss relevant to the plane strain excavation state in the finite element analysis was equal to the measured value reported for each case history.

3.1 *Case 1: Heathrow Express Trial Tunnel*

Deane and Basset (1995) documented measurements of induced ground movements caused by construction of the Heathrow Express Trial Tunnel. The excavation of three different tunnel cross sections was documented and the largest cross section (Cross section type 3) was chosen for study here. The displacement field predicted by the finite element analysis was compared against analytical solutions and the field measurements. The diameter of the tunnel was 8.5 m with maximum reported ground loss of 1.33%. The comparison can be found in Figures 1 and 2, which also include a summary of the parameters used in the finite element analyses. These figures show a comparison of the predicted and measured horizontal ground movements at distances of 6 m and 9 m measured horizontally from the centre of the tunnel. Some minor discrepancies between measurements and predictions can be observed and it is evident that the proposed method generally provides predictions which are slight underestimates of the horizontal displacements of the ground at shallow depth. However, Figures 1 and 2 also show that the maximum horizontal displacements predicted by the FE analyses are conservative, i.e., slight overestimates.

3.2 *Case 2: Thunder Bay Tunnel*

Another well documented case history is from Palmer and Belshaw (1978), who reported measurements of the induced ground movements due to construction of a sanitary trunk sewer tunnel in the city of Thunder Bay, Ontario, Canada. The diameter of the tunnel excavated through soft clay soil using a tunnel boring machine was 2.47 m.

It was reported by Palmer and Belshaw (1980) that the measured maximum ground loss was 7.5% for this case, and this value corresponds to the maximum recorded surface subsidence trough induced by the tunnelling. However, Lee *et al.* (1992), Rowe and Lee (1992) and Loganathan (1998) independently estimated the ground loss for this case study, using a gap-parameter approach, to be approximately 14%. In the current study it was found that an assumed ground

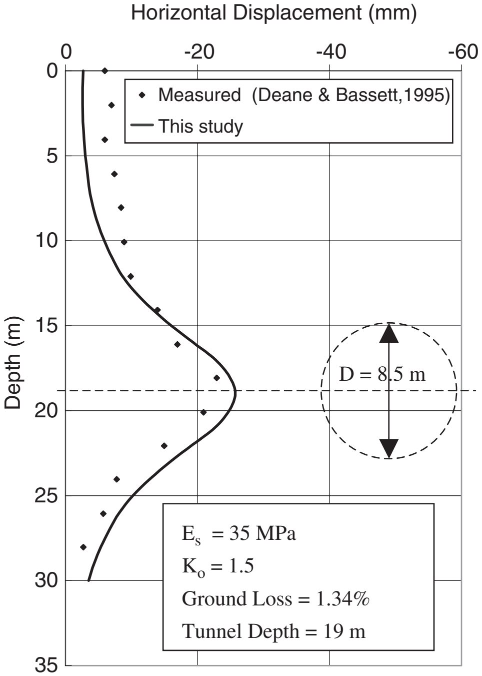

Figure 1. Measured and predicted horizontal displacements 6 m from the centreline of the Heathrow Express Trial Tunnel.

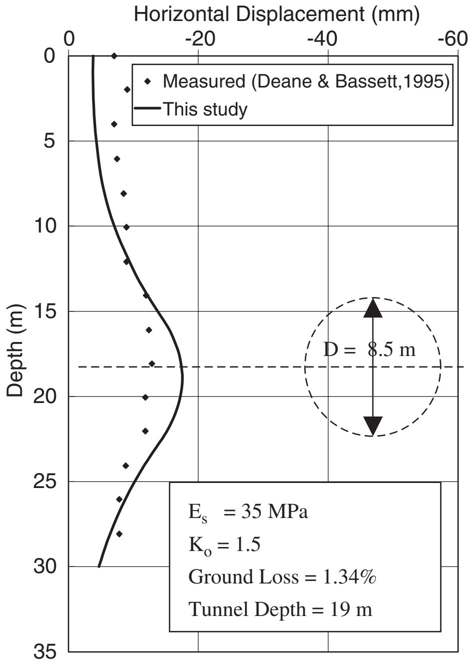

Figure 2. Measured and predicted horizontal displacements 9 m from the centreline of the Heathrow Express Trial Tunnel.

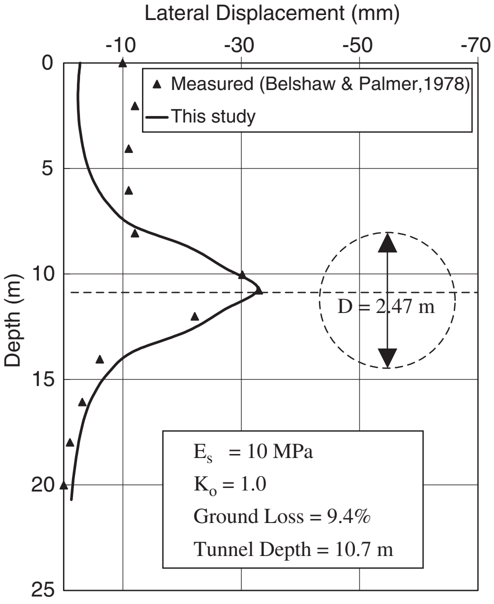

Figure 3. Measured and predicted horizontal ground displacements 2.16 m from the centreline of the Thunder Bay Sewer Tunnel.

loss of approximately 9.4% provided predictions of lateral ground displacements that were close to the field measurements reported by Palmer and Belshaw (1980). As will be seen, the predictions of the maximum lateral displacement were particularly close to the maximum field measurements if a ground loss of 9.4% was adopted in the numerical simulation.

Figure 3 shows comparisons between the measured and predicted horizontal displacements 2.16 m away from the tunnel centreline. Again, some minor discrepancies between the predictions and the measurements can be observed at shallow depth. However, Figure 3 shows that the maximum horizontal displacement predicted by the FE analysis is generally in good agreement with the measured value.

3.3 *Discussion of cases 1 & 2*

The presented comparisons of ground movements provide a degree of confidence with regard to the prediction of horizontal displacements using a 3D linear elastic FE model, provided an appropriate value for the ground loss is assumed as input to the analysis. In both cases it is observed that the FE method provides a conservative prediction of the horizontal ground movements in the vicinity of the tunnel. However, it is also evident that the FE predictions slightly underestimate the horizontal displacements at shallow depth. This raises the question of the importance of this discrepancy in relation to the behaviour of a pile if it was placed within the zone of influence of the tunnel. This question will be addressed in the following section.

4 ANALYSIS OF PILE RESPONSE

As previously indicated, the free-field soil displacements predicted by the finite element model were adopted as input to a special boundary element analysis of a single pile surrounded by elastic soil in order to predict the response of the pile to those soil movements and therefore to the tunnel excavation. In this study the boundary element computer program PALLAS (Hull, 1998) has been used for this purpose. Comparisons of these predictions with field measurements of pile response to tunnelling have been conducted. These provide a means of evaluating the proposed FAB method and of assessing the significance of the discrepancies between finite element predictions and measurements of ground movements, described previously.

4.1 *Case 3: Chen et al. (1999) benchmark case*

Loganathan and Poulos (1998) provided semi-analytical solutions for predicting tunnelling-induced horizontal ground movements in soils ranging from stiff to soft clays. These solutions have been used by Chen *et al.* (1999) in combination with a boundary element method to produce solutions for single pile behaviour, and they have been shown to provide reasonable predictions. A benchmark case provided by Chen *et al.* (1999) was chosen to investigate the accuracy of the FAB method. It involves a pile of length $L_p = 25$ m, diameter $B_p = 0.5$ m and Young's modulus $E_p = 30{,}000$ MPa. The soil was represented as an elastic continuum with Young's modulus $E_s = 24$ MPa and Poisson's ratio, $\nu_s = 0.5$. The tunnel diameter, D = 6 m, and the depth of the soil cover over the tunnel, H = 17 m. The horizontal centreline of the tunnel was located 4.5 from the vertical axis of the pile and the ground loss during tunnel excavation in this example, provided by Chen *et al.* (1999), was assumed to be 5%.

Comparison of predictions from Chen *et al.* (1999) and the current study can be found in Figures 4 to 6. Figure 4 shows comparisons of the predicted free-field ground movements at the location of the pile axis (i.e., 4.5 m from the tunnel centreline), while Figures 5 and 6 show predictions of lateral displacements of the pile and the bending moments induced in the pile by these ground movements. It is clear from these figures that the predictions from both studies are generally in good agreement. Some minor discrepancies in the predicted displacements can be observed in Figures 4 and 5 and it is evident that the method described in the current study (FAB) provides predictions which are slight underestimates of the displacements of the pile at shallow depth. However, Figures 5 and 6 show that the maximum pile displacements and the bending moments predicted by the FAB method are slightly conservative. Figure 6 indicates that the bending moment distributions predicted by both studies generally agree remarkably well. It is also noted that the properties selected in this example characterise a pile that is quite flexible, so that the presence of the pile in the soil does not have a great influence on the induced lateral pile movements. The agreement between solutions predicted by the current FAB method and those proposed by Chen *et al.* (1999)

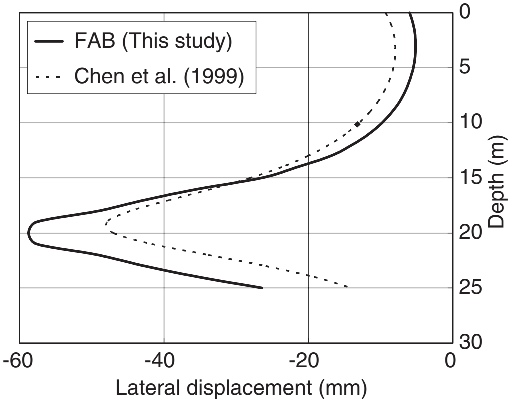

Figure 4. Comparison between Chen et al. (1999) and predictions of the current study of lateral ground displacements 4.5 m from the centreline of an excavated tunnel.

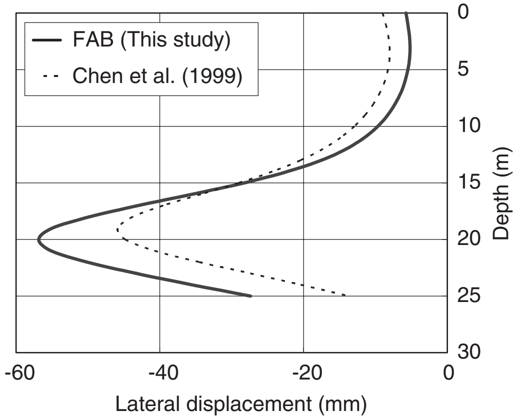

Figure 5. Comparison between Chen et al. (1999) and predictions of the current study of the lateral pile displacements induced by excavation of a long tunnel.

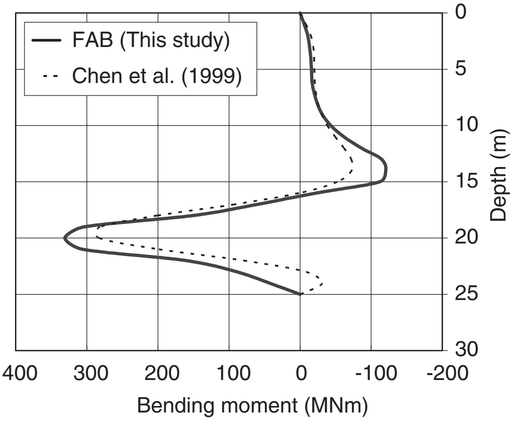

Figure 6. Comparison between Chen et al. (1999) and predictions of the current study of lateral bending moments induced in the pile by excavation of a long tunnel.

may not always be so close, particularly if the piles are located further from the tunnel.

4.2 *Case 4: Angel Underground Station*

A case history was reported by Lee *et al.* (1994) and Mair (1993) in which the lateral pile displacements were measured and recorded. The tunnel was excavated for the Angel Underground Station in London. Construction of the tunnel involved 2 stages: a pilot tunnel of 4.5 m diameter, followed by enlargement of the pilot tunnel to 8.25 m diameter. The measured incremental ground loss ratio was 1.5% for the pilot tunnel and 0.5% for the enlargement. Further details of the soil type and pile details can be found in the cited literature. No details of the stiffness of the pile have been reported and so an assumption of $E_p = 35{,}000$ MPa was used in this study.

In order to simulate the two construction stages, separate FAB analyses with corresponding tunnel geometry and ground loss values were conducted, i.e., the 4.5 m diameter pilot tunnel with a ground loss of 1.5% and an 8.25 m diameter tunnel assuming the extra 0.5% ground loss. The final ground response was obtained by superposition of the results of the two separate analyses. The cumulative lateral soil displacements obtained from this simple superposition were then used to predict the displacements of the pile located adjacent to the tunnel.

Figure 7 shows predictions of lateral displacements of the pile together with the predictions published by Chen *et al.* (1999) for this case and the measured lateral pile displacements reported by Lee *et al.* (1994). Figure 7 indicates that the FAB method provides a slightly conservative prediction relative to the measured values and to the predictions of Chen *et al.* (1999). Furthermore, the discrepancy observed at shallow depth for previous cases is not observed in Figure 7. This observation suggests that the FAB method might provide conservative predictions, even at shallow depth, for a stiff clay (like London clay) with small ground loss (2% or less).

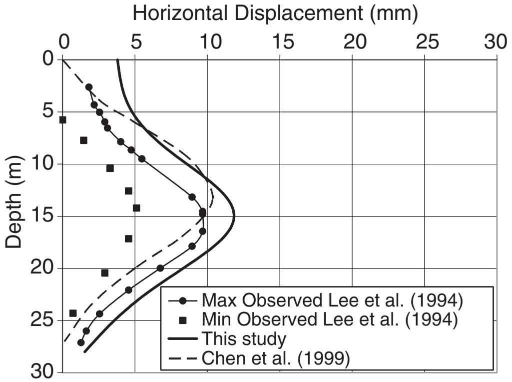

Figure 7. Measured and predicted horizontal pile displacements 5.7 m from the centreline of the tunnel for the Angel Underground Station, London, UK.

5 ADVANTAGES OF FAB METHOD

The major advantage of the combined finite and boundary element method (FAB) when used for tunnelling problems is that a unique 3-D finite element analysis is required for each tunnel configuration only, independent of the multitude of configurations of pile foundations that may be of interest. The displacement field generated by the finite element analysis, corresponding to tunnel excavation, is input as the free-field soil displacements in a separate boundary element analysis of the pile foundation. As accurate 3-D finite element predictions are relatively expensive in terms of data preparation (pre- and post-processing) and computer execution times, while boundary element analysis of a pile foundation is relatively inexpensive, this combination provides a good, practical compromise for design situations where detailed parametric studies may be required. For cases 3 and 4, the finite element and boundary element computation times are 952 seconds (55,650 d.o.f) and 1 second (86 d.o.f) respectively. In both cases the analysis was computed on a machine with an Intel Pentium 4 processor running at 3.07 GHz and the times quoted are for the set up and solution of only one load step (one tunnel excavation stage by 3-D finite element analysis and one corresponding pile analysis by PALLAS). It may be seen that in terms of execution time the boundary element solution time is a mere fraction (approximately 1/1000th) of the time needed for the full 3-D finite element analysis, thus representing a major saving over the cost of conducting the analysis of each pile and tunnel arrangement using the 3-D finite element approach.

This method therefore has the potential to generate economical predictions for a very large number of cases of practical interest, allowing design charts to be readily generated for this problem.

6 CONCLUSION

This paper has described an efficient and practical method of analysis to predict some important effects of tunnelling on single pile foundations. A brief summary of the method, its verification and applicability and a demonstration of its computational advantages have been discussed.

It was noted that only one 3-D finite element analysis is required, since the displacement field generated is then used as the input free-field soil displacements in a number of separate boundary element analyses of the proposed pile foundations. Hence, this will provide an economical method for detailed study of different pile foundations.

The proposed method was evaluated against well-documented case-histories and published solutions to investigate the extent of its applicability. Results were presented for horizontal components of induced ground displacements, pile displacements and bending moments induced in the pile by tunnel excavation. For the cases examined it was found that for soft clay conditions and large ground loss values, the proposed method provided a slightly lower prediction of the ground displacements at shallow depth. However, it still provides a conservative prediction of the ground movements in the vicinity of the tunnel and the bending moments induced in the pile. For stiff clays and for a tunnel with a small ground loss value (2% or less) the proposed method indicated remarkable agreement with measurements of pile and ground movements.

The method of analysis and the comparisons have been presented for the case of a single pile only. Although not reported here, this method of analysis has been extended to model the axial mode of pile deformation and to include pile groups in the boundary element treatment. Similarly, it is not necessary for the 3-D finite element method to be restricted to the analysis of linear elastic ground. The incorporation of non-linear soil behaviour into this method of tunnel analysis is relatively straightforward and can be combined with a separate boundary element treatment of the pile, which may also include the effects of non-linear soil behaviour, such as plastic yielding and the dependence of soil stiffness on strain level, on the pile-soil interaction. These additional complications are beyond the scope of the present paper but it is expected they will be described in future papers by the authors.

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