Combined Finite- and Boundary-Element Analysis of the Effects of Tunneling on Single Piles

J. Surjadinata[1]; T. S. Hull[2]; J. P. Carter[3]; and H. G. Poulos[4]

Abstract: An efficient and practical method of analysis to predict the effects of tunneling on existing single pile foundations is described. The method involves a combination of the finite- and boundary-element (FAB) methods, 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. The method allows prediction of the full three-dimensional (3D) response of the pile as tunnel excavation proceeds towards the pile and away from it. Very good agreement is obtained between predictions of the pile response obtained by the FAB method and a 3D finite-element analysis which specifically includes the pile in the finite-element mesh. The vastly superior computational efficiency of the FAB method over the full 3D finite element approach is also illustrated.

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Introduction

Underground construction, including tunneling, causes both vertical and lateral ground movements. For existing structures, the ground movements induced by activities such as tunneling may cause a reduction in bearing capacity of the foundations as well as the development of additional settlements, differential settlements, and lateral movements. If the existing building is supported on pile foundations, which extend down to, or just above, the level of the underground cavity, the effects of tunneling may possibly be more severe than if the building were supported on shallow foundations.

Research has been conducted into the effects of tunnel construction on buildings and pile foundations (e.g., Morton and King 1979; Lee et al. 1994; Burd et al. 2000) and especially for estimating the effects of tunnel construction for the London underground system on historic structures (e.g., Higgins et al. 1996; Standing et al. 1996; Potts and Addenbrooke 1997). Poulos and co-workers at the University of Sydney (e.g., Chen et al. 1998, 1999, 2000; Loganathan and Poulos 1998; Loganathan et al. 2000; Loganathan 1999), focused attention on the influence of tunnel excavation on single pile foundations. They demonstrated that the influence of tunneling on a single pile depends on a number of factors, including tunnel geometry, ground loss, soil strength, pile diameter, and the ratio of pile length to tunnel cover depth.

There is a need to understand much better the interaction between tunneling operations and existing pile foundations, and to develop efficient methods for predicting the influence of tunneling on the behavior of existing single piles and pile groups. Essentially the problem is three dimensional and so the cost of completing parametric studies may be very high if a conventional three-dimensional (3D) finite-element analysis is conducted for each and every case. The cost of such studies may become prohibitively high if nonlinear behavior of the soil surrounding the tunnel is to be included and if complicated construction sequences are to be taken into account.

The aim of this technical note is to describe an efficient method of analysis that can overcome the need for full 3D finite-element analysis of every case that might be considered in a parametric study. By combining the results of a single 3D analysis of tunnel excavation with a boundary-element analysis of a pile foundation or a pile group, a large number of cases can be analyzed very efficiently. The 3D finite-element analysis is required only for each tunnel configuration, 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 used as input as the free-field soil displacements in a separate boundary-element analysis of the pile foundation. This method, designated here as finite- and boundary-element (FAB) method, therefore has the potential to generate economical predictions for a very large number of cases of practical interest, allowing design charts to be generated for any given problem.

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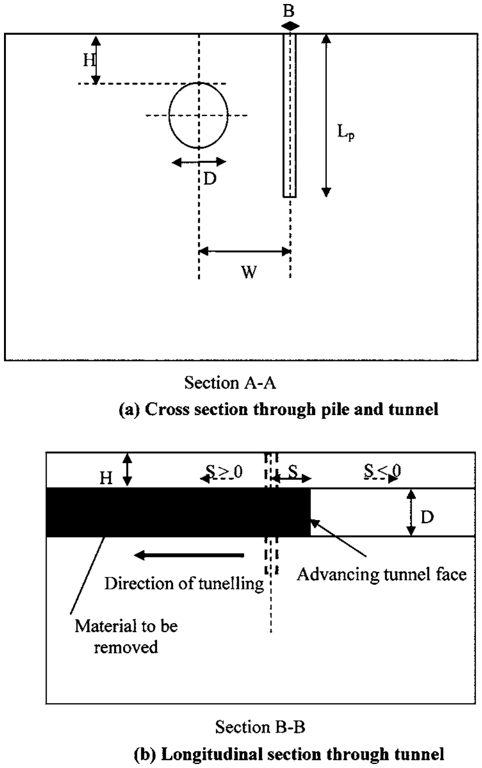

Fig. 1. Problem definition

Problem Definition

The hypothetical problem chosen to illustrate the combined method is indicated in Fig. 1, which shows vertical sections in the lateral ($x-y$ plane) direction and the longitudinal ($z-y$ plane) direction, respectively. The specific behavior of the pile discussed here is limited to the horizontal displacements and bending moments in the pile in the lateral (x) and longitudinal (z) directions. The circular tunnel has a diameter $D=7$ m with the depth of the soil cover over the tunnel, $H=17.5$ m $(2.5D)$. The various excavation stages considered in the analysis are distinguished by the distance along the axis of the tunnel between the tunnel face and the vertical plane passing through the centerline of the pile and perpendicular to the tunnel axis, denoted by the parameter S, as indicated in Fig. 1(b).

The soil is modeled here as a homogeneous isotropic elastic material throughout the depth of the model, with a uniform Young's modulus $E_s=35$ MPa and Poisson's ratio, $\nu_s=0.25$. The pile has a square cross section with its length $L_p=42$ m $(6D)$, width $B_p=1.2$ m, and Young's modulus $E_p=35{,}000$ MPa. For purposes of illustration it was also assumed that the distance between the tunnel axis and the pile axis, W, is one tunnel diameter $(W=D)$, i.e., the minimum possible distance between the vertical pile axis and the tunnel wall is 3.5 m $(0.5D)$.

Finite-Element Analysis of Soil Movements

The first step in this analysis of tunnel-pile interaction is to predict the elastic free-field soil displacements induced by a tunneling operation using a full 3D finite-element analysis. The model of the problem does not include a pile adjacent to the tunnel, but rather estimates the soil displacements due to tunneling without the pile in place. The finite element mesh used for this example includes 4,186 20-node isoparametric hexahedral elements with 18,550 nodes. Excavation of the tunnel was modeled in 14 discrete steps, covering a range of distances of the tunnel face from the vertical plane containing the pile, S [see Fig. 1(b)]. Each excavation stage was simulated in the conventional manner by removal of elements from the finite-element mesh to create the appropriate increment of tunnel void. In the present example appropriate force increments are applied to the new tunnel boundary to simulate complete removal of stress from the surface created by excavation, corresponding to the tunnel walls and face. Thereafter in the incremental analysis, this surface remains stress free. The number of steps used to excavate does not affect the results since the model is linear elastic (Brown and Booker 1985). Of course, in a more realistic model of the construction sequence, and especially for cases where the ground is represented by more sophisticated nonlinear soil models, the excavation would normally be more complex and might be represented, for example, by the imposition of tunnel boundary displacements corresponding to a predefined value of ground loss. The adoption of more realistic modeling of the construction sequence is possible with the proposed method, but for simplicity only the creation of a stress free tunnel boundary has been adopted for this illustrative example.

Although for convenience an isotropic elastic model has been used here to represent the ground behavior, the overall method is not limited to such simple idealizations. Indeed, it is important to note that the same approach can be adopted with much more sophisticated and complex material models of the ground response.

Boundary-Element Analysis of Pile Response

The free-field soil displacements predicted by the finite-element model are used as input to a special boundary-element analysis (Hull 1998) of a single pile surrounded by elastic soil in order to predict the response of the pile to those soil movements and thus also in response to the tunnel excavation. In this method use is made of integration of the solution of Mindlin (1936) for displacements due to a point load embedded in a semi-infinite elastic half space, as published by Douglas and Davis (1964).

In order to carry out an elastic analysis of the lateral movements of the soil and the pile in a single vertical plane, each pile is discretized along its length to have N elements and the finite difference solution of the beam bending equation is applied at discrete nodal locations along the pile. It is found that typically $N=30-40$ provides an accurate boundary element representation of most single piles.

Verification

In order to establish confidence in the predictions of pile response using the boundary-element method, comparisons have been made with predictions obtained using a full three-dimensional finite-element analysis, in which the pile is explicitly included in the mesh. These comparisons are presented in Figs. 2–5. Figs. 2 and 3 provide comparison of lateral displacements of the pile and the corresponding bending moments, respectively, while Figs. 4 and 5 show comparisons of the longitudinal displacements of the pile and the corresponding bending moments. All figures suggest at least reasonable, but mostly very close agreement between the predictions of the two numerical methods, providing confidence

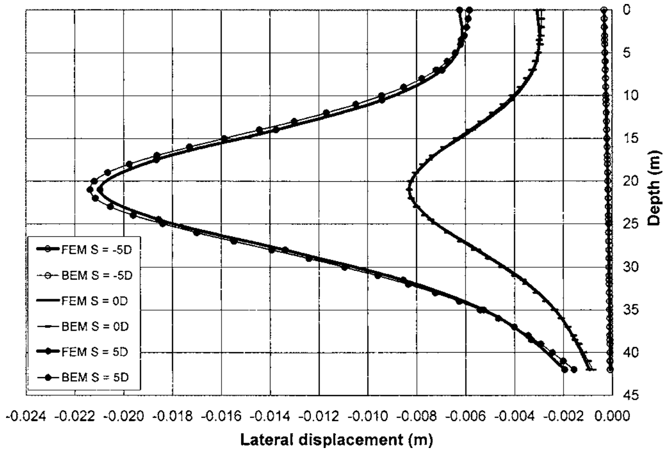

Fig. 2. Comparison of FE and BE predictions of lateral pile displacements

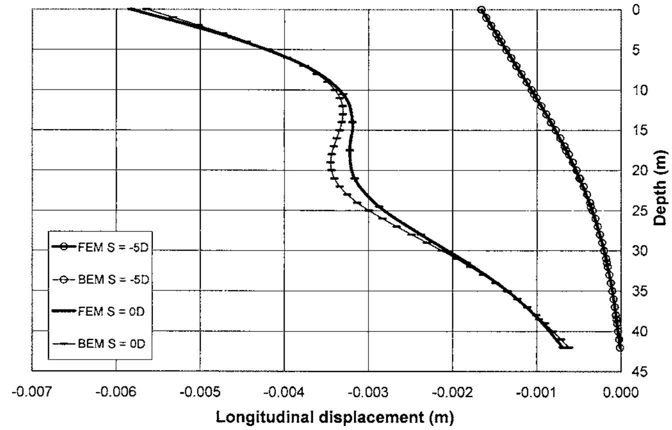

Fig. 4. Comparison of FE and BE predictions of longitudinal pile displacements

in the use of the boundary-element method to predict the pile response.

Advantages of Combined Method

The major advantage of the combined FAB method for this type of problem is that a unique 3D finite-element analysis is required only for each tunnel configuration, 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 an entirely separate boundary element analysis of the pile foundation. As accurate 3D 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. An indication of the relative cost of the finite-element and boundary-element computation times is presented in Table 1 for the typical problem investigated in this paper. Each was computed on a machine with an Intel Pentium 4 processor running at 3.07 GHz and the times quoted are for the setup and solution of only one load step (one tunnel excavation stage by 3D finite-element analysis and one corresponding pile analysis using boundary elements). It may be seen that in terms of execution time the boundary-element solution time is a mere fraction (approximately 1/1,000th) of the time needed for the full 3D finite-element analysis, thus representing a major saving over the cost of conducting the analysis of each pile and tunnel arrangement using the 3D 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.

Conclusions

An efficient and practical method of analysis to predict some important effects of tunneling on single pile foundations has been suggested. It is noted that the 3D finite-element analysis is required only for each tunnel configuration, independent of the multitude of configurations of pile foundations that may be of interest. Indeed, just one finite-element analysis with an appropriate mesh can furnish all the ground movement data required to predict the response of the pile in any chosen number of positions

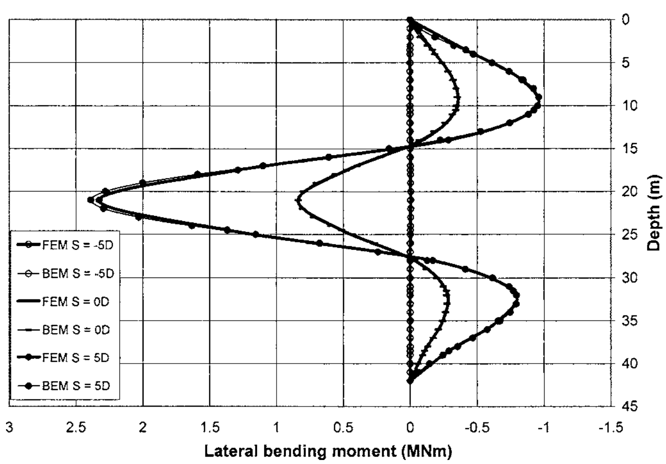

Fig. 3. Comparison of FE and BE predictions of lateral bending moments in pile

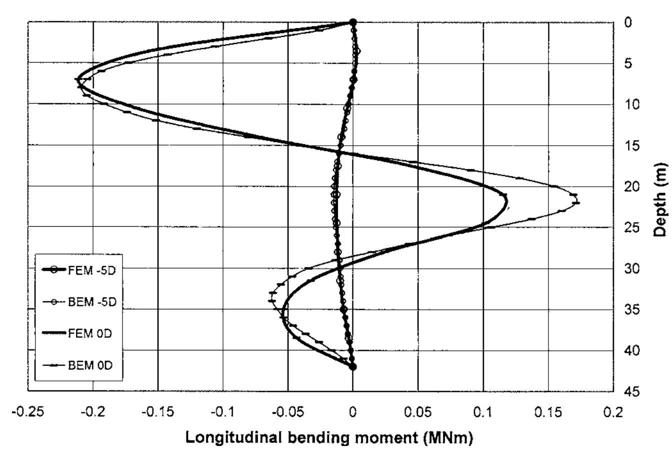

Fig. 5. Comparison of FE and BE predictions of longitudinal bending moments in pile

Table 1. Comparison of Computer Execution Times for Pile and Tunnel Problems

Method	Typical problem size	CPU time for single excavation stage (sees)	Processor
3D finite element	18,550 nodes 4,186 elements 55,650 degrees of freedom	952	Pentium 4 at 3.07 GHz
2D boundary element	43 nodes 43 elements 86 degrees of freedom	1	Pentium 4 at 3.07 GHz

corresponding to various distances S from the tunnel face. The displacement field generated by the finite-element analysis, corresponding to tunnel excavation, is used as input as the free-field soil displacements in a separate boundary-element analysis of the pile foundation, thus providing an economical method for detailed study of problems of this type.

The method of analysis and some typical results have been presented for the case of a single pile only, and then only for the bending response of the pile. It is not difficult to extend this method of analysis to include the axial mode of pile deformation and to include pile groups in the boundary-element treatment. Similarly, it is not necessary for the 3D finite-element method to be restricted to the analysis of linear elastic ground. The incorporation of nonlinear soil behavior 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 nonlinear soil behavior, 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 note but it is expected they will form the basis of future papers by the writers.

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