Analysis of tunnel-induced settlement damage to surface structures
Analyse des dégâts créés par tunnels sur les constructions en surface

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ABSTRACT: Transport developments in cities often involve tunnelling, which inevitably leads to ground movements. These must be carefully predicted if there is a risk of settlement damage to nearby structures. Tunnel-induced settlements may be predicted empirically for greenfield sites, but surface structures modify these movements. Two-dimensional models, often used in practice, neglect the effect of transients as the tunnel is excavated, and do not allow realistic models of buildings. Research on a 3-D numerical model of tunnelling is described. This includes a building and a simulation of tunnel construction processes. Interactions between the building and the ground are investigated. Settlement, and structural damage, is studied as the tunnel installation proceeds. An analysis of a building unsymmetrical in plan to the tunnelling direction is presented.

RÉSUMÉ: Le développement des transports implique souvent la construction de tunnels qui entraine des mouvements du sol. Ceux-ci doivent être prédits en cas de risque de dégâts sur les contructions avoisinantes. Les effets peuvent être présdits empiriquement pour des terrains vierges mais la présence de constructions en surface modifie ces mouvements. Les modèles 2D, négligent les effets transitoires dus à la periode d'excavation du tunnel. Les recherches sur un modèle numérique 3D sont décrites. Elles comprennent la prise en compte d'un batiment et une simulation des processus de construction d'un tunnel. Les interactions entre le batiment et le sol sont étudiées. Settlement et les dégâts structuraux sont étudiés à mesure que l'installation du tunnel se fait. L'analyse d'un batiment non symétrique par rapport au plan de la direction du tunnel est présentée.

1 SUMMARY OF THE RESEARCH PROGRAMME

The purpose of the research described here is to develop a comprehensive numerical model, able to provide realistic modelling of the interaction between tunnelling processes and buildings. The long-term intention is that such a model should become a useful predictive tool for design. Central to the analysis is the recognition that the tunnel, the ground and any adjacent buildings are inextricably linked, and that the analysis must take into account their mutual interaction. This contrast with many current techniques (some even involving quite sophisticated numerical methods) in which an analysis of the ground deformation is made without accounting for the influence of buildings. It is further recognised that, in spite of the attractions of simplified 2-dimensional analysis, it is only possible to model the interaction if the 3-dimensional nature of the problem is accounted for.

The research programme has been divided into three main phases as detailed below.

1.1 *Preliminary studies*

These included:

- 2-D finite element analysis examining the effect of different material models on the shape of greenfield settlement troughs (Chow, 1994). This showed that the most realistic (*i.e.* narrowest) settlement troughs were predicted when the nonlinearity of soils at small strains was modelled.
- Modelling of masonry structures using a commercially available package (ABAQUS). Simple displacement profiles were applied to building façades, using a variety of different material

models (Parry-Jones and Cline, 1993). Some information on likely patterns of damage for buildings was obtained, and further research was needed on the modelling of the masonry.

- Preliminary 3-D studies investigating methods of coupling the ground and building (Hurst, 1994, Curtis, 1995). These proved the value of commercially available mesh generation software (I-DEAS) for this project.

1.2 *The main research phase*

This involved the development of a finite element model with the following features:

- A 3-D block of ground, modelled as undrained clay, using a specially developed soil model accounting for the nonlinearity of soil at small strains using a nested-surface plasticity approach. Tunnel construction is modelled by progressive removal of elements (Augarde, 1997).
- A model of a masonry building in which the structure is represented by a series of interconnected façades constructed from 2-D plane stress elements. The masonry behaves as elastic in compression, but as unable to sustain tension. Specially developed tie elements are used to connect the 2-D façades together, and to connect them to the ground (Liu, 1997).
- Modelling of the installation of a tunnel lining. The liner is modelled using special shell elements which use the overlapping facet technique to avoid the need for rotational degrees-of-freedom in the analysis (Phaal & Calladine, 1992, Augarde, 1997). The ground loss associated with imperfect installation of the liner is modelled by a method in which the liner diameter is shrunk by a controlled amount after installation.

The main conclusions from this phase of the research (some of which are illustrated below, and others reported by Burd *et al.*, 1998) are:

- A building has an important effect on the settlements caused by nearby tunnelling operations.
- Façades subjected to sagging displacements are resistant to crack damage because of the restraint provided by the ground; they retain much of their bending stiffness and therefore suffer differential settlements that are less than would be estimated from greenfield analysis.
- Façades subjected to a hogging mode of displacements are highly susceptible to crack damage, with consequential loss of bending stiffness.

1.3 *Development phase*

The research is currently continuing, with developments being in four main areas:

- Confidence in any numerical analysis technique can only be achieved by careful comparison with case histories. Work is in progress comparing analyses with the results of monitoring exercises at a number of sites, principally in London, where tunnels and shafts have been excavated close to major masonry buildings. Analysis of particular sites inevitably leads to more complex models than those used in the earlier main research phase.
- The complex 3-D analyses using non-linear soil models are extremely demanding on computing resources (both in terms of memory and processor time), since finely detailed meshes and many analysis steps are necessary to capture the details of the problem. Some success has been reported in reducing computation time using iterative solution techniques, so these methods are being explored. Most computations are now being made on the Oxford Supercomputing Centre’s 84-processor Origin 2000 machine, so that parallel computing techniques can be exploited. Equally important is the machine’s exceptionally large RAM memory (21Gbytes), which makes possible large analyses which could not be attempted on a conventional machine.
- Further attention is being given to the details of the tunnel lining, and of the modelling of the processes of volume loss.
- In many cases where it appears that predicted settlement damage might be unacceptable, compensation grouting is becoming the favoured technique for alleviating the problem. It is necessary therefore to model compensation grouting in the analysis, so that alternative grouting schemes can be examined and their efficacy assessed. Modelling of grouting is in progress.
- The present analysis examines short-term (undrained) movements only, since these are viewed as being of primary importance. This will be extended to include time-dependent response, which will be of particular interest in the cases where compensation grouting is employed.

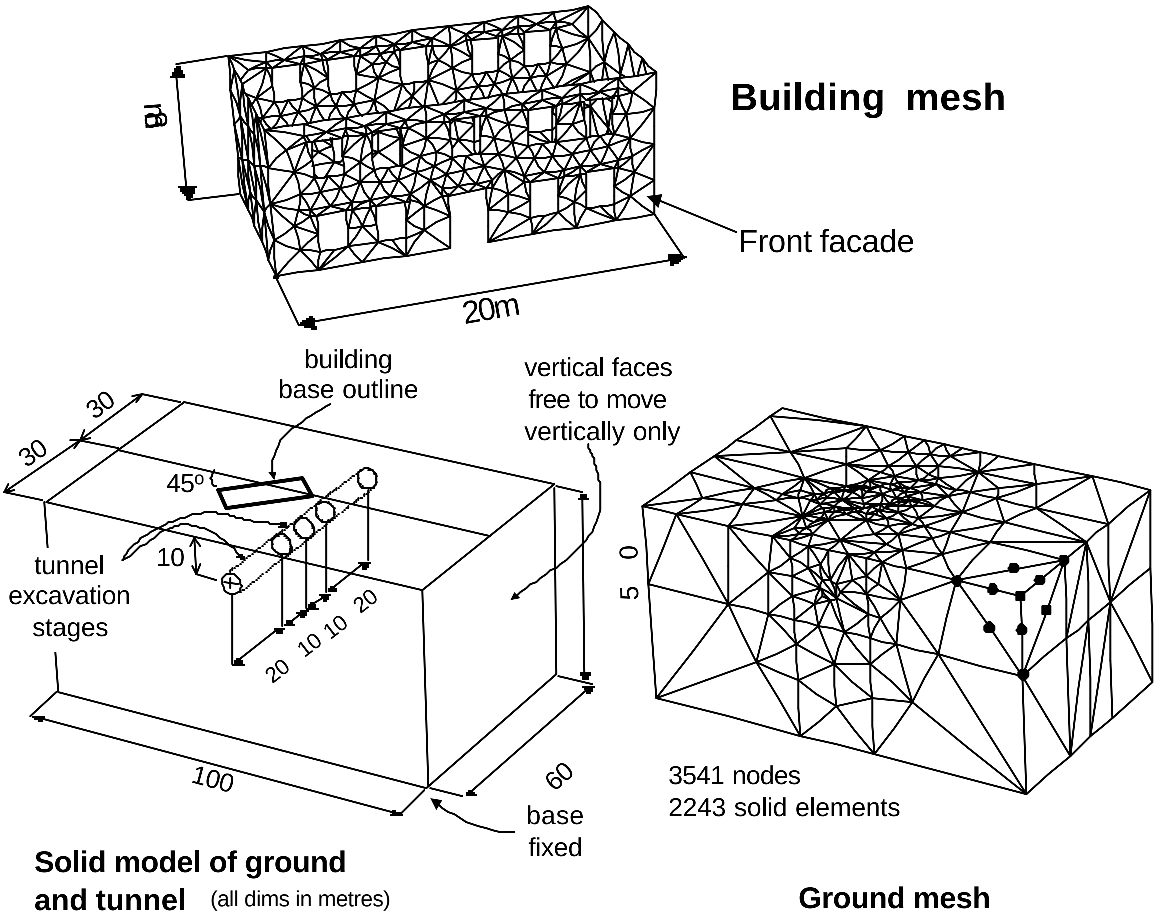
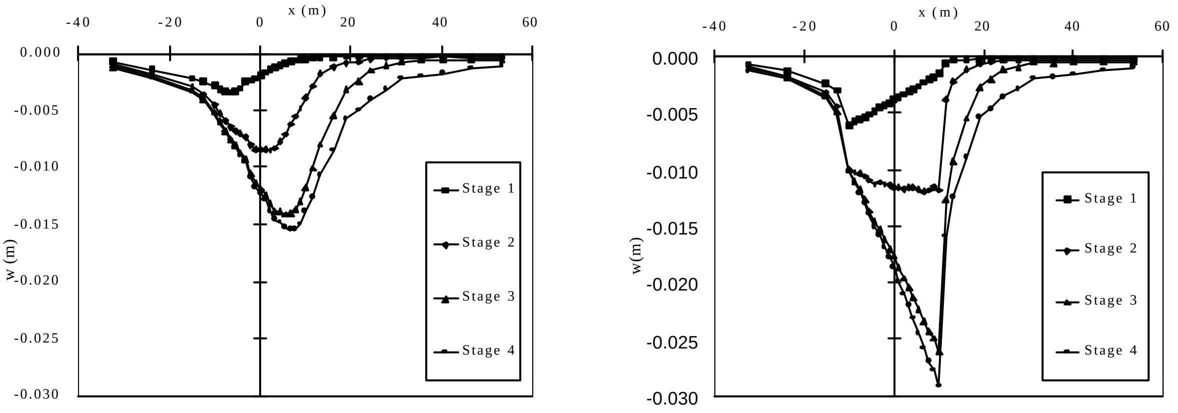


Figure 1. Outline of finite element analysis

2 AN EXAMPLE CALCULATION

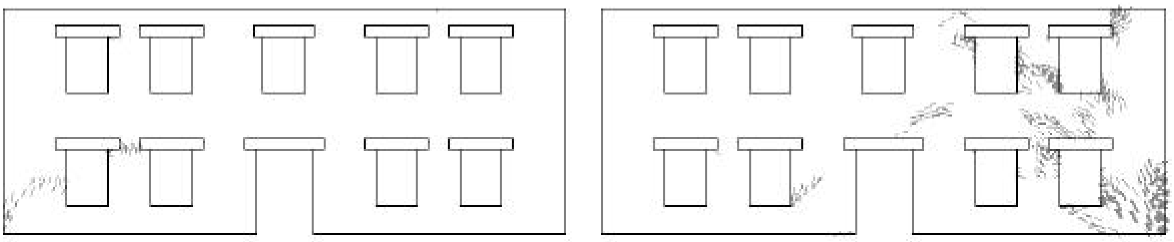
The example used here is drawn from the analyses in the main phase of the research, and is reported in detail by Liu (1997). It concerns a single tunnel of diameter 5m, excavated at a depth (to centreline) of 10m. The properties of the soil through which the tunnel is excavated are chosen to be typical of London Clay. Analyses of unlined tunnels are reported here, but in other analyses a liner is included (Augarde, 1997). The tunnel passes obliquely under the corner of a masonry building, 20m by 10m in plan, see Figure 1. The building is modelled as four planes of six-noded triangular elements to form the façades. The longer sides include a regular pattern of openings for windows and doors, whilst the shorter sides are plain gables. No internal structure of the building is modelled, since in a masonry building the internal structure is usually considerably lighter and more flexible than the main façades.

Two analyses are briefly reported here. In the first the tunnel is constructed as if it were under a greenfield site. The predicted settlements around the perimeter of the building are then applied to a separate model of the structure. In the second analysis the building is fully coupled to the foundation, so that there is an interaction between the stiffness of the building and the ground. Clearly the second analysis is expected to be the more realistic, and the comparison between the two analyses is made to highlight the importance of carrying out the coupled analysis.



(a) greenfield analysis (b) coupled analysis

Figure 2: Settlement profiles for greenfield and coupled analysis



(a) end of Stage 1 (b) end of Stage 4

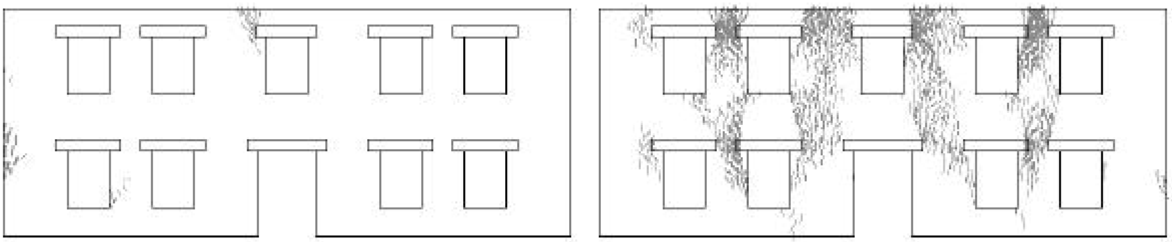
Figure 3: Patterns of cracking damage to front façade (greenfield analysis)

The settlement profiles along the front façade of the building (*i.e.* the one facing the advancing tunnel) are given in Figure 2(a) for the greenfield analysis for four stages in the advance of the tunnel. The maximum settlement is at first near the left-hand end of the façade, since at first this is closest to the advancing tunnel, but shifts to the right as tunnelling progresses, since the centreline of the tunnel passes under the right hand end of the building. The corresponding results for the coupled analysis are shown in Figure 2(b). Note that the stiff façade maintains an almost straight base. At first it tilts slightly to the left, then more strongly to the right. The absolute value of the settlements is larger than for the greenfield. This is because the weight of the building triggers larger local downward movement.

Figure 3 shows schematically the predicted pattern of cracking damage to the front façade at the end of Stage 1 (Figure 3(a)) and the end of Stage 4 (Figure 3(b)). On these figures a line is drawn parallel to the crack direction for each integration point where cracking exceeds $500\mu\varepsilon$, and two lines if cracking exceeds $1000\mu\varepsilon$ and so on. A cracking intensity of $1000\mu\varepsilon$ would represent one crack of 1.0mm every metre. Although an averaged indication of cracking intensity can be obtained, the analysis does not predict the precise size and location of individual cracks. It can be seen that early in the analysis some minor cracking at the left hand end of the façade is predicted, and later these cracks re-close and more major cracking occurs at the right hand end. Bearing in mind the fact that the cracks are parallel to the direction of major principal stress, it can be seen that there is arching action in the masonry over the settlement trough at the right hand side of the façade.

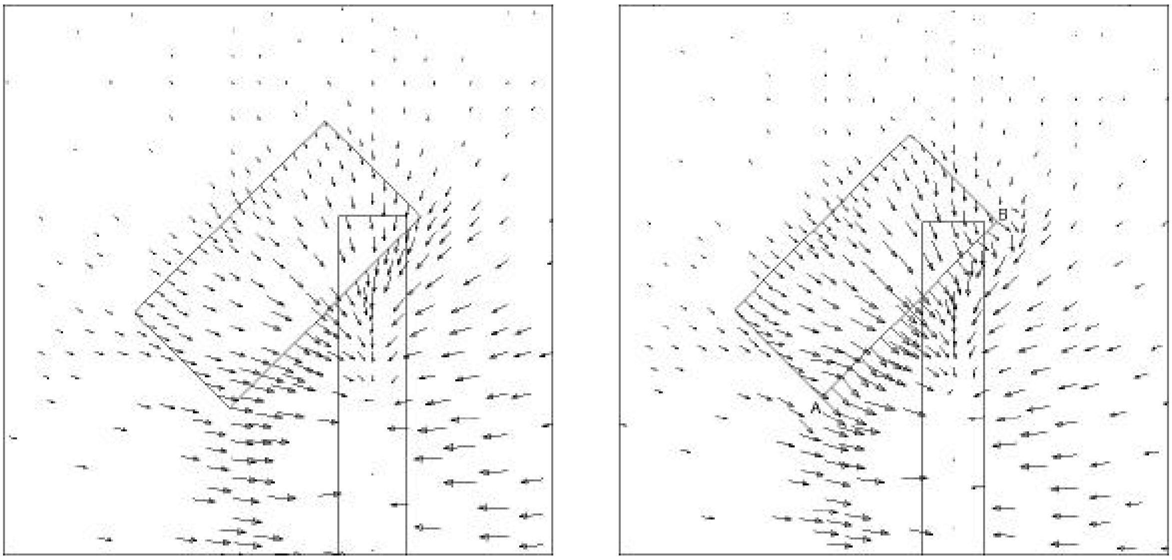
In contrast, Figure 4(a) shows the predicted crack damage for the front façade at the end of the coupled analysis. The cracking damage is much more localized, because the distortion of the masonry structure is much less than that implied by the greenfield analysis. The contrast between Figures 3(b) and 4(a) demonstrates clearly the need for the coupled analysis.

The cracking pattern predicted from the coupled analysis for the rear façade is shown in Figure 4(b). This part of the masonry structure is subjected to hogging deformation, which causes the top



(a) front façade (b) rear façade

Figure 4: Patterns of cracking damage for front and rear façades from coupled analysis



(a) greenfield analysis (b) coupled analysis

Figure 5: Horizontal movements in greenfield and coupled analysis

of the structure to crack vertically, and results in almost total loss of bending stiffness of the rear façade. As a result it has much less influence on the local ground deformations than the front façade, so in this case the crack pattern is in fact rather similar to that predicted in the greenfield analysis. It is interesting to note that, in this case, the rear façade is subjected to more severe cracking than the front façade. This reflects a consistent feature of the numerical model that façades subjected to hogging deformations, such as the rear façade, are more prone to damage than façades subjected to a sagging mode, such as the front. This demonstrates that it is not sufficient to model the masonry as elastic: masonry structures show complex non-linear responses which depend on the nature of the loading.

Figure 5(a) and (b) show the horizontal movements of the ground surface predicted at the end of Stage 2 for the greenfield and coupled analyses respectively. Horizontal movements often do not receive as much attention as settlements, but they can be equally damaging to buildings. In the greenfield analysis it can be seen that the displacement vectors (much exaggerated) are all directed towards the tunnel centreline and are of course undisturbed by the building, the outline of which is shown on the figure. Close attention to Figure 5(b) shows that the pattern of horizontal movement around the building is significantly different, particularly near the front corners A and B. The stiffness of the building changes the local pattern of deformations.

Clearly the details of horizontal movements (as well as settlements) would depend on precise nature of the foundation of the building. In the analysis presented here the foundation was effectively modelled as a strip surface footing, with no detail included. More advanced modelling of the foundation is clearly desirable.

3 CONCLUSIONS

Advanced numerical techniques are capable of modelling complex problems of soil-structure interaction involving the influence of tunnelling operations on masonry buildings. The model described here does not model the fine detail of the building or its foundations, and further work is needed to develop it as a practical design tool. It does, however, suggest some general mechanisms of interaction between the building and the ground. These are summarized as follows:

- The presence of the building modifies the pattern of ground movements both qualitatively and quantitatively
- The nature of any cracking damage changes as the tunnel progresses. Crack systems may open and close as the tunnel passes beneath the building.
- Façades subjected to hogging deformation are more prone to cracking damage than those subjected to sagging deformation.

4 ACKNOWLEDGEMENTS

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