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An example of a pile-tunnel interaction problem

K.G. Higgins & H.D. St. John
Geotechnical Consulting Group, London, UK

I.L.J. Chudleigh
London Underground Limited, UK

D.M. Potts
Imperial College of Science Technology and Medicine, London, UK

ABSTRACT: This paper discusses problems associated with the analysis of piles installed close to existing tunnels. The need for a rational set of guidelines for developers and owners of tunnels is highlighted. A case history is reviewed and a procedure for analysing such problems is outlined.

1 INTRODUCTION

In a dense urban environment such as London, re-development of sites is commonplace and this often involves installation of piles. With an underground system as extensive as London Underground Ltd's, and with other sub-surface infrastructure, piles are often installed very close to tunnels. However, the interaction between piles and tunnels is not a particularly well understood problem, possibly because of its complexity.

This lack of knowledge presents a problem, not only for developers, but also for the owners of the tunnels. The presence of a tunnel, and the inevitable disturbance to the ground caused by its construction, may have implications for the design of the piles. Equally the effects of piles on tunnels must be considered. Apart from implications for the structural integrity of the lining, in the case of an underground railway, excessive distortions may reduce clearances between the tunnels linings and trains. Installations, such as escalators, might be affected and under certain circumstances this can pose a threat to passenger safety.

2 BACKGROUND

There are a number of instances where tunnels have been constructed close to piled foundations and detailed observations have been made. Mair & Taylor (1997) reviewed case histories relating to the effects of tunnelling on piled foundations and reported two examples:

- A 7.5m diameter tunnel constructed between bored pile foundations for a six storey building in London (Mair 1993 & Lee et al 1994). The tunnel was constructed between the piles, the closest pile being approximately 1m form the extrados of the tunnel. The foundations allowed for the construction of the tunnel; piles were slip coated along their entire length to within 4m of their base. Measurements were made of lateral movements of the piles and up to 10mm was recorded. Vertical displacements were negligible.
- Two 7.9m diameter tunnels constructed adjacent to a building with piled foundations in Hong Kong (Forth & Thorley 1996). Measured settlement due to construction of the tunnel was 12mm.

Mair & Taylor (1997) also reviewed the results of numerical analyses and model tests relating to the same problem. Procedures have been developed for the analysis of this problem (e.g. Chen & Poulos 1997) but it is apparent that very few case histories exist and there is a need for more field measurements in order that these procedures, numerical models and model tests can be validated.

A review of the literature suggests that there are even fewer case histories of pile construction close to existing tunnels and yet in an urban environment, such as London, this is a relatively common problem. There is therefore a need for research into this problem in order that a set of rational guidelines can be developed for use in practice.

3 CURRENT GUIDELINES

Owners of tunnels generally set criteria which range from "there will be no effect" to limits on distortion of the tunnel, limits on absolute movement or limits on the applied loading. Other criteria include limits on how close to a tunnel, or tunnels, piles may be constructed.

However, these criteria rarely relate to the size of a tunnel, the form of the lining, the presence of other tunnels in close proximity that may affect behaviour, the type of pile, the size of piles, pile spacing or their capacity. They make no statement about the structural integrity of the tunnel lining; under some circumstances a small change in load may prove problematic, under other circumstances much larger changes of loading may be well within the capacity of the lining. Equally under certain circumstances a small distortion may be critical (e.g. in the case of a railway tunnel, clearances between the lining and the kinematic envelope are reduced to unacceptable levels) but under other circumstances larger distortions may be quite acceptable particularly if there is a tendency to restore the original profile of the tunnel.

These general guidelines are very useful as part of a screening process to determine whether or not certain situations may be problematic. However, there is continual pressure from developers to relax these guidelines since adhering to them can have serious cost implications. It is not necessarily in the interests of the owners of a tunnel to do so.

It is only by a rational approach that it can be demonstrated whether or not piling close to a tunnel will be detrimental or not.

4 SLIP LINERS AS A MEASURE TO MITIGATE THE EFFECTS OF PILE LOADING

A commonly adopted procedure for reducing the interaction between piles and tunnels, due to application of load to the piles, is to install piles with slip coated sleeves above the level of the tunnel's invert. There are no hard and fast rules concerning the use of slip liners although they are often installed as reassurance to the owners of tunnels.

When slip coats are used, theoretically, all the applied loads are transferred into the ground below the tunnel. While this might limit circumferential distortions of a lining, it is possible that longitudinal distortion could be greater with a slip liner than if there were no liner. This is simply because displacements below the tunnel are greater. The effect of omitting the slip liner is to increase the load carrying capacity of the pile and therefore decrease displacements of the ground.

However, preliminary numerical studies of a particular situation have compared the effects of loading piles, of the same dimensions, with and without slip coating. It was shown that in reality there is little difference between the two conditions when ground distortions created near to tunnels are compared. This is particularly true for end bearing piles but similar results are obtained with friction piles provided conventional design criteria are met. Further work is needed to fully investigate how slip liners actually behave under these circumstances.

It is also worth considering the whether or not the risks involved with the installation of slip liners outweigh the benefits of such precautions. Installing slip liners necessitates creation of oversized holes near to tunnels and delays construction

There is obviously a balance to be obtained and each situation must be considered very carefully.

5 REQUIREMENTS FOR ANALYSIS

Any analysis must consider the existing stress state within the tunnel lining and its profile before piling starts. The analysis must therefore consider the following:

- The stress history of the site including tunnel construction and subsequent development that may affect the tunnel in the long term.
- It must represent the tunnel lining in a realistic way ensuring that artificial restraints are not imposed. It would not be conservative to model the lining only as a stiff ring because this is likely to underestimate distortions. Equally modelling the lining as a fully flexible element would not be conservative when considering its structural integrity. The elements that make up the lining must therefore be considered together with the connections between them. In the case of a segmental lining this makes the problem very complex.

The piles must also be modelled in a realistic way. This should include installation effects and any measures taken to mitigate the effects of the foundation on the tunnel (e.g. slip coating and sleeving).

When making assessments of the effects of construction on tunnels it is normally necessary to consider longitudinal distortion and to make some statements about it. It may be that longitudinal distortion is more critical than distortion of a ring.

6 METHOD OF ANALYSIS

The method of analysis adopted must realistically represent the non-linearity of soil behaviour combined with the non-linearity of the tunnel lining (articulation between segments in the case of a segmental tunnel and strain/stress dependant behaviour for other forms of lining). This has to be combined with a realistic representation of piles which may vary in size, loading and position (piles may be sufficiently far apart that the tunnel reacts to a series of isolated piles). Only full numerical analysis is really capable of considering all these possible influences but these problems are obviously very complex.

Eventually fully 3D analysis will be used to analyse these problems. Despite the ever increasing capacity of computers, it is questionable if, at present, reliable 3D analyses can be undertaken that met all the requirements outlined, particularly in a commercial environment. In practice there are often severe restrictions on time, and cost, and any approach has to be fully justified. Certainly before such an approach could be justified some comparisons between predictions and measurements have to be made but unfortunately there is a lack of reliable data.

7 CASE STUDY

The following example is fairly typical of situations that are encountered.

A development is to be constructed above an Underground station and the building is to be supported on piles. Figure 1 shows a schematic plan of the Site. Piles were to be installed either side of station tunnels (approximately 7m in diameter), running tunnels (approximately 4m in diameter) and an escalator shaft (there is obvious sensitivity about the behaviour of the escalator within the shaft). The escalator shaft runs from ground level to meet the station tunnels approximately 18 m below ground level.

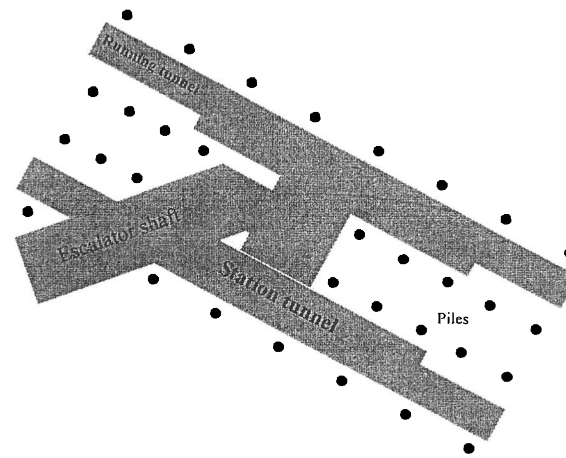

Figure 1. Schematic layout of the site

There is approximately 9 m of Made Ground, Alluvium and Gravel above London clay. Beneath the London clay are the Lambeth Beds which are about 40m below ground level. The piles are up to 60m deep, they vary in size up to 1.8m in diameter and are typically at 7 x 14m centres on a grid. They are to be loaded up to 26MN per pile. The upper section of the piles, from the top of the piles down to the level of the tunnel's crown, was sleeved in order to minimise the load transferred from the pile to the tunnel. Importantly ground level was to be reduced to form a piling platform before piles are installed.

To analyse the problem a procedure based on two dimensional analyses was developed. This was as follows:

Stage 1: A two dimensional analysis of historic site development and tunnel construction in order to assess the state of stress within the ground before pile installation. This analysis, and all the subsequent analyses, used non-linear elastic (Jardine et al. 1986) perfectly plastic constitutive models for the soil. To model tunnel construction the approach described by Panet & Guenot (1982) was adopted (suites of analyses were run different values of "λ", a measure of the degree of stress relief associated with tunnel construction, corresponding to volume losses in the range 1.5% to 2%).

Stage 2: An axi-symmetric analysis of pile installation using the initial stress distribution derived from Stage 1. This included excavation of the shaft, installation of sleeving and application of pressure to the boundary of the excavation to account for the pressure exerted by concrete. In this case the pressure distribution was based on the observations reported by Ng (1992).

Stage 3: Extension of the Stage 2 analysis to account for undrained loading and drainage in the clays in the long term.

Stage 4: Integration of the results from Stages 2 and 3 to account for interaction between piles.

Stage 5: Extension of Stage 1 analysis with imposed boundary conditions from Stage 4 including pile installation, undrained loading and long term conditions.

Analyses (Stages 1 to 5) were run with the tunnel lining represented as a "stiff ring" with the appropriate bending and axial stiffnesses. The suite of analyses were repeated with an allowance made for articulation between segments under specified loading conditions. Bolt action was ignored. The first suite of analyses, with the tunnel as a "stiff" ring, were therefore conservative as far the structural integrity of the lining was concerned, the second set of analyses were conservative as far as distortion was concerned. Analyses were also run with variations in the assumed volume loss during tunnel construction.

Although there are obvious limitations to the analyses and the procedure is lengthy it was considered to be superior to a plane strain analysis in which the piles were effectively represented as a continuous strip.

The results of the analyses suggested that during pile installation the distortion of the tunnel would be no more than 1mm and that loading of the piles would cause the tunnel to move downwards by about 5mm but distortion was still about 1mm in the short term. Predicted movements of the pile were consistent with experience of similar sized piles under similar loadings, approximately 11mm settlement measured at the pile head. In the long term, distortion of the tunnel was about 5mm with the slip coated sleeves as specified.

Analyses were also undertaken with the slip coating and sleeving installed only through the superficial material, down to the top of the London Clay. This analysis showed that, in the short term, the reduction in length of sleeving did not compromise the structural integrity of the lining and distortions were similar in both cases.

Obviously any procedure can only be validated by field measurements. Such measurements are very difficult to make in tunnels that are in use (e.g. sewers or rail tunnels). At this site monitoring schemes have been installed in order that the predictions can be compared with measurements. The piles have yet to be fully loaded but it appears installation effects have been predicted reasonably well.. Measurements will continue to be taken in order to obtain information on short term and long term effects.

8 MEASUREMENTS

Field measurements require the co-operation of the tunnel owners. In the case of a railway, access is restricted to times when the track is not operational and power has been turned off. The co-operation of developers is also needed in order that these measurements can be related to construction activity.

At the site discussed two monitoring systems have been installed. One system is the minimum required by the tunnel owner to ensure that construction does not compromise the integrity of the lining and clearances do not fall below acceptable levels. A second system has been installed, at the expense of the owner of the tunnels, in order to obtain more detailed information and to compliment current numerical research at Imperial College which they are partially sponsoring.

So far instruments have only been installed in the running tunnels and in the Station tunnels. There are plans to install instruments on the escalator and in the shaft when that part of the development goes ahead. However, measurements are currently being made of tunnel distortion and the segmental cast iron linings have been instrumented with strain gauges. In addition to the "basic package" measurements are being made of ground movements around the tunnel. Horizontal strings of electolevels have been installed in the ground from the tunnels to measure relative vertical ground movements together with extensometers, which also radiate from the tunnel, that are intended to measure relative horizontal displacement. In addition to these readings a geodetic survey is being undertaken at regular intervals in order to measure absolute, rather than relative, movements.

9 CONCLUDING REMARKS

Although the installation of piles close to tunnels is a relatively common problem in a dense urban environment such as London, there is very little information on how piles and tunnels interact. There is an obvious need for more information on the subject and for reliable and detailed measurements combined with rigorous analysis to develop rational guidelines. This need was recently recognised by the Institution of Civil Engineers through a research and development enabling fund award to one of the authors.

Unfortunately this is a very complex problem that necessitates the tunnel lining being modelled in such a way that neither distortions or structural forces and bending moments are underestimated. In the case of a segmental lining, not uncommon in London, there are real difficulties in producing meaningful analyses. Even so a procedure has been proposed for the analysis of these problems. Although this is no substitute for a fully three dimensional analysis, despite its limitations, it is a reasonable approach and economic to perform. Validation of this approach is currently underway by comparing results with observations but a preliminary assessment is encouraging.

REFERENCES

Chen L.T. & Poulos H.G. 1997. Effects of tunnelling on piled foundations. *Proceedings of the 9th International Conference on computer Methods and Advances in Geomechanics,* Wuhan, November 1997, Balkema.

Forth R.A. & Thorley C.B.B 199). Hong Kong Island Line - Predictions and Performance. *Proc. of the Int. Symp. on Geotechnical Aspects of Underground Construction in Soft Ground,* City University, London. Balkema.

Jardine, R.J. Potts, D.M. Fourie A.B. & Burland, J.B. 1986 Studies of the influence of non-linear stress-strain characteristics in soil-structure interaction. *Geotechnique*, 36, No. (3): 377-396.

Lee K.M., Turner A.J., & Whitworth L.J. 1994 Deformations caused by tunnelling beneath a piled structure. *Proceedings 13th International Conference on Soil Mechanics and Foundation Engineering*, New Deli, vol (2): 873-878.

Mair R.J. 1993. The Unwin Memorial Lecture 1992 Developments in geotechnical engineering research: application to tunnels and deep excavations. *Proceedings of the Institution of Civil Engineers*. Civil Engineering, 1993, 93, Feb: 27-41.

Mair R.J. & Taylor R.N.1997. Bored tunnelling in the urban environment. Theme lecture to the *14th International Conference on Soil Mechanics and Geotechnical Engineering,* Hamberg, September 1997.

Ng C.W.W.1992. Discussion, session1. *Proceedings of Conference on Retaining Structures*, Cambridge. Thomas Telford, London, 1992.

Panet M & Guenot A.1982. Analysis of convergence behind the face of a tunnel. *Tunnelling* '82, IMM, 197-204.