Geotechnical Aspects of Underground Construction in Soft Ground, Kusakabe, Fujita & Miyazaki (eds)
© 2000 Balkema, Rotterdam, ISBN 90 5809 1 066

Modelling and prediction

R.N.Taylor
Geotechnical Engineering Research Centre, Department of Civil Engineering, City University, London, UK

ABSTRACT: Session 3 - Modelling and Prediction - of the 2^{nd} International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground contains 23 papers. This report presents a synthesis of the main features of those Papers in advancing our understanding of mainly tunnelled excavations.

1. INTRODUCTION

A total of 23 Papers are included in the Session 3 entitled Modelling Prediction, and they are listed at the end of this report. Of these, 22 concern tunnelled excavations, and the session concentrated on physical and numerical modelling of stability, ground movements and construction processes related to tunnelling; papers on modelling related to deep excavations can be found in other Sessions. Six of the Papers made use of data from physical models, and of these 2 used centrifuge model tests and 4 used 1g-laboratory models. Interestingly, 4 Papers concerning the behaviour of tunnel headings when reinforced with soil nails or spiles, which was the major new construction process featuring in the Session. Most of the Papers (19 in total) made some use of numerical modelling or analysis. Eight of these had comparisons with some form of real data, either from centrifuge tests (1), 1g laboratory tests (3) or field measurements (4).

It is interesting to note the range of constitutive models used for the various numerical studies, and these are summarised in Table 1.

The majority of Papers made use of traditional soil models. Most used linear elastic behaviour prior to yield with perfectly plastic behaviour. This was somewhat surprising since it is known that linear elasticity, even with perfect plasticity often leads to poor predictions of ground movements due to tunnelling. Only 10% of the Papers made use of the more modern "non-linear" type of constitutive soil models.

Table 1. Summary of constitutive models used in the numerical studies

Constitutive model	No. Papers
Linear elastic	2
Elasto-plastic (Tresca)	2
Elasto-plastic (Mohr-Coulomb: c - ϕ)	7
Modified Cam-clay / Drucker-Prager / Cap model	3
"Beams-and-springs"	2
Neural networks	1
Non-linear elasto-plastic	2

It is clear from the Papers presented that a significant difference with the previous Symposium is the increase in 3D analyses. Clearly, some Authors see this as the way ahead, even though such analyses are very complex and require major computing resources, and as a consequence often use relatively simplistic, and therefore possibly unrepresentative, constitutive models for the soil behaviour. It is known that good quality predictions require proper evaluation and calibration of the analyses. To achieve this, some Papers made use of data from model tests or field studies, but it is perhaps disappointing to note that less than half the Papers tried to evaluate the analyses presented. This issue will become more important as complex analyses are developed to investigate difficult construction processes.

2. THE PAPERS

Following is a review of some, but not all, of the Papers included in the Session, and they have to some extent been grouped together into themes. It has not been the intention to summarise the Papers, but more to give an overall impression of the main aspects of the work covered in the Session. Only a few comments are made on some of the individual Papers.

2.1. *Tunnel Heading Reinforced by Nails*

Wong et al applied a type of closed-form analysis to assess the potential of soil nails in controlling ground movements at a tunnel face. The soil parameters required for the analysis were assessed by a steering committee, and the predictions compared very well with the field measurements. There was some suggestion that from the analytical point of view, the soil nails had little influence on the development of ground movements, but overall the Authors considered that the nails were in fact more effective than the analyses suggested. This was a good demonstration of the need to compare numerical predictions with observed behaviour.

Yoo and Shin present a numerical parametric study on the effect of soil nails used to stabilise a tunnel heading. The series of analyses undertaken were able to demonstrate the relative influence of, for example, the length and number of soil nails used. The analyses predicted that relatively short nails would provide effective support, and this is probably a direct result of the constitutive model adopted. Thus such analyses may not give direct predictions of behaviour, but nevertheless are very useful in a qualitative assessment of potential benefits of nail reinforcement at a tunnel face.

Centrifuge modelling techniques were used by *Calvello and Taylor* to investigate the influence on ground movements of soil nails at a tunnel heading. This was also in the form of a parametric study with some variation in length of nails used and their distribution over the front vertical face of the heading. Although arguably an incomplete set of tests, they were nonetheless useful in demonstrating the potential effectiveness of nails in reinforcing a heading. The improved stability resulted in reduced ground movements for the same degree of temporary support, and the ground movements also became more widespread. An important feature of the experiments was the determination of patterns of ground movements using analysis of digital images obtained during the centrifuge tests. This technique has greatly enhanced the ability of centrifuge tests to provide comprehensive data on ground movements at pre-failure conditions and will therefore be a valuable source of data for validation of numerical analyses.

2.2. *Numerical Predictions linked with Physical Models*

Grant and Taylor used centrifuge tests on plane strain models of tunnels in clay to provide records of deformations for comparison with a simple "thick cylinder" analytical model. The distributions of ground movements were found to be consistent with the predictions, but understandably, the movements measured were not exactly radial in nature. The discrepancies with the analysis were used to indicate the lateral extent of ground movements. Again, the deformation data were obtained using digital image analysis rather than using discrete displacement transducers.

The model tests reported by *Komiya et al* were designed to investigate the relative influence of the shape of a tunnel cross-section on failure. The concentration of stresses at the upper corner of the rectangular tunnel section had a big influence on stability compared to a tunnel with a more circular cross section. The differences in stability were evident both in the laboratory model experiments and numerical analyses.

Hosokawa and Akagi investigated ground movements during a shield tunnel advance. For the model tests in sand, they developed a new strain-gauged strip transducer that could give ground movements from within the body of soil. The effectiveness of the new transducer was first investigated in a number of calibration tests. The device was then used in conjunction with the 1g-laboratory model tests. From these, they were able to conclude that when slurry shield tunnelling is used to minimise movements at the ground surface, there are still subsurface ground movements which can be significant at the side of the tunnel.

Wakai et al present results from large 1g laboratory model tests designed to investigate the lateral earth pressure acting on a shaft wall or front of a tunnel face. As might be expected, this lateral pressure was found to be a function of permitted displacement. The measurements compared well with a numerical analysis using a Mohr-Coulomb soil model. That a relatively simple analysis gave a very good prediction is perhaps slightly surprising, and might reflect the fact that the change in pressure is predicted at the same location as the imposed displacement and hence the constitutive model for soil behaviour used might then have less of an overall effect.

Nakai et al present an interesting series of model tests and associated numerical analyses investigating the effect of construction sequence on the distribution of ground movements due to tunnel construction. A careful series of 1g model tests allowed the "excavation" at the crown or side wall of a rectangular tunnel and the sequence of these excavations could be varied. The procedure adopted in the laboratory tests was followed, as closely as possible, in the numerical simulation. Reasonable correlation was found between the physical and numerical modelling. However, the 1g model tests in dry sand are arguably at too low effective stresses to give a quantitative assessment, but are valuable in giving a qualitative indication of this important aspect of construction.

Broere and van Tol use a limit equilibrium approach to investigate the effectiveness of a slurry filter-cake forming in front of an advancing tunnel shield in assisting face stability. An interesting aspect of this work was the prediction of pore pressure changes ahead of the advancing shield, and was one of the very few papers which considered the importance of pore pressure changes due to tunnelling.

A novel application of neural networks in analysing tunnel convergence was presented by *Fifer*. Measurements of convergence of two tunnels were compared with predictions obtained from a trained neural network. Although these predictions were found to be generally reasonable, or slightly conservative, it is not clear what minimum training of the neural network is needed to produce good and consistent results. This might be important for new tunnels where variations in ground conditions may be an important issue. Nevertheless, this type of approach is an interesting development.

2.3. *Numerical Modelling*

Negro and Braga de Queiroz present an excellent synthesis of many papers utilising numerical modelling of tunnelling. They note that most reported analyses represent predictions after construction when some data from the case history are known. This leads inevitably to the conclusion that calibration of a model is needed for successful predictions; it is not possible in general to simply obtain some soil parameters and then get a good prediction. Consistent with this Session, the Authors discovered that most reported predictions use traditional soil models rather than "more modern non-linear analyses". As an example of the outcome of their synthesis, the Authors found that the publications reviewed tended to conclude that maximum surface settlement due to tunnel excavation could be reasonably well predicted, but that the distortion or curvature of the surface settlement trough was not so well predicted. This might, in some situations, be unfortunate, since it is often the case that distortion effects can be much more damaging to near surface structures.

Dias et al used the numerical analysis package FLAC to perform 3D simulations of a tunnelling operation. The details of the constitutive model used were unclear. However, the Authors were able to predict, using the 3D analysis, a ground movement settlement trough which was apparently closer to the normal Gaussian-distribution shaped trough than that predicted by a more conventional 2D analysis. However, the exact correlation between the predictions and the standard Gaussian distribution were not very clear.

Tang et al use a 3D finite element analysis to investigate the details of stress path changes due to tunnelling, especially in the vicinity of a tunnel invert. The results are compared to the behaviour of the Heathrow Express trial tunnel in London, UK.

Guedes de Melo and Santos Pereira use a finite element analysis to investigate the effects of different initial K_0 distributions on predicted ground movements due to tunnelling. The constitutive model used was linear elastic with Young's modulus increasing with depth. This relatively simple soil-model makes it difficult to assess the full implications of the findings, since some aspects of the predictions may result from the constitutive model rather than the imposed stress history.

Fotieva et al present a closed-form analytical solution for stresses imposed on a tunnel lining by surface loads. Although a linear elastic soil model was used, the results are useful in assessing the critical loading geometry which can be important in design.

2.4. *Practical Considerations*

There were a few Papers which concerned the more practical aspects of tunnel construction. *van Empel et al* presented analyses designed to investigate the longitudinal and axial behaviour of tunnels when a curvature is imposed on the tunnel lining. This infrequently considered case is relevant for conditions near tunnel access shafts, or where there is s significant change in ground conditions.

Sramoon and Sugimoto consider the case of non-uniform ground loading on a tunnel shield and lining, imposed perhaps by non-uniform ground conditions, or over-excavation at part of the tunnel face. In the analysis, this was accounted for by an imposed boundary deformation, and therefore the Authors looked at the relative effect of the problem rather than present a direct prediction. *Sugimoto et al* go on to present an interesting prediction of the potential "snaking" progress of a tunnel shield with deviations in line and level during tunnel advance.

Soga et al consider the problem of controlling compensation grouting operations. They outline a numerical procedure for simulating the effects of this relatively new construction procedure for minimising ground movements.

3. SUMMARY

An interesting feature of this Session was the number of papers concerned with problems related to construction processes. Also, in a number of cases model tests were used to provide data to compare with the numerical predictions. An important aspect of a numerical analysis is the constitutive model used to describe the soil behaviour. It was found that many Authors had chosen traditional soil models rather that more modern or advanced models with significant non-linear behaviour at small strains. The choice of soil parameters then becomes an important issue, and in general there was very little description of how soil parameters were obtained. For the future, an important issue will be in selecting appropriate soil models and associated parameters for successful predictions of ground movements.

Arising from this Session is the need for discussion on the roles of physical model testing in understanding tunnelling problems, the benefits, problems and requirements of numerical modelling applied to tunnelling, and, as an example of a tunnelling construction process, the potential for soil reinforcement for reducing ground movements at a tunnel face. On this latter point, a key question is to what extent can models, either physical or numereical, provide successful quantitative predictions of actual ground behaviour.

REFERENCES

Symposium Papers in Session 3: Modelling and Prediction

Broere, W. & A.F. van Tol. *Influence of infiltration and groundwater flow on tunnel face stability.*

Calvello, M. & R.N. Taylor. *Centrifuge modelling of a spile-reinforced tunnel heading.*

Dias, D., M. Maghazi & R. Kastner. *Three dimensional simulation of slurry shield tunneling.*

van Empel, W.H.N.C., R.G.A. de Waal & C. van der Veen. *Segmental tunnel lining behaviour in axial direction.*

Fifer, K.B. *Neural networks as. a means for predicting convergence in tunnels*

Fotieva, N.N. N.S. Bulychev & A.S. Sammal. *Designing shallow tunnel linings upon the action of moving surface loads.*

Fukushima, K. *An improved FEM program and its applications for tunnel stability analysis*

Grant, R.J. & R.N. Taylor. *Evaluating plasticity solutions for the response of clay around tunnels.*

Guedes de Melo, P.F.M. & C. Santos Pereira. *The role of the soil K_0 value in numerical analysis of shallow tunnels.*

Gurung, N. Y. Iwao, K. Ishibashi, S. Hongo & M.R. Madhav. *A field case of rock-bolt deformations in pullout tests.*

Hosokawa, K. & H. Akagi. *Displacement of saturated sand during slurry shield driving.*

Komiya, K., E. Shimizu, T. Watanabe & N. Kodama. *Earth pressure exerted on tunnels during subsidence of sandy ground.*

Koudelka, P. & C. Fisher. *Earth pressure model with curved slip surfaces by AIM.*

Nakai, T., M.M. Farias, H. Matsubara & S. Kusunoki. *Effects of excavation sequence on the 3D settlement of shallow tunnels.*

Negro A., & P.I. Braga de Queiroz. *Prediction and performance of soft ground tunnels.*

Sadrnejad, S.A. *Numerical solution upon multilaminate elastic-plastic model for instability of underground cavity.*

Soga, K., M.D. Bolton, S.K.A. Au, K. Komiya, J.P. Hamelin, A. Van Cotthem, G. Buchet & J.P. Michel. *Development of compensation grouting modelling and control system.*

Sramoon, A. & M. Sugimoto. *Development on ground reaction curve for shield tunneling.*

Sugimoto, M., N. Yoshiho & A. Sramoon. *Study on shield behavior by 3-D shield simulator.*

Tang, D.K.W., K.M. Lee & C.W.W. Ng. *Stress paths around a 3D numerically simulated NATM tunnel in stiff clay.*

Wakai, A., K. Ugai & K. Anan. *Evaluation of active earth pressure on the facing of the shield entrance in a shaft.*

Wong, H., V. Trompille, D. Subrin & A. Guilloux. *Tunnel face reinforced by longitudinal bolts analytical model and in situ data.*

Yoo, C.S., & H.K. Shin. *Behavior of tunnel face pre-reinforced with sub-horizontal pipes.*