Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)
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Calculation and design methods, and predictive tools

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ABSTRACT: This general report covers 19 papers that are included in session 6 of the symposium, related to the design or calculation methods and predictive tools for tunneling and deep excavations. For this report, the papers have been classified in 3 main subjects: i) excavations, ii) tunneling, iii) general papers on design methods and tools. There are a greater number of papers concerning tunnelling, covering a large numbers of subjects, subdivided in the following topics: T.B.M. simulation, Ground reaction curve, Longitudinal behaviour of segmented lining, Settlement troughs, Effect of vibrations.

1 INTRODUCTION

This session with a very broad theme, contains 19 papers. Tables 1 and 2 present a classification of these papers, by countries and by themes. There are papers from 8 countries, but more than half of the papers (11/19) are from China.

Table 1. Classification by countries.

Countries	Number of papers
Brazil	2
China	11
Japan	1
Kazakstan	1
Korea	1
Netherlands	1
UK	1
USA	1

Table 2. Classification by subjects.

Topics	Sub-topic	Number of papers
Excavations		3
Tunnels	TBM simulation	1
	Ground reaction curve	2 + 2 (rock)
	Settlement trough	2
	Longitudinal behaviour	2
	Effect of vibrations	3
General		4

The content of the papers can be broadly divided into calculation and design of tunnelling works, excavations, and more general papers. 3 papers deal with excavation, considering 3 different aspects: basal stability, strut loads, and effect on nearby piles. There are a greater number of papers concerning tunnelling, covering a large number of subjects. Among these 12 papers, 1 reports on TBM numerical simulation, 2 present analytical methods for the ground reaction curve, 2 deal with the assessment of the settlement trough, 2 consider the problem of the longitudinal behaviour of the segmented tunnel lining, 3 report on the effect of vibrations or on the seismic response, the 2 remaining concerning more problems related to rock tunnels. Finally there are 4 general papers concerning the simulation tools or presenting a national report.

Considering this large number of subjects, it is not really possible to highlight a main emphasis, some of the papers covering very narrow subjects and others concerning very general topics.

In the following sections of this report, the major findings and key features of each paper are presented and briefly discussed.

2 EXCAVATIONS

Song and Huang studied the basal stability of an excavation in soft clay by an upper bound approach. The failure mechanism considered (Figure 1) is based on the classical Prandtl failure mechanism. Their original contribution to this problem is to consider the dependence of the short term shear resistance of soft clays on the local orientation of the failure surface. They propose an analytical upper bound solution based on this

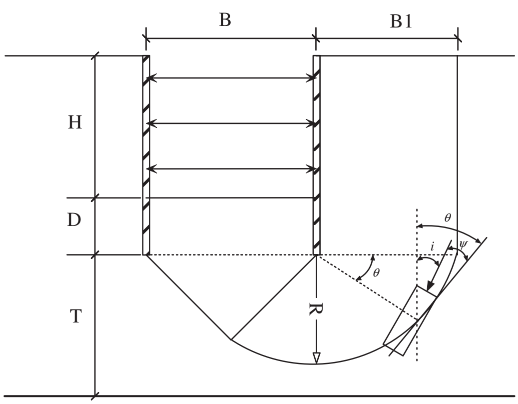

Figure 1. Definition of geometric parameters.

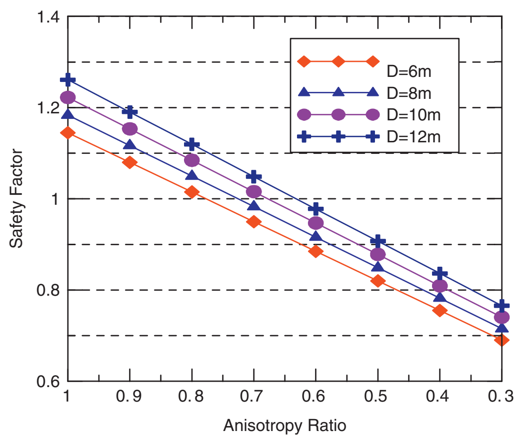

Figure 2. Influence of D/H on the factor of safety ($\gamma = 18\,\text{kN/m}^3$, undrained shear strength $S_{uv}(z) = 0.33\sigma'_v$, width of the excavation B = 15 m, depth of the excavation H = 12 m).

kinematical mechanism and on the equation proposed by Casagrande and Carillo (1944) for describing the anisotropy of shear strength:

$$S_{ui} = S_{uh} + (S_{uv} - S_{uh}).\cos^2 i \qquad (1)$$

where S_{uh} and S_{uv} are obtained by undrained triaxial compression and extension tests.

Figure 2 presents the results of a parametric study on the evolution of the safety factor with the anisotropy ratio, for different values of the embedment depth. It appears clearly that the anisotropy ratio has more influence than the embedment depth which increases only slightly the safety factor. The authors studied also the influence of the depth of the bedrock, when the bedrock limits the extension of the failure mechanism.

This approach compared well with a 2D FE analysis of a deep excavation in Boston Blue Clay a presented by

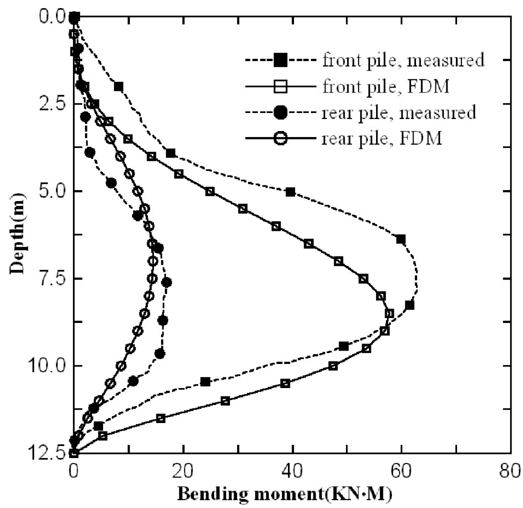

Figure 3. Comparison of free head pile group.

Hashash and Whittle (1996) using an advanced effective stress soil model, MIT-E3. The authors analysed also a case of failure in Shanghai where the standard codes led to safety factors of more than 1.4 and where this approach leads to a safety factor of 0.97, explaining the basal instability.

Zhang and co-authors present a method for estimating the response of piles to lateral soil movements induced by a nearby excavation.

For a single pile, the method is based on the classical two-stage approach (Poulos & Chen 1997):

– in a first step, the free-field soil movement must be determined either by measurement or by calculation;
– in a second step, these soil movements are imposed to the piles through a Winkler subgrade reaction model: the pile is represented by an elastic beam, the pile-soil interaction is modeled using linear elastic soil springs, the effect of axial load on the pile is ignored. The Winkler subgrade reaction equation is solved by a FD approach, permitting to take into account heterogeneous soils.

This classical method has been extended by the authors to pile groups. In the case of pile groups, the shielding effect of piles is modelled by superposing to the free field soil movement the reduction of the displacement due to neighbouring piles. This shielding effect is calculated using an attenuation function based on simplified Mindlin's equation.

The authors present a comparison of their approach with centrifuge model tests and finite element simulation published by Leung et al (2000).

A comparison of calculated and measured bending moments is given on Figures 3 and 4 in the case of

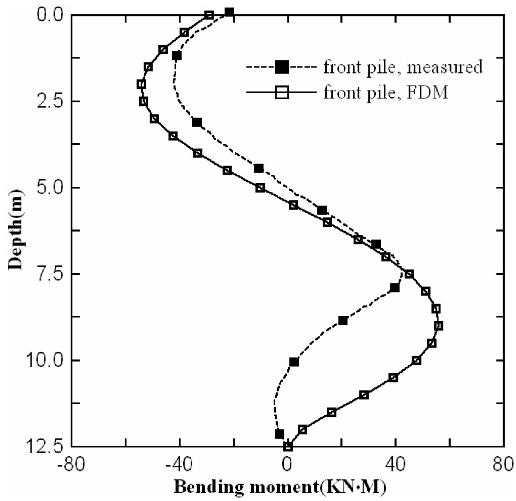

Figure 4. Comparison of front pile in capped head pile group.

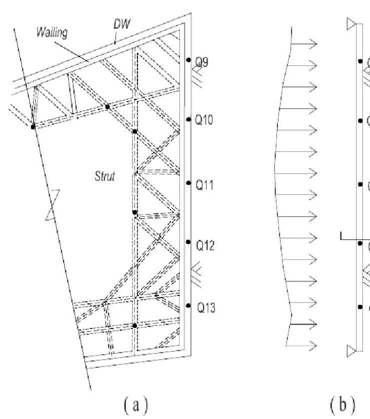

Figure 5. Example of strut system.

pile groups: this simplified model fits quite well with the experimental results for free headed piles but there are some differences in the case of capped piles. The authors explain that this difference could be reduced by using a non-linear elastic spring hypothesis, but perhaps is it due to the Winkler's hypothesis itself.

Finally, it must be noted that this method is not specific to excavations, and could be used for other works inducing lateral soil movements, such as tunnelling or embankments on soft clays.

Shi and co authors present a method for estimating by back-analysis the strut loads in a complex concrete strut system, such as the system presented on Figure 5.

The proposed method is based on measured displacements of the wall in the horizontal plane of the strut system, the load distribution between the different struts at the same level being calculated by back-analysis.

As there are no direct load measurements, the magnitude of the loads obtained by this approach depends strongly on the a priori hypothesis concerning the distribution of soil pressure acting on the wall. Therefore this method can only give an indication on the relative distribution of the loads.

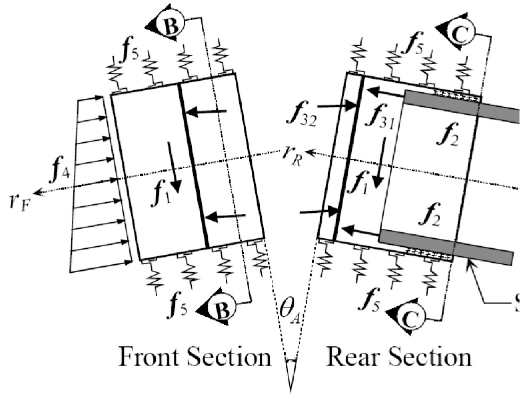

Figure 6. Forces acting on the TBM.

3 TUNNELING

3.1 *T.B.M. simulation*

Chen and co-authors present an interesting paper on the behaviour of a TBM when following a curved alignment. They propose a comprehensive numerical model of an articulated shield which is an extension of a kinematic shield model proposed for a single circular shield (Sugimoto & Sramoon 2002). Their model is focused on the tunnel boring machine, considering all the forces acting on the shield, such as for example (Figure 6)

- the different jack thrust forces,
- the pressure acting on the face,
- the forces acting on the shield periphery.

These latter forces represent the interaction between the shield and the surrounding soil. They are simulated by a spring model. Therefore, in this model, the tunnelling operation is seen mainly from the point of view of the TBM.

The simulation of the TBM behaviour is obtained by imposing to the model the main operation parameters of the shield.

A comparison between an observed and simulated behaviour is presented in Figure 7. The actual shield trajectory, in the vertical and horizontal plane, and in

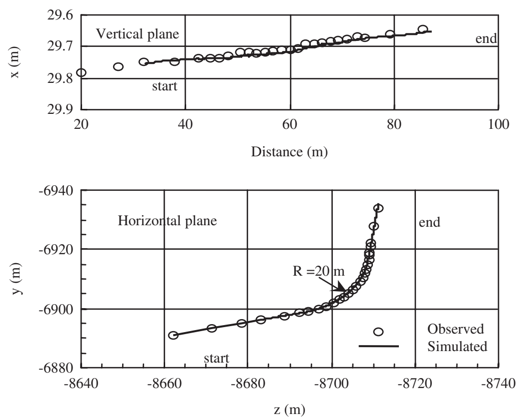

Figure 7. Simulated and observed behaviour.

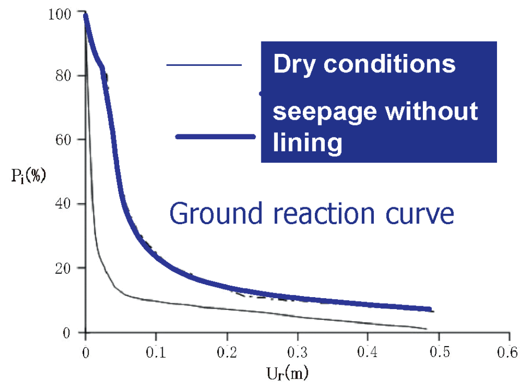

Figure 8. Effect of radial seepage on the ground reaction curve.

extreme conditions of a sharp curve, is well simulated by this very comprehensive model.

This model gives also the field of soil pressure acting on the shield, derived from the spring model, as shown on this figure. In a further step, it could be interesting to use these calculated contact stresses between the shield and the soil in a continuum model of the soil mass for modelling the soil deformation and to check if these calculated contact stresses lead to a realistic simulation of observed displacements and settlement troughs.

3.2 *Ground reaction curve*

Shin and co-authors propose an analytical model of the ground reaction curve taking into account the seepage forces. The following classical hypotheses are adopted:

– The tunnel is bored in an infinite soil mass subjected to a hydrostatic in situ stress,
– The soil is linear elastic perfectly plastic with the Mohr-Coulomb yield criteria,
– Radial seepage forces are taken into account, as indicated in the equilibrium equation:

$$\frac{d\sigma'_r}{dr} + \frac{\sigma'_r - \sigma'_\theta}{r} + i_r.\gamma_w = 0 \qquad (2)$$

The hydraulic gradients are calculated separately, considering a steady state of seepage.

Based on these hypotheses, the authors propose an analytical solution of the elasto-plastic state of stress, expressed in terms of stress state and displacement. Due to these assumptions, this model is more adapted to deep tunnels.

The authors present an application of their model for a 50 m deep tunnel, with a diameter of 5 meters. Different cases are examined: fully drained or with a semi impervious lining, having the same mechanical properties than the surrounding soil. A comparison between the dry soil case and the fully drained case is presented in Figure 8:

– in dry conditions, the pressure decreases rapidly with the convergence, as the soil resistance is mobilised,
– when fully drained seepage is considered, there is a marked increase of the convergence for a given internal pressure, as the seepage forces do not depend on the soil convergence and remain constant.

Despite the diverse simplifications of such an analytical model, this paper gives interesting indications on the influence of seepage forces and shows clearly that they should be taken into account for modelling the ground reaction curves and for assessing the stability of the excavation.

In a second paper on ground reaction curves, *Sozio* presents a 2D or 3D analytical model representing the tunnel and the soil cover by a thick sphere or a thick cylinder (Figure 9). The soil model is the classical linear elastic-perfectly plastic Mohr-Coulomb model.

The originality of this model is that the gravity forces are emulated by radial body forces. This enables to take into account a limited cover depth, with a surface load and an internal pressure. The author proposes to use this 3D model for a preliminary assessment of the stability of the unlined length of a tunnel, the problem being to estimate the radius of the sphere equivalent to the tunnel unsupported heading.

Such analytical models are generally based on restrictive hypotheses. It is the case for this model, but it has to be highlighted that in his paper, the author indicates very clearly the limitations of the proposed models. It should be interesting to compare this model to the classical approach based on the assumption of a tunnel bored in an infinite soil mass.

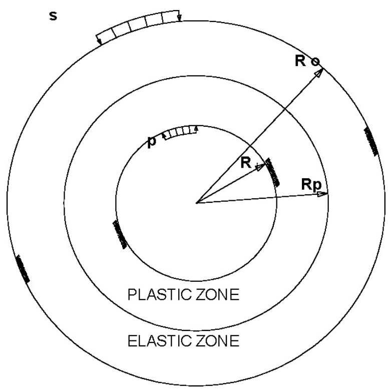

Figure 9. Representation of the soil tunnel interaction.

The papers presented by *Zhang & Wang* and *Lu et al* concern more specifically deep rock tunnels.

Zhang & Wang study the ground reaction in the case of a pressure tunnel, the rock mass being not unloaded but loaded by the internal pressure. In this specific situation, quite far from urban tunnels in soft ground, the softening of the rock considered by the authors can lead to a broken zone around the tunnel.

Lu et al studied by 3D numerical simulations the stability of different types of intersections between deep mine tunnels and the influence of the construction sequences. The method of simulation is not precisely described. If this study is not directly applicable to shallow tunnels in soft ground, some of their results can be considered from a qualitative point of view such as the fact that excavating towards the intersection appears more dangerous than excavating from the excavation.

3.3 *Longitudinal behaviour of segmented lining*

The paper proposed by *Hoefsloot* is based on the observation that the staged construction of segmented tunnel linings induces a permanent longitudinal bending moment in the lining. Based on solutions proposed by Bogaards & Bakker (1999), and Bakker (2000), the author proposes an analytical solution by considering the segmented tunnel lining as a beam on an elastic foundation.

The longitudinal loading scheme (Bending moment and shear force from jack forces, shear force from steel brushes, weight of lining segments, uniformly distributed load of limited length: back up train) advances with the progress of the TBM (Figure 10). This analytical model has been built in a spreadsheet, and verified using PLAXIS 2D.

The result of this model is compared with strain measurements made in the lining of the GROENE HART tunnel in the Netherlands. As illustrated on Figure 11, a bending moment is induced in the lining by

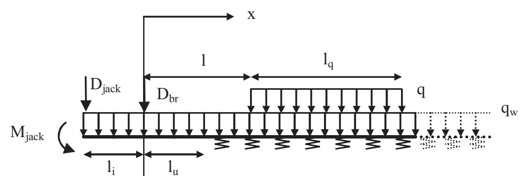

Figure 10. Model used by Hoefsloot to represent the stage construction of the tunnel lining.

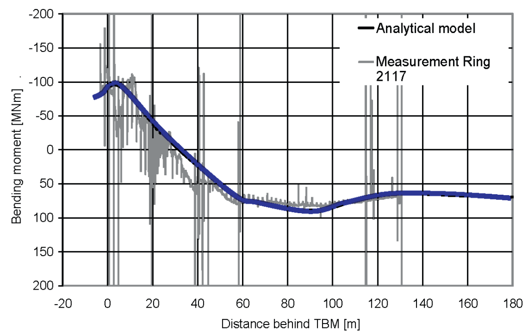

Figure 11. Groene hardt tunnel – evolution of the bending moment with the advance of the TBM.

the advancement of the TBM and becomes permanent after about 60 meters. Despite the simple hypothesis of a spring model, the evolution of the bending moment is quite well modelled. Nevertheless this result has been obtained by adjusting some parameters which are difficult to assess, such as the lining bending stiffness and the effect of grouting (Talmon et al. 2008).

Finally, this analytical model, validated on field measurements, shows that the staged construction of the segmental lining in a straight alignment results in a permanent longitudinal bending moment, that should be considered in the design of the lining and for the installation of the segments.

A second paper on the longitudinal behaviour of segmented lining is presented by *Zhu et al.* The authors examine the problem of the actual longitudinal stiffness of segmented linings which is one of the parameters which was necessary to adjust in the model proposed by *Hoefsloot.*

The assessment of the lining stiffness is based on a 3D numerical model, composed of shell elements (Figure 12) and joints with shear and normal stiffness at all the interfaces between the individual elements. The complete numerical model, loaded as a cantilever beam, is compared to a simplified equivalent continuous model, which is not precisely described in the paper.

The stiffness deduced from the numerical model appears on their example to depend on the segment length and to be lower than the stiffness obtained

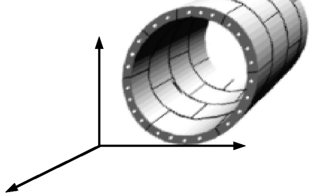

Figure 12. Lining model.

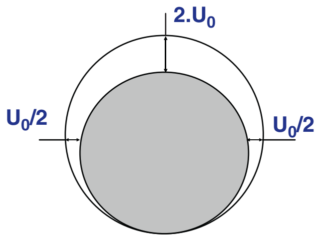

Figure 13. Convergence scheme proposed by Heli Bao et al.

by the equivalent continuous model. But both models are based on hypothesises concerning the joint behaviour, which need to be measured or assessed based on the observation of the actual behaviour of full scale segmented linings.

3.4 *Settlement troughs*

There is generally a large consensus about the use of the Gaussian type curve for describing the settlement trough.

The direct estimation through elastic calculations or by numerical simulations often leads to larger settlement troughs than observed. The result depends in fact on different assumptions, one being the convergence profile of the ground around the tunnel.

Heli Bao and his co-authors present an analytical solution, using conformal mapping of an elastic half space. In order to fit with the observed settlement troughs, they propose an elliptical convergence shape, based on the solution proposed by Park (1974), as indicated on Figure 13.

This approach is compared with the observed settlements during the construction of a 6.2 m diameter tunnel in Shanghai. The calculated settlement trough fits quite well with the observed one. But no indication is given concerning the assessment of the magnitude of the convergence, the authors indicating simply the gap between the TBM and the lining, gap which is in fact certainly partially filled by grouting.

In their paper, *Zu and Liu* compared different methods for settlement trough assessment: Peck's empirical approach (Peck 1969), stochastic medium theory, and the solution proposed by Verruijt and Booker (1996).

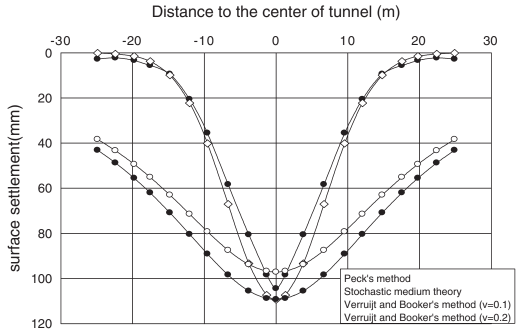

Figure 14. Settlement trough calculated using 3 different methods (Zu and Liu).

The example presented on Figure 14 exhibits very large differences, but it is in fact an extreme case, with a cover depth of less than one meter for a tunnel 6 meters in diameter.

They present also some observed settlement troughs from Shanghai metro line 7 construction. It would have been interesting to have more details on the tunnel works leading to these settlement troughs and to compare the observed settlement troughs to the calculation methods presented in the first part of the paper.

3.5 *Effect of vibrations*

In their 2 complementary papers, *Cui and co-authors* investigate experimentally the dynamic loading and the development of pore pressure of saturated silty clays near Shanghai subway Line No.2, during the passage of metro trains. On the observed site, settlements exceeding 20 cm where observed, but no details on the evolution of these settlements is given.

The experimental study is based on field observations and dynamic triaxial tests.

Based on in situ measurements, the authors propose an experimental law of attenuation of the dynamic loading with the distance to the tunnel. This law, due to the polynomial approximation adopted, has certainly a limited domain of validity, and cannot be extrapolated outside the range of distance corresponding to the measurement points.

They studied also the development of pore pressure with the dynamic loading, both in the field and by triaxial tests; but the relation of field measurements results with dynamic triaxial tests is not clearly described.

It would have been interesting to have more details concerning the long term evolution of pore pressure in situ, combined also with the evolution of soil deformations during cycling loading tests, in order to explain the observed large settlements.

Baimakhan and co-authors propose a coupled approach (analytical and numerical) to determine the stresses induced by earthquakes on the lining of tunnels of subway lines.

Using a concept of homogeneous anisotropic elastic medium they consider the effect of the succession of different soil or rock layers.

They analyse in a more specific way the case of tunnel or galleries with a longitudinal axis making an angle with the major direction of anisotropy.

4 GENERAL PAPERS ON DESIGN METHODS AND TOOLS

Koungelis & Augarde compare, on an academic example, the results given by 2 different FE codes, Strand 7 and Plaxis. They investigate the effect of surface loading on wished in place tunnels in soft ground assuming plane strain conditions.

The initial conditions and soil characteristics are the same in all their simulations, except for dilatancy. The two meshes used in their comparative study are quite different: in Plaxis the mesh is more refined and consists of fifteen – noded triangular elements, and in Strand 7 the mesh is coarser, and moreover consists of simple 6 noded triangular elements.

The authors compare the changes in horizontal and vertical diameters for different position of the surface load. There are actually small differences although there is a great difference between the refinement of the meshes and the type of triangular elements.

Although no indication is given in the paper, one can suppose that in this example, plastic zones are certainly very limited or absent around the tunnel. Therefore, this paper compares essentially the influence of the mesh refinement and of the type of element in a linear elastic case, which explains the fact that only minor difference is noted. Such comparisons should be extended to less academic situations, where the tunnel construction is simulated and where small strain behaviour is modelled or where large plastic zones are mobilised.

Jeon and coauthors present an interesting communication on the use of geostatistical methods for assessing the spatial distribution of the rock mass characteristic named RMR. They compare a method named SIS (Juang et al., 2003, Feng et al., 2006) to the more classical kriging (Marinoni, 2003; Pardo-Igúzquiza and Dowd, 2005).

The problem considered here, is how to assess, on the base of limited bore holes, the ground characteristics along the tunnel alignment. The application presented concerns deep rock tunnels, where geostatistical estimations of RMR around a tunnel are compared.

Compared to kriging which gives a deterministic value at each point considered, SIS gives a statistical distribution of the unknown value with different characteristics of this statistical distribution as illustrated on Figure 15.

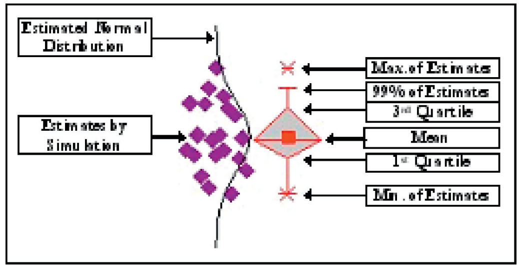

Figure 15. Distribution of estimated value.

Such a distribution is important information for tunnelling projects, based on a limited number of investigation points, in order to evaluate the limits of the design and for risk assessment.

One of the difficulties for multiplying 2D or 3D numerical simulations on tunnelling projects is that the pre-processing tasks are much time consuming.

Li and co-authors propose in their paper a methodology to derive a FEM model from numerical geological models, which are more and more used in the frame of large geotechnical projects.

The figures presented Figure 16 show some of the stages, beginning from the geological model and ending to a 3D finite element mesh and where the soil characteristics are imported from the geological model.

In such an approach, coupling the geological model with the geostatistical method presented in the previous paper could be certainly a very powerful tool for helping the designer to test different hypothesis of the soil parameters.

Negro presents the results of a comprehensive survey of current design practice in Brazil. The analysis of this survey is based on the answers of 20 experts. The topics of the survey concern the main aspects of tunnel design:

- Tunnel heading stability,
- Settlement,
- Damage to existing structures,
- Lining design,
- Account of ground water loading,
- 2D/3D FEM or FDM models,
- Soil models in FEM/FDM models,
- Soil investigations,
- Monitoring.

The results of this survey are clearly summarized and analysed in the paper by Negro, therefore, in this report are given only some typical examples.

From this survey, it results that the typical scenario for tunnel projects in Brazil is the following: tunnels with equivalent diameter larger than 6 m, driven under

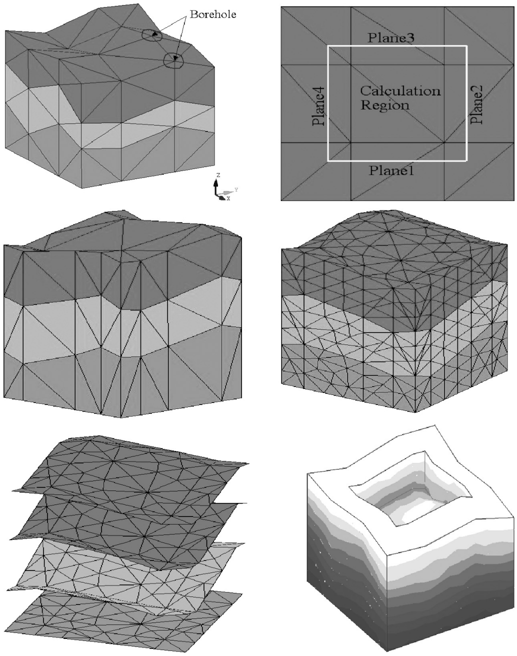

Figure 16. Some stages from the geological model to the 3D FE model.

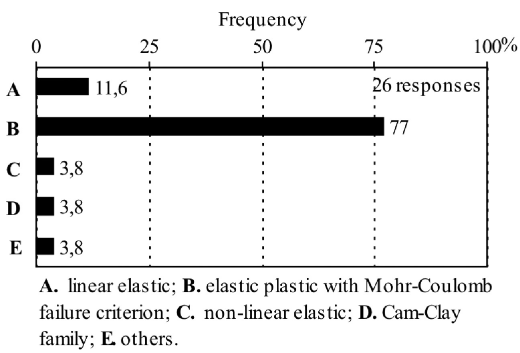

Figure 17. Soil models used in numerical analyses.

mixed face condition, in cohesive soils, below water table, and using sprayed concrete as lining (NATM).

Concerning the assessment of tunnel face stability, the survey shows that there is a large range of methods currently used, and it is noticed that some of these methods such as limit equilibrium, upper bound solutions or empirical methods can be unsafe.

It is highlighted also that Practitioners are in fact unhappy with the available methods for stability analysis, which certainly explains this broad range of methods used in practice.

Another interesting result concerns the constitutive models used in numerical analysis (Figure 17).

A large majority still use the linear elastic/plastic Mohr Coulomb model which is well known, but certainly often not adapted to shallow urban tunnels where the limitation of soil movements lead to small strains. Very few or no plasticity will be mobilised, and the model will be equivalent to a simple linear elastic model which very poorly describes the small strain behaviour of the soil. It can be added that this simple model can be unsafe in coupled analysis, as the volume changes in the soil are not correctly described.

This example shows that, with the large availability of 2D or 3D Finite element or finite difference powerful codes, there is certainly a need for clarifications concerning the types of soil models to be used in different situations and also a need for dissemination of this knowledge.

The rich conclusions of such a survey could be certainly a good base for developing and enhancing good practices in the field of tunnel design. For this reason TC28 has proposed to launch national surveys based on the example proposed by Negro, to be collected and analysed for the next TC28 symposium.

5 CONCLUSION

After excluding the 4 general papers, the 15 remaining papers allocated to this session, were related to 9 different specific topics.

This highlights that tunnels and deep excavations are complex works, with strong interaction with their environment, and that there is obviously a demand for simple calculation tools addressing specific problems, easy to use, especially at the preliminary design phases.

Concerning the calculation methods, it can be noticed that 9 papers concern analytical or mixed approaches as only 5 concern numerical methods. Therefore, considering the limits of the analytical approaches, due generally to the restrictive hypotheses necessary to obtain a closed form solution, it should be certainly useful now to develop simple numerical tools, easy to use and time saving, dedicated to limited specific problems. These tools could be based on existing codes and therefore able to take into account advanced soil models and realistic geometries. Such tools, after a comprehensive evaluation of their limits, could be certainly useful for practitioners.

Another way to be considered is the development of easy to use pre-processing tools, such as the example presented in this session, to facilitate the use of complex 3D models.

And finally, it should be stressed that all these calculation methods have to be validated carefully and in a scientific way against comprehensive measurements, and that the limitations of these models should be clearly indicated.

LIST OF PAPERS WITHIN SESSION

Baimakhan, R.B., Danaev, N.T., Baimakhan, A.R., Salgaraeva, G.I., Rysbaeva, G.P., Kulmaganbetova, Zh.K., Avdarsolkyzy, S., Makhanova, A.A. & Dashdorj, S. Calculation of the three dimensional seismic stressed state of "Metro Station–Escalator–Open Line Tunnels" system, which is located in inclined stratified soft ground.

Bao, H., Zhang, D. & Huang, H. A Complex Variable Solution for Tunneling-Induced Ground Movements in Clays.

Chen, J., Matsumoto, A. & Sugimoto, M. Simulation of articulated shield behavior at sharp curve by kinematic shield model.

Cui, Z.D., Tang, Y.Q. & Zhang, X. Deformation and pore pressure model of the saturated silty clay around a subway tunnel.

Hoefsloot, F.J.M. Analytical solution of longitudinal behaviour of tunnel lining.

Jeon, S., Hong, C. & You, K. Design of tunnel supporting system using geostatistical methods.

Koungelis, D.K. & Augarde, C.E. Comparative study of software tools on the effects of surface loads on tunnels.

Li, X.X., Zhu, H.H. & Lin, Y.L. Geologic model transforming method (GMTM) for numerical analysis modeling in geotechnical engineering.

Lu, T.K., Guo, B.H., Cheng, L.C. & Wang, J. Review and interpretation of intersection stability in deep underground based on numerical analysis.

Lu, Z.P. & Liu, G.B. Analysis of surface settlement due to the construction of a shield tunnel in soft clay in Shanghai.

Negro, A. Urban Tunnels in Soil: Review of Current Design Practice in Brazil.

Shi, Z., Bao, W., Li, J., Guo, W. & Zhu, J. A study on loads from complex support system using simple 2D models.

Shin, Y.J., Shin, J.H. & Lee, I.M. Ground Reaction due to Tunnelling below Groundwater Table.

Song, X.Y. & Huang, M.S. Basal Stability of Braced Excavations in K0-consolidated Soft Clay by Upper Bound Method.

Sozio, L.E. Analytical Two and Three Dimension Models to Assess Stability and Deformation Magnitude of Underground Excavations in Soil.

Tang, Y.Q., Cui, Z.D. & Zhang, X. Dynamic Response of Saturated Silty Clay around a Tunnel under Subway Vibration Loading in Shanghai.

Zhang, C.R., Huang, M.S. & Liang, F.Y. Lateral Responses of Piles due to Excavation-Induced Soil Movements.

Zhang, L.M. & Wang, Z.Q. Elastic-plastic analysis for surrounding rock of pressure tunnel with lining based on material nonlinear softening.

Zhu, W., Kou, X., Zhong, X. & Huang, Z. Modification of Key Parameters of Longitudinal Equivalent Model for Shield Tunnel.

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