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Numerical analysis of tunnels and deep excavations

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ABSTRACT: This report covers 33 papers submitted to the session Numerical Analysis of Tunnels and Deep Excavations. The majority of papers (26) addresses aspects related to tunnelling, both NATM and bored tunnels. As compared to previous conferences analysis of interaction between tunnel construction and surrounding structures such as buildings and pile foundations seems to have become more important. Only about 30% of the papers include actual field data but some additional papers cover practical aspects of tunnel construction. In this report the key points of each contribution are summarized. Finally some concluding remarks on the role of numerical modelling in underground construction in soft ground are added from a personal point of view.

1 INTRODUCTION

Numerical modelling by means of finite element, finite difference, boundary element and discrete element methods have become a standard tool for assessing the serviceability limit state (SLS) and, at least to some extent, the ultimate limit state (ULS) of geotechnical structures in soft ground. However, a gap between research and practice can still be observed. In the former large 3D models with sophisticated constitutive equations are frequently employed whereas in the latter simple elasto-perfectly plastic constitutive models are applied in (2D) analyses in most cases. That this trend has only slightly changed in recent years towards more advanced analysis in practice is confirmed by the papers presented to this symposium.

The question arising from this is obviously whether results obtained from relatively simple analysis are meaningful at all or whether sophisticated models concentrate on issues which are not of great importance in practice. Probably the answer is somewhere in between and depends strongly on the goal of the analysis in each particular case. However, one should always keep in mind that numerical models (and in fact all models in civil engineering but in particular in geotechnical engineering) are *models* and do not represent *reality* whatever complexity is introduced.

2 CLASSIFICATION OF SUBMITTED PAPERS

33 papers have been submitted to this session, 26 dealing with problems relating to tunnelling and 7 addressing deep excavations.

Out of the 26 tunnel papers 8 have investigated the influence of tunnel construction on existing structures

such as buildings and piles, 6 papers provide (limited) comparison with in situ performance. Only 1 paper involves model tests. Some papers specifically deal with problems related to bored tunnels highlighting the increasing importance of numerical analysis in this field.

3 of the deep excavation papers include field measurements; again only 1 contribution makes use of model test data. 1 paper presents data from a comprehensive data base where measured and calculated displacements are compiled for a large number of deep excavation problems.

In the following section the most important aspect raised in each of the papers will be briefly summarized. An attempt is made to group them according to the main topic of the papers but of course there is some overlap between the different categories chosen.

3 KEY POINTS OF PAPERS – TUNNELLING

3.1 *Practical aspects dominating*

Stability analysis of the marly formation around a tunnel in Iran by Fahimifar & Soroush: describes the analysis of a tunnel excavation for a highway in the south part of Iran. Analytical calculations based on ground-support interaction curves as proposed by Hoek & Brown (1980) are used as well as numerical analysis employing the discontinuum code UDEC. The preliminary findings from the simple analytical analysis were confirmed by the numerical analysis, namely that a 200 mm shotcrete lining and rock bolts are not sufficient for stabilizing the tunnel but additional lattice girders are required.

Calculating GRC for tunnels supported by grouted rock bolts by Palassi & Qoreishi: ground reaction curves based on numerical analysis using the finite difference code FLAC are presented. Results are shown for a simplified example and comparison is made with analytical approaches suggested by Indraranta & Kaiser (1990) and Zakariaee (2003) whereas better agreement was achieved with the latter.

Design of initial support system of Isfahan twin tunnels in soft ground by Shahriar, Rastbood & Azar: the influence of the thickness of the shotcrete lining on the factors of safety of tunnels is investigated but unfortunately no details are given on how this factor of safety is obtained from the numerical analysis.

Soil-structure interaction and its influence on displacements induced by tunnel excavations by Chissoluncombe, Assis & Farias: a real situation encountered during construction of the Brasilia Metro is analysed where a fuel station founded on piles suffered some damage due to tunnel excavation. By means of 3D finite element analyses the influence of existing structures on the displacement pattern around the tunnel is discussed.

Numerical analysis of foundation for underground bridge project in Moscow by Kolybin, Razvodovsky, Skorikov & Starshinov: this paper presents an interesting study of a very complex practical problem by means of a combination of 2D finite element and 3D spring models highlighting the importance of interaction between structural and geotechnical engineers in solving such problems.

Rigid-plastic analysis of tunnel face stability affected by ground water by Konishi, Kawashima, Tamura, Kitagawa, Lida & Matsunaga: the assessment of tunnel face stability by means of a rigid finite element analysis including water pressure as additional force is suggested. The proposed method has been applied to railway tunnels under construction but no field data from construction are available as yet. A concept for a design chart separating stable and unstable conditions is included.

A new stress-strain approach for tunnel face stability by Guilloux, Kurdts, Bernhardt & Wong: a simplified, but practical, approach for assessing the safety factor of tunnel faces, including face reinforcement in open face tunnelling or stabilizing pressures for bored tunnels, has been developed. The method is conceptually similar to the convergence-confinement method frequently applied for analysing tunnel sections well behind the face. Validation is provided by means of 2D axisymmetric and 3D finite element analyses. A simple design example is also given.

3.2 Theoretical aspects dominating

Numerical analysis for provision of tunneling – induced ground deformation in granular soil by

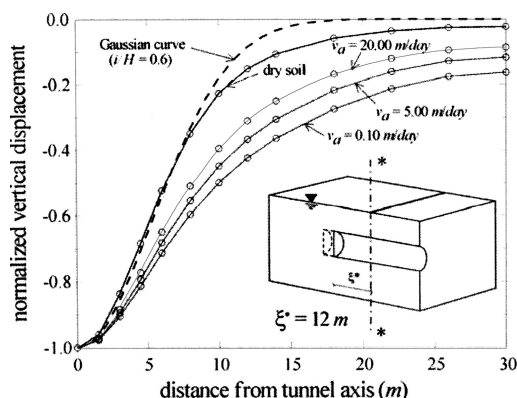


Figure 1. Influence of advance rate on normalised settlement trough (Callari & Casini).

Castelli & Motta: verification of settlement troughs based on a Gaussian distribution curve by means of a discrete element analysis (PFC) is attempted. Although a good agreement could be achieved a slight question mark remains on the validity of the results because a scaled model has been used in order to reduce the computational effort. In addition, some of the input parameters for the PFC model would need further justification.

Numerical analysis of settlements related to tunnelling: the role of stress-induced anisotropy and structure degradation in fine-grained soils by Amorosi & Boldini: the results of undrained analyses of tunnel excavation considering stress-induced anisotropy and structure degradation for different volume losses are discussed. The authors conclude that anisotropy has little effect on the settlement trough for the case considered, which however is in contradiction to other data published in the literature. It is acknowledged that generalization might be difficult and the negligible influence of anisotropy could be due to the formulation used in this study. As expected destructuration has some influence on tunnel stability but for moderate volume losses the effect on settlements is again not significant.

Three-dimensional analysis of shallow tunnels in saturated soft ground by Callari & Casini: fully coupled analyses in medium to low permeability soils are presented. It is shown that the settlement trough in saturated soil is wider than in dry soil, depending on the advance rate, and is not consistent with a Gaussian distribution (Figure 1). A slow advance rate leads to higher settlements. The importance of taking lining permeability into account is pointed out.

Influence of lagging distance on the interaction of two open face parallel tunnels by Tang & Ng: describes results from a theoretical study by means of a 3D coupled consolidation analysis on the effect of the lagging distance between two parallel tunnel excavations. The

conclusions drawn are that horizontal movements are stronger influenced by the lagging distance than vertical movements and that there is a shift of maximum surface settlement, the amount of which depends on the lagging distance. The maximum settlement does not occur at the centre line of the pillar between the two tunnels. Distribution of bending moments in linings is also influenced by the lagging distance.

3.3 Theoretical aspects – field data

Numerical Simulation of a strain softening behavior of a shallow tunnel for a bullet train by Akutagawa, Lee, Doba, Kitagawa, Konishi & Matsunaga: it is shown that even with a simple strain softening constitutive model good agreement between numerical analysis and in situ measurements can be achieved in a back analysis. However, no details on the numerical implementation are provided and thus no information is given how mesh dependence of results, as would be expected in this type of problems, is overcome.

Numerical analyses of a tunnel in London Clay using different constitutive models by Masin & Herle: data from the Heathrow Express trial tunnel are used to study the performance of different constitutive models, namely Mohr-Coulomb, Non-linear elastic Mohr-Coulomb, Non-linear elastic with cross-anisotropy, Modified Cam-Clay, Advanced kinematic hardening (3SKH) and Hypoplastic including intergranular strains. An attempt was made to model the full stress history and the results clearly show, not surprisingly however, that more advanced models show better agreement with measured data than simple models. But even with the advanced models the calculated settlement trough tends to be slightly too wide as compared with measurements (Figure 2). It is pointed out that non-linear elasticity plays an important role which confirms data published in the literature. It is further emphasized that none of the models predicted horizontal displacements very well.

Prediction of settlements and structural forces in linings due to tunnelling by Möller & Vermeer: a very useful comparison of 2D and 3D analyses of tunnel excavation employing the so-called β -method (load reduction method, convergence-confinement method respectively) is presented. As expected, it is concluded that β -values differ for settlements, bending forces and normal forces and therefore care has to be taken when choosing these values in engineering practice for design. The influence of the round length and soil strength is also investigated.

3.4 Bored tunnels – general

4D grouting pressure model PLAXIS by Hoefsloot & Verweij: it is reported that no clear connection between grouting pressure and observed settlements, which

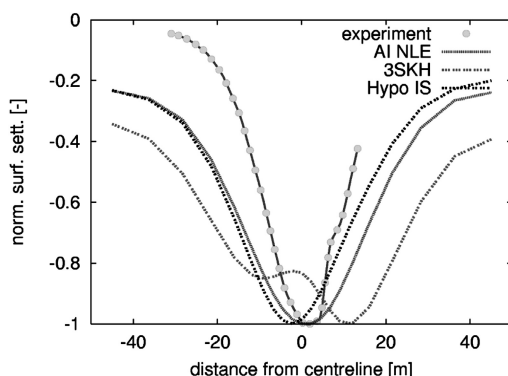


Figure 2. Normalised settlement trough for advanced models and measurement (Masin & Herle).

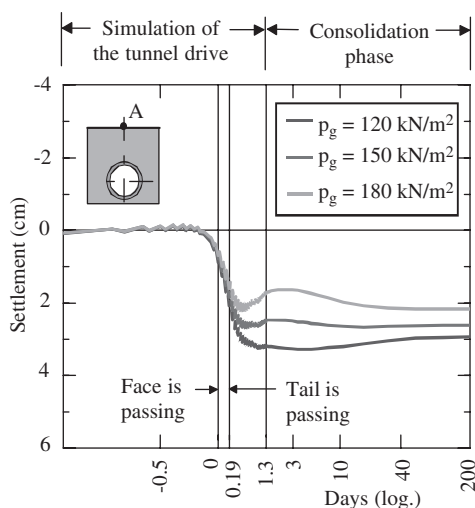


Figure 3. Influence of grouting pressure on calculated settlements (Kasper & Meschke).

however have been very small in the particular case considered, could be established. A 3D FE-model was developed and the influence of various parameters such as grouting pressure, face pressure, tunnel bending stiffness and soil stiffness on calculated settlements has been studied.

Parametric studies for shield tunnelling in soft soils by Kasper & Meschke: results from a comprehensive numerical study investigating the influence of the filter cake, the slurry pressure, the bending stiffness of jacks, the weight of the TBM, the conicity and the friction angle of ground by means of a fully coupled analysis are presented. The influence of each of these factors on the development of settlements with time is shown in diagrams (e.g. Figure 3).

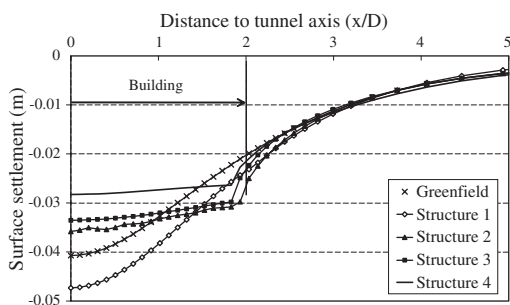


Figure 4. Calculated settlement trough for different stiffness of structure (Jenck & Dias).

3.5 Bored tunnels – lining

Axial pre-stresses in the lining of a bored tunnel by Koek, Bakker & Blom: the importance of longitudinal forces in tunnel linings and the effects of a sudden in- or decrease of jack forces, leading to an exponential change in the axial force, is addressed. It is emphasized that using plywood as joint material may cause axial forces to vanish in case of deterioration, with consequences for possible ring sliding and leakage.

Numerical modelling of the behavior of shield tunnel lining during assembly of a tunnel ring by Mashimo & Ishimura: in situ measurements and analysis based on a subgrade reaction method investigating the loading on linings during assembly are compared. It is concluded that these stages should not be ignored in the analysis because of the thrust force required to install keystone elements and the pressure caused by tail seals and tail grease.

3.6 Tunnel-structure interaction

Numerical analysis of soil-structure interaction during TBM tunnelling under a structure by Jenck & Dias: the importance of 3D analysis when assessing the influence of tunnelling on existing buildings is highlighted. The main conclusions from this study are that the Mohr-Coulomb constitutive model predicts wider settlement troughs than observed and the settlement trough is only influenced if a certain stiffness of the building is exceeded (Figure 4). Applying greenfield results to the building would be too conservative. It is acknowledged that higher order models for soil and structures (linear elastic in this study) would improve the accuracy of the results.

Numerical analysis of soil-foundation-building interaction due to tunnelling by Boonpichetvong, Netzel & Rots: again the influence of tunnelling on shallow foundations is studied whereas in this contribution emphasis is put on the interface behaviour between structure and ground (Figure 5). It was found that the roughness of the foundation has a significant

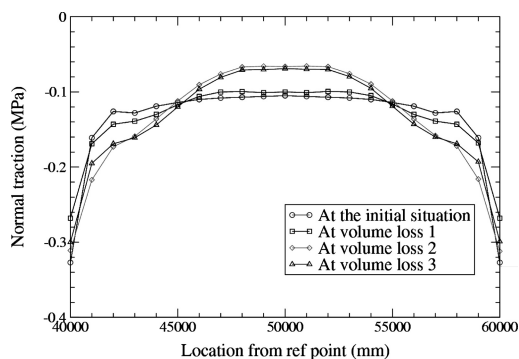


Figure 5. Normal traction on rough foundation for different values of volume loss (Boonpichetvong, Netzel & Rots).

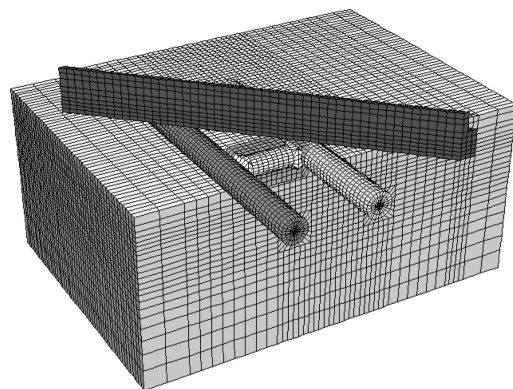


Figure 6. 3D numerical model used by Viggiani, Soccodato & Burghignoli.

influence on the calculated displacements and thus on the strains transferred to the foundation of a building. A fixed smeared crack model was applied for representing the nonlinear behaviour of masonry buildings.

A study of the interaction between the new C Line of Roma Underground and the Aurelian Wall by Viggiani, Soccodato & Burghignoli: a detailed 3D numerical analysis (Figure 6) employing a Mohr-Coulomb model is described. It was found that the crucial construction phase depends on the stiffness of the wall. For stiff walls it is at the end of construction whereas for flexible walls it is when the tunnel is passing.

A study of the response of monumental and historical structures to tunnelling by Burghignoli, Lacarbonara, Soccodato, Vestroni & Viggiani: various models with different levels of complexity have been applied to calculate the effect of tunnelling on monumental structures, in this particular case the Basilica of Massenzio. The basilica was discretized by means of a fully three-dimensional finite element mesh employing a nonlinear material model for

Roman concrete which was subjected to the settlement profiles obtained from semi-empirical relationships and 2D finite element analyses. The results show that computed effects of tunnelling on the structure are less pronounced when using more refined models as compared to simplified analysis.

3.7 Tunnel-pile interaction

Three-dimensional analyses of piled raft foundation subjected to ground movements induced by tunnelling by Matsumoto, Kitiyodom & Kawaguchi and Analyses of pile foundations subjected to ground movements induced by tunnelling by Kitiyodom, Matsumoto & Kawaguchi: these companion papers discuss the performance of single piles, a pile group and a piled raft subjected to the influence of tunnelling employing different models (3D FDM, Beam-Spring) treating soil and structures as elastic materials. Good agreement with respect to lateral pile deflection and bending moments in the piles was achieved with all approaches employed.

Analysis of effects of tunnelling on single piles by Surjadinata, Carter, Hull & Poulos: a method based on a combination of finite elements and boundary elements is proposed. A 3D finite element analysis for the free-field situation (no pile present) is performed and the resulting displacement field is imposed on a 3D boundary element model of the pile. Thus the computational effort is significantly reduced because only one 3D finite element analysis is required when investigating different pile arrangements. The applicability of the model is demonstrated by comparing calculated and measured horizontal displacements for 3 case histories and one benchmark case.

Simulations of tunnel excavation in 2D and 3D conditions considering building loads by Nakai, Sung, Shahin & Yamamoto: compares 2D and 3D finite element analyses and model tests of a comprehensive study investigating the deformation mechanisms and earth pressure distributions during tunnel excavation when a group of piles or a piled raft is situated in the vicinity of the tunnel. As in other contributions to these proceedings it is highlighted that the presence of structures leads to significantly different settlement troughs as compared to the greenfield situation.

4 KEY POINTS OF PAPERS – DEEP EXCAVATIONS

4.1 General aspects

A 3D FE model for excavation analysis by Bakker: a very general paper, highlighting the importance of 3D analyses for modelling excavation problems and the influence of soil stiffness on the extension of the calculated settlement trough. Technical standards

codes have to meet from a practical point of view are discussed.

Study of soil-retaining wall interaction by the Contact Finite Element Method by Ras & Bekkouche: a short contribution presenting some results from a numerical study on the influence of wall friction on the earth pressure distribution of concrete retaining walls.

4.2 Practical aspects dominating

Soil improvement during excavation in soft ground and development of analysis method for earth retaining structure by Motoi: presents an extension of the subgrade reaction method to account for soil improvement on the passive side during excavation. The developed model has been successfully applied to analyse a practical project.

Numerical analysis of displacements of a diaphragm wall by Mitew-Czajewska: compares subgrade reaction models and numerical analysis employing a Mohr Coulomb constitutive model with in situ measurements (back analysis). Only results for maximum horizontal displacement are presented and generally a good match could be achieved, numerical results being closest to measured values. The difficulties in obtaining realistic spring constants for subgrade reaction models and their influence on the results are addressed.

4.3 Theoretical aspects dominating

Passive resistance of soft clay in deep excavations by Tamano, Nguyen, Kanaoka, Matsuzawa & Mizutani: numerical analyses and physical model tests are employed to evaluate time effects on the passive resistance of retaining walls. It is advocated that the decrease of passive resistance with time should be taken into account when analysing practical projects. However, it was found that Rankine's formula provides a reasonable lower bound for the steady state passive resistance.

4.4 Interaction with structure

Settlement of single foundations due to diaphragm wall construction in soft clayey ground by Schäfer & Triantafyllidis: 3D FEM analysis of diaphragm wall construction are presented and its influence on the settlement of an adjacent footing using a hypoplastic constitutive model, varying the panel length and the position of the footing is investigated.

4.5 Data base

New developments of the MOMIS database applied to the performance of numerical modelling of underground excavations by Mestat & Riou: presents interesting data from the comprehensive MOMIS database

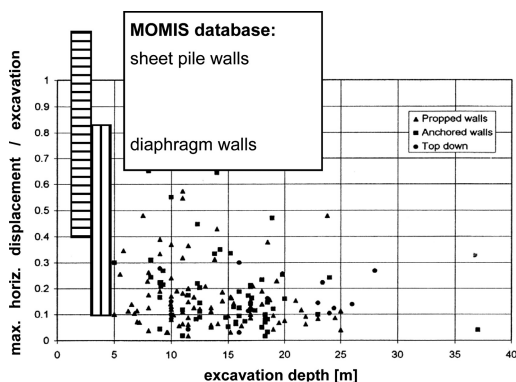


Figure 7. Range of values for ratio of maximum horizontal wall displacement vs excavation depth as suggested from MOMIS data base (reproduced from Long, 2001).

including 168 cases of retaining structures. It contains comparison of numerical analysis and in situ measurements with most of the analyses being back analyses. The main conclusions drawn in the paper are that errors in horizontal wall displacements are much smaller than for settlements and that errors in bending moments are much higher than for strut loads.

If horizontal displacements are related to the depth of the excavation (as compiled e.g. by Clough et al., 1989 and Long, 2001) the MOMIS database suggests 0.1 to 0.8% for diaphragm walls and 0.4 to 2% for sheet pile walls, which is rather on the upper end and above the data presented by Long, 2001 (Figure 7). However, further information, in particular on the stiffness of the retaining measures, not provided in the paper, would be required before conclusions on the discrepancies between the two compilations can be drawn.

5 CONCLUDING REMARKS

The papers submitted to this session cover a wide range of topics important in the analysis of tunnels and deep excavations. Tunnel – structure interaction analyses seem to have gained significant importance.

It is observed that analyses for practical projects are still using “simple” constitutive models in many cases but, certainly depending on the purpose of the analysis and the expertise of the user, valuable results can be achieved using these models. It would not be appropriate to dismiss them as some of the more theoretical papers may suggest.

Sophisticated theoretical investigations provide valuable insight into a certain problem, but despite their high level of modelling, generalization is often difficult suggesting the conclusion that each project is a prototype and requires separate analysis.

Summarizing the topics of the papers in wider terms, such as whether real practical problems have been analysed or particular aspects, some of them in great theoretical detail, have been investigated only a slight overhead of “theoretical” papers is observed. This clearly indicates that numerical methods are established both in practice and research, with different levels of complexity though. It has to be pointed out that only numerical models are capable of taking into account the influence of the stiffness ratio of ground and interacting structures such as piles or buildings with reasonable accuracy. The importance of this, also from a practical point of view, has been addressed in a number of papers submitted to this session.

Despite the advances made, further research in numerical modelling is essential, given e.g. the fact that it is still a challenge to predict a settlement trough following a Gaussian distribution curve. From a practical point of view some rough guidelines on how sophisticated models have to be for serving a given purpose of an analysis would be helpful for geotechnical engineers in practice.

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