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Numerical and physical modelling of tunnels and deep excavations

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ABSTRACT: This paper presents an overview of the papers submitted for the session on numerical and physical modelling of tunnels and deep excavations, submitted for the proceedings of the Fifth International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, held from 16 to 18 May 2011 in Rome.

1 INTRODUCTION

A total of 26 papers were submitted for the session on numerical and physical modelling of tunnels and deep excavations. The subjects covered, affiliation of authors and methods of investigation followed by the various researchers are presented in this paper. This is followed by a review of the individual papers submitted, after which the papers selected for presentation at the symposium are reviewed.

1.1 *Aspects covered*

Aspects covered by the papers in this session are summarised in Table 1 below, indicating the number of papers received covering the subjects listed. Aspects related to tunnelling were the most common topic, followed by aspects of excavations, subsidence of buildings and others.

1.2 *Affiliations of authors*

Papers were received both from academics and practitioners, with a total of 18 papers received from academics, 6 produced by academics and practitioners working together and 2 papers by practitioners only. The reason for the relatively small number of practitioners taking part in this session is probably related to the theoretical nature of this session, i.e. numerical and physical modelling, which appears to be most at home in an academic environment.

The authors are from 14 countries, mostly located in Asia and Europe. The following countries are represented: Australia, China, France, India, Iran, Italy, Japan, Korea, Malaysia, the Netherlands, Portugal, Switzerland, Taiwan and the United Kingdom.

1.3 *Investigative approach*

The methods applied by the authors to investigate the problems forming the subjects of their papers are summarised in Table 2 below.

Interestingly, most papers were based on work carried out using numerical modelling, with fewer papers discussing physical modelling. The reason is likely to be attributable to an abundance of software packages now available for the analysis of geotechnical problems. Four papers presented the results from mathematical or closed form solutions.

Four of the papers on physical modelling were based on the results of 1G modelling, with only

Table 1. Aspects covered by papers.

Topic	Number of papers
Excavations	5
Grouting	2
Materials	2
Pipe jacking	1
Subsidence of buildings	3
Various aspects of tunnelling	13

Table 2. Investigative approached adopted by authors.

Method	Number of papers
Numerical modelling	13
Mathematical or closed for solutions	4
Physical modelling at 1G	4
Physical modelling in the centrifuge	2
Both numerical and physical modelling	3
Literature review	1

two papers presenting the results of centrifuge modelling. It is the opinion of the session reviewer that the authors of papers which are based on 1G modelling should indicate how the results from their models can be extrapolated to the prototype scale without attempting to replicate the stress distribution in the prototype.

2 OVERVIEW OF INDIVIDUAL PAPERS

In this section an overview of the various papers contained in the session on numerical and physical modelling of tunnels and deep excavations is presented. The papers are grouped according to the topics which they discuss as listed in Table 1.

The discussion of each paper focuses briefly on the problem investigated, the approach followed to investigate the problem, followed by a short summary of the most important findings. Readers are referred to the individual papers for detail.

2.1 *Papers on excavations*

2.1.1 *An investigation into inclined struts method as type of shoring by Fakher & Sadeghian*

The authors reported that limited information was available in the literature regarding the use of inclined struts to support buildings adjacent to open excavations. The bottom end of the strut was located in the excavation, supporting the building at the edge of the excavation. Different strut geometries were investigated.

The problem was investigated by means of a three dimensional finite difference analysis and followed on earlier two dimensional work by the authors. The struts were modelled as beams and the soil as a linear elastic—perfectly plastic material obeying a Mohr-Coulomb failure criterion.

It was found that the building displacements were dependant on the sequence of excavation. The best performance in terms of displacements was achieved when the excavation was carried out, leaving some material behind, then installing the strut and then removing the material left behind.

2.1.2 *Understanding ground deformation mechanisms during multi-propped excavation in soft clay by Lam, Haigh & Bolton*

The authors investigated the performance of a propped excavation in slightly over-consolidated clay. They examined the effects of wall stiffness, the effect of the depth to the stiff stratum and the effect of toe fixity conditions.

The problem was investigated by means of a sophisticated centrifuge model in which the construction of a multi-propped retaining wall could be modelled. Pore pressures, ground settlements and wall deflections were monitored. Instrumentation used comprised LVDTs and PIV.

The maximum wall displacement was found to be a non-linear function of the wall stiffness. It was observed that stiffening of the wall was not the most economical method for the reduction of wall movements. The fixity at the base of the wall was found to have a very significant effect on the control of wall movement below the final excavation level. Control of toe movement of the wall was reported to be important to limit adjacent soil deformation.

2.1.3 *Water table lowering effects on excavations by Raposo & Topa Gomes*

This paper investigates the effect of how the lowering of the water table in the residual granites in Porto, Portugal was modelled on the predicted behaviour of the excavation. Lowering of the water table results in an increase in the strength and stiffness of the soil and is common practice in Porto.

The problem was investigated by means of numerical modelling in which the lowering of the water table was modelled by different means. Wall bending moments, wall displacements and surface displacements were examined.

The consideration of non-saturated conditions resulted in reduced bending moments, wall deflections and surface settlements. Realistic analysis of unsaturated conditions was found to be important, resulting in less conservative designs. The authors recommended *in situ* tests for the evaluation of the relationship between soil stiffness and suctions.

2.1.4 *3D finite element analysis of deep excavations with cross-walls by Rampello & Salvatori*

The effect of leaving cross-walls of different geometries supporting diaphragm walls was investigated in the soil profile of ancient Rome.

The work was carried out using finite element analyses and examined wall deflections and ground settlement behind the diaphragm walls. Different cross-wall spacings and lengths were investigated and results were compared with the results of 2D analyses. The walls were modelled using brick elements, the soil using a non-linear, elastic-plastic model (the Plaxis Hardening Model) and the wall-soil contact was modelled using interface elements.

It was found that cross-walls reduce wall deflections and ground settlements. For small cross-wall spacings, 2D and 3D results predicted similar deflections down to the excavation depth. It was however found that 2D analyses over-estimated deflections below excavation depth and over-estimated soil settlement behind the wall. Large differences between 2D and 3D analyses were reported for large wall spacings.

2.1.5 *Effects of excavation procedure on the stability of diaphragm wall panels by L'Amante & Flora*

The paper investigated the effect of the position of the excavator carrying out the excavation of a diaphragm panel on the stability of the panel.

A case study was presented illustrating an excavation panel failure that occurred when the excavator was standing adjacent to the long side of the diaphragm wall. The case study was analysed using a 2D and 3D finite element parametric study using the Plaxis Hardening Soil Model.

It was found that the position of the machine can play a positive *or* negative roll on panel stability. It was found that it was generally more favourable for the excavator to be standing along short side of the panel.

2.2 *Papers on grouting*

2.2.1 *The efficiency of compensation grouting in sands by Soga, Bezuijen & Eisa*

The authors investigated effects of the following aspects on the compensation efficiency achieved during the grouting of sands:

- Water/cement ratio
- Bentonite content
- Injection rate

The work was carried out using parallel physical modelling at the Universities of Delft and Cambridge. Models were set up to measure grouting efficiency in fine saturated sand.

Reasonable agreement between the Cambridge and Delft results were reported. Efficiency was found to be correlated with sand density, with low densities yielding low efficiencies. Higher water/cement ratios also resulted in lower efficiencies and increasing bentonite content resulting in increased efficiency and less pressure filtration.

2.2.2 *Experimental and numerical study of grout injections in silty soils by Masini, Rampello, Viggiani & Soga*

This study investigated the efficiency of compensation grouting in silty soils.

The problem was investigated by means of physical modelling using an 850 mm circular tub containing 400 mm of silica flour into which grout was injected. The injection volumes, heave and pore pressure responses were measured. Numerical analyses were carried out to attempt replication of the physical model. For the purposes of the numerical model, the silt was modelled as a non-linear elastic-plastic model using the Plaxis Hardening Model and the grout was modelled as a non-porous linear elastic material modelling cavity expansion. Soil parameters were calibrated by comparison with triaxial test data.

Compensation efficiencies of well below unity were found and it was found that efficiencies reduced with time. The initial loss due to pressure filtration was, however, small. The numerical analysis could replicate stress changes and induced excess pore pressures outside the injection body relatively well. The authors reported that it is important to take large strains into account when modelling grout injections numerically.

2.3 *Modelling of materials*

2.3.1 *Analysis of excavation using a stress path dependent undrained soil model by Ou & Hsieh*

The development of a total stress constitutive model for excavations was presented. The model is a variation on the Duncan and Chang (1970) model and requires 6 parameters.

The authors presented the model and results, validating it against laboratory data and a case history. Because the model is a total stress model, it does not conform with the effective stress principle. Parameters therefore have to be determined empirically. The model and parameters must take stress path effects into account in order to be realistic. Advantages of such a model are that it is relatively simple, disregarding anisotropy, small strain behaviour, pore pressures etc. However, it is important that parameters must be obtained from stress paths comparable to what will be analysed.

2.3.2 *Review of Newtonian and non-Newtonian fluids behaviour in the context of grouts by Kazemian, Prasad & Huat*

This paper examined various rheological models for grouts. Rheological models describe the relationship between shear stress and shear rate of the material under consideration. These properties naturally change in cementitious grouts as hydration takes place.

A literature review was carried out and an overview of Newtonian and non-Newtonian fluids were presented looking at the behaviour of pseudo-plastic fluids, dilatant fluids, viscoplastic fluids and thixotropic fluids.

The authors mention that no single model is available that characterises the behaviour of cementitious grouts during all its phases of hydration. It is difficult to find a rheological model to characterise cement grout adequately, e.g. the Bingham model is also not exact.

2.4 *Paper on pipe jacking*

2.4.1 *Influence of overcut length on jack force and acting earth pressure during pipe jacking by Asanprakit, Sugimoto & Chen*

The effect of overcutting on jacking force required during pipe jacking was examined. The authors reported that most available models do not consider overcutting.

A 3D finite element pipe jack model was set up in which the soil was modelled as springs, the tunnel lining as shell elements and the lining-soil interface using a Mohr-Coulomb criterion.

It was reported that the model was adequate i.t.o. the predicted earth pressure acting on the pipe, the jacking force and the frictional resistance encountered. It was found that overcutting greatly influences loads on the jacked pipe and the jacking resistance.

2.5 *Subsidence of buildings*

2.5.1 *Assessment of building damage induced by excavation using plate analogy by Namazi & Mohamad*

A model for the prediction of damage to buildings caused by nearby excavations was presented. Most existing models are based on tensile strain, deflection ratio (ω) and the angular distortion (β) suffered by the building under consideration. It reported that in 3D, twist increases bending and diagonal strains, resulting in greater tensile strains.

In their model, the authors proposed that the building be modelled as a thick, uniformly loaded, rectangular plate. The model accounts for warping and twisting using Levinson elastic plate theory to calculate tensile strains. It does, however, not account for soil structure interaction.

It was reported that when the length/widht ratio exceeds 3, beam analogy is sufficiently accurate to model the building. It was recommended that the method be validation against case studies.

2.5.2 *The ground movement simulator: an interesting facility for the study of the behaviour of buildings submitted to ground subsidence by Caudron, Heib, Hor & Emeriault*

This study examined the effect of soil subsidence on overlying development (soil-structure interaction).

A 1G model study of subsidence under buildings using Fontainebleau sand was carried out. Stress levels were not modified. A model platform measuring 3 m × 2 m, comprising 48 retractable (250 × 250 mm) jacks when complete was described. Subsidence could be created at any location in the model by retracting the desired jack. Surface settlements were measured using stereo imagery. Buildings were modelled using a hollow "waffle" frame with lead powder. This was sized to posses the correct stiffness and exert the correct stress. A parametric study, looking at buildings at different locations w.r.t. the zone of subsidence, was carried out. Building behaviour was compared with the settlement of the greenfield.

The authors concluded that it is important that soil structure interaction be taken into account.

2.5.3 *Centrifuge modelling of the response of buildings to tunnelling by Farrel & Mair*

Modelling of building response due to tunnelling was the topic of this paper.

The problem was investigated using centrifuge modelling looking at soil structure interaction effects and examined both elastic and non-elastic buildings. Model buildings of various geometries and stiffnesses were investigated (using aluminium, micro concrete and masonry). The authors examined building settlement in relation to the greenfield settlement, the effect of building embedment on horizontal behaviour and the subsequent damage.

It was reported that buildings do not deform as the greenfield, with the greenfield response being modified both vertically and horizontally. The interaction depends on the relative building stiffness. It was found that negligible horizontal strains were transferred into model buildings even for buildings with extremely low horizontal stiffness. This could have implications for existing damage criteria which depend on tensile strains. It was reported that it is generally over-conservative to estimate damage based on greenfield settlement and horizontal distortions.

2.6 *Aspects of tunnelling*

2.6.1 *Tunnelling induced deformation of a masonry structure: a numerical approach by Amorosi, Boldini, de Felice & Malena*

This paper focuses on the prediction of damage to ancient structures due to underground construction.

A numerical model of tunnelling under a masonry structure was created. Initially, the free field was modelled to validate the model, after which the masonry structure was included. The soil was modelled as a linear elastic-perfectly plastic undrained material. The masonry model took the discrete nature of a brick wall into account and was based on a linear elastic-perfectly plastic model with anisotropic elasticity and strength.

It was found that the settlement trough was wider than predicted by a closed form solution at 0.7% volume loss. Better agreement was, however, reported at 2.3% volume loss. The presence of building changes the greenfield deformations. Plastic strains were reported in the in masonry wall.

2.6.2 *Stability of cohesive-frictional soils with square underground openings by Yamamoto, Lyamin, Wilson, Abbo & Sloan*

The stability of twin square openings in plane strain conditions was investigated using rigorous upper and lower bound numerical limit analysis from plasticity theory. Results were compared with several rigid block upper bound mechanisms and a parametric study, examining different tunnel depths and tunnel spacings, was carried out. The soil was modelled as a drained Mohr-Coulomb material. (This is valid for soils obeying the associated flow rule).

Good correlations were reported between the upper bound and lower bound predictions for relatively shallow tunnel depths at close spacing and when the value of the effective friction angle (ϕ') was small. It was reported that upper bound mechanisms performed better for square openings than circular openings. Future work will include the refinement of an upper bound model giving realistic results for high ϕ' values and openings at larger spacings.

2.6.3 *Bearing capacity analysis of cohesive-frictional soil with dual circular tunnels by Yamamoto, Lyamin, Wilson, Abbo & Sloan*

This paper is similar to the paper discussed in Section 2.6.2 above, but investigated circular tunnels rather the square tunnels. As mentioned above, it was found that upper bound mechanisms performed better for square openings than circular openings.

2.6.4 *The dynamic behaviour of shield circular tunnels and surrounding granular soils during earthquakes by Hatambeigi, Pashang Pisheh & Pashang Pisheh*

The performance of a shield tunnel during an earthquake was investigated by means of a 2D dynamic numerical model. An 8 m diameter tunnel, centred at 12 m depth in medium dense sandy soil under a volume loss of 2% was modelled. A parametric study was carried out in which various soil and lining properties were varied. The soil was modelled as an elastic-plastic Mohr-Coulomb material and the lining as an elastic material. The model was first validated using a static analysis, after which the acceleration record of the 1940 El Centro earthquake was applied at the model base.

It was found that ground and tunnel deformation decreased with increasing soil and lining stiffness, cohesion and damping ratio. A stiffer lining resulted in larger lining forces.

2.6.5 *Face stability control for EPB tunnels in a non-homogeneous till formation with highly permeable layers by Graziani, Lembo-Fazio, Moccichino and Romualdi*

This paper examined the influence of muck permeability in a TBM head chamber on face stability.

The problem was investigated by means of a 3D finite difference modelling of a mixed face of till with a sandy layer in-between, representative of the situation in Vancouver. The conditioned soil in the head chamber and screw conveyor was explicitly modelled. The soil was modelled as a linear elastic-perfectly plastic material with a Mohr-Coulomb yield criterion. The tunnel excavation was first modelled without and then with the TBM in place. The conditioned soil properties and associated ground response, water pressure drawdown and minimum support pressures required to ensure face stability were investigated.

It was found that when the muck permeability was equal or less than the in situ permeability, drawdown effects associated with the tunnel excavation were avoided. It is important to control muck conditioning and the most important factor governing the soil response to tunnelling was found to be the permeability of the conditioned soil.

2.6.6 *Influence of leakage on tunnel behaviour in soft soils by Zhang, Huang & Fan*

The authors investigated the effects of tunnel leakage on tunnel settlement and lining moments over time by means of a small scale models in saturated sand at 1G. Both permeable and impermeable tunnels were modelled.

Tunnels with permeable tunnel linings were found to settle, while tunnels with impermeable tunnel linings were found to rise (float). Leakage resulted in differential settlement along the tunnel. Moments in the tunnel lining were reported to increase with time in the case of permeable tunnels, but remained constant for impermeable tunnels.

2.6.7 *Effect of soil stratification on pipe behaviour due to tunnelling-induced ground movements based on the displacement controlled method by Zhang, Huang, Zhang & Wang*

This paper investigated the effects of tunnelling near pipes in a anisotropic soil by means of numerical modelling. Results were compared to centrifuge data from Cambridge.

The numerical model incorporated stiffness anisotropy, but modelled the soil as linear elastic. Imposed greenfield soil movements were based on the model by Loganathan and Poulos (1998).

It was reported that good correlation was obtained between the centrifuge data and the predictions from the proposed model for pipe settlement and bending moments in isotropic soil at small volume losses. Poorer correlation was, however, obtained when anisotropy was modelled. The authors concluded that the consideration of soil anisotropy is important when studying tunnelling under pipes.

2.6.8 *An analytical method to control the tunnel lining settlements by Garini*

The author proposed to use pre-stressed anchorages at points on a tunnel lining to reduce lining convergence under soil pressure. He then presented a structural analysis method to analyse the stability of the tunnel lining segments using virtual work principles. For the application of the method, the tunnel lining arch is subdivided into sub-arches, each with a span of less than 90°. The paper contains the mathematical background and the author reported that the method is suitable for applications in soft soils and shallow bored tunnels. The method can be applied in either force or displacement form.

2.6.9 *Interaction between tunnelling and bridge foundation—3D numerical investigation by Yoo & Wu*

This paper examined the effects of tunnelling under a pile-supported bridge that was studied by means of a 3D finite element model. The piles, pile caps and piers were modelled explicitly. A pile-soil interface was introduced which allowed slip. The soil was modelled using an elastic-plastic Mohr-Coulomb material with a non-associated flow rule.

It was found that the mobilised load on piles close to tunnel reduces due to downward movement relative to soil. Loads on piles further away were found to increase due to load redistribution in the bridge.

2.6.10 *Numerical analysis of precast tunnel segmental lining supported by full-scale experimental results by Cignitti, Sorge, Meda, Nerilli & Rinaldi*

The behaviour of precast tunnel segments under TBM jacking loads was investigated by means of numerical analysis and full-scale load tests on lining segments in the laboratory. The numerical model incorporated a non-linear fracture mechanics approach to model cracking in lining segments. The lining concrete and reinforcement steel, as well as the jacking shoes and teflon interface plates, were modelled explicitly. The numerical modelling first focussed on one segment and then a complete ring.

In the full-scale laboratory tests, single lining segments could be loaded up to 4000 kN per jacking shoe. First crack initiation and the subsequent development with increasing load were investigated.

Cracking was found to initiate between jacking shoes and not under them. It was reported that, at crack initiation, similar loads were predicted for single segments and completed rings. Good correlation between the numerical and physical trials were reported regarding the replication of crack onset.

3 PAPERS PRESENTED

The following three papers were selected for presentation at the symposium. It was the intention to invite presentations from a variety of topics, subject to the availability of authors attending the symposium to present their work.

3.1 *Numerical simulation of long-term twin-tunnel behaviour at St James's Park by Laver & Soga*

It was reported that long term settlements still occur at an unexpectedly high rate in St James's Park, London above the twin-tunnels of the Jubiliee Line Extension. This was attributed to creep or unexpected soil softening. The authors presented work modelling the long term performance of the twin-tunnels using coupled consolidation finite element analysis.

The effect of different soil and lining permeabilities on the long term consolidation above the tunnels was investigated and included a study of the effect of soil anisotropy. Also examined was the performance of a fissure softening model recently developed after observing softening on fissures in triaxial extension tests and softer than expected behaviour observed under torsional shearing in the hollow cylinder apparatus.

The authors reported that by adjusting the permeability of the soil and the lining, the deformation around tunnel could not quite be matched. Unexpectedly high permeability anisotropy values had to be applied at the tunnel crown, perhaps indicative of stress induced permeability changes.

It was reported that the fissure model developed gave a narrower settlement trough than conventional finite element models and this is more representative of field observations.

3.2 *Tunnelling in stratified soft ground: experimental study on 1g EPBS reduced scale model by Berthoz, Branque, Wong, Généreux, Subrin & Humbert*

The authors presented results obtained from reduced scale modelling of an Earth Pressure

Balanced Shield, tunneling in soft ground at 1G. Surface settlements and arching effects around the TBM were examined in homogeneous and stratified soils, paying particular attention to the influences of face pressure and the soil mass composition. Face collapse mechanisms in homogeneous pure frictional and frictional-cohesive materials, as well as stratified soils (two and three-layered soils), were also presented. In the stratified profiles, the frictional soil was located above the tunnel axis, with frictional-cohesive material below the tunnel axis. Similar failure mechanisms were observed in the homogeneous and stratified profiles, although failure tended to take place in stages in the case of a three-layered soil.

3.3 *Comparing the limit equilibrium method and the numerical stress analysis method of tunnel face stability assessment by Parazzelli & Anagnostou*

Two approaches for the evaluation of tunnel face stability of tunnel faces reinforced by bolts were investigated, i.e. a limit equilibrium method (Anagnostou & Serafeimidis, 2007) and a numerical stress analysis method. Comparative calculations were carried out modelling a dry cohesive-frictional soil using the finite difference code FLAC3D. The soil was modelled as an elastic—perfectly plastic material obeying the Mohr-Coulomb yield criterion.

The first results presented apply to an unreinforced tunnel face and compares the predicted tunnel support pressure. The influence of tunnel shape, in situ stress and dilatancy was investigated. It was found that the limit equilibrium method and the numerical stress analysis method provided results comparable with those from other analysis methods.

The reinforcing effect of the bolts was investigated in the second part of the paper. The numerical stress analysis method indicated that shear failure of the soil around the bolts controlled the bolt-soil interaction ahead of the face. This suggests that the bond strength (i.e. the resistance of the interface between grouted bolt and soil) used in the limit equilibrium analysis should account for the shear resistance of the ground and thus the normal stresses ahead of the face. A simplified procedure was presented by which this can be achieved.

4 CONCLUSIONS

A total of 26 papers have been received in the field of numerical and physical modelling of tunnels and deep excavations. The most popular topic was aspects of tunnelling, with a total of 13 papers received. This was followed by 5 papers on various aspects of excavation, 3 papers on the subsidence of buildings, 2 each on materials and grouting and 1 paper on pipe jacking.

In terms of modelling approaches, the most popular method was numerical modelling, followed by 1G modelling and mathematical and closed form solutions. Three papers were based on both physical and numerical modelling. Only 2 papers presented the results of centrifuge modelling. One paper comprised a literature review.

The majority of authors in this session were from an academic environment, with a relatively small number from industry.

A brief review of the individual papers are included above.

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