General report for the session 2 C-underground structures

V.M. Sharma
AIMIL Limited, New Delhi

1 INTRODUCTION

People have been making underground structures for different purposes, for a very longtime. Probably, the first tunneling was done during prehistoric period to enlarge their caves. All major ancient civilizations developed tunneling methods. In Babylonia, tunnels were used extensively for irrigation; and a brick-lined 900 m long tunnel was built about 2180 BC under the Euphrates river to connect the royal palace with the temple. The Egyptians developed techniques for cutting soft rocks with copper saws and hollow reed drills, both surrounded by an abrasive, a technique probably used first for quarrying stone blocks and later in excavating temple rooms inside rock cliffs. Even more elaborate temples were later excavated within solid rock in Ethiopia and India. The three main uses of rock-cut architecture were temples (like those in India), tombs (like those in Petra, Jordan), and cave dwellings (like those in Cappadocia, Turkey).

With the advancement of civilization, tunnels were constructed for the generation of hydroelectric power, transportation of people, material,water, and strategic purposes. Large caverns have been excavated for underground powerhouses, storage of materials like oil and gases, stadia for games and sports and shelters in the event of wars.

It is not surprising, therefore, to see that the Session on Underground Structures, has papers dealing with investigations, design and construction of underground structures for different purposes on one hand, and those dealing with the safety of old underground heritage structures on the other.

There are a total number of 24 papers from 17 countries selected for discussion in the Session. The papers can broadly be classified into the following six categories;

1. Geotechnical Investigations and Seismic Analysis	4
2.Experimental Simulation in the Laboratory	5
3. New Design Methods	4
4. Numerical Modeling and 3D Simulation	6
5. Field Measurements and Soil Behavior	3
6. Use of Field Measurements for Predictions	2

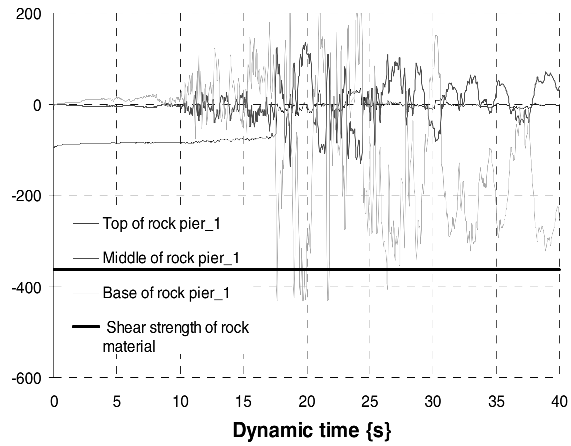
A brief discussion on the papers selected for the Session follows:

2 GEOTECHNICAL INVESTIGATIONS AND SEISMIC ANALYSIS

1. Pitilakis, Bandis and Hemeda in their paper *Geotechnical investigation and seismic analysis of underground monuments Alexandria, Egypt* describe the geotechnical investigations carried out at three catacombs in Alexandria Normally underground structures are safe against earthquakes, but if they have other structures inside which are projecting out like tombs and catacombs, there could be problems. These investigations were carried out to see the effects of weathering, aging and human activity, to estimate the safety margin in the existing monuments and to look at the potential improvement of their behavior applying required retrofitting techniques.Very thorough investigations have been carried out to look at the composition, the strength and weathering parameters besides the shear wave velocities and creep characteristics of the soft limestone formations.

Using these parameters 2D and 3D numerical analyses have been done. The results have indicated that the underground monuments have a low factor of safety and need strengthening with a well designed retrofitting program.

Three different earthquakes have been used for the analysis and using the analyses, threshold PGA values and the corresponding stresses have been calculated. It would have been of interest to see some results of dynamic analysis showing distribution of stresses and deformations and the time frame for which these stresses remain in a range higher than permissible.



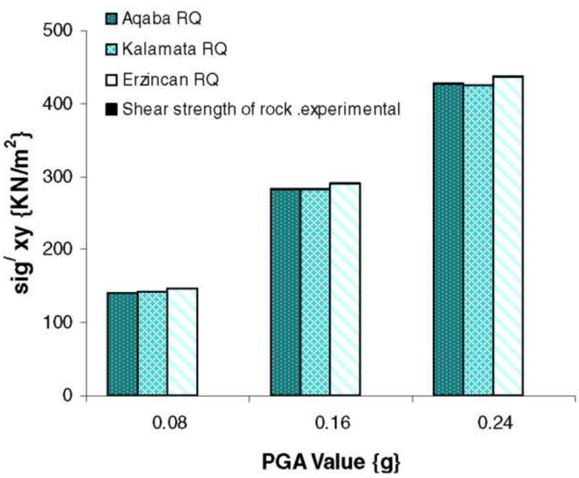


Figure1. Effective shear stresses – time histories and maximum effective shear stresses at the base of rock piers for 3 earthquakes scaled to PGA values (after Pitilakis et al).

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2. ***Zhusupbekov, Sedmarova and Matsumoto*** have described the geotechnical investigations carried out for the design of the foundation piles of a twelve-storied building. Static vertical load tests were carried out on two square shaped reinforced concrete piles, besides carrying out the odometer tests on soil samples and CPT at site. Using this data and assuming the pile is behaving as an elastic column supported by springs, load displacement curves were generated which were found in close agreement with the in-situ results obtained.For the calculation of displacements, axial forces and the mobilized shaft and tip resistance, a one-dimensional FEM was used.

An empirical factor has, however, been used for matching the computed performance with the observed one and it is stated that this factor depends on the soil type, the pile type and the pile installation method. There is a lot of valuable data lying locked in the files of several contractors who do this type of work and it is suggested that this data be fished out and used to determine this empirical factor with little more certainty.

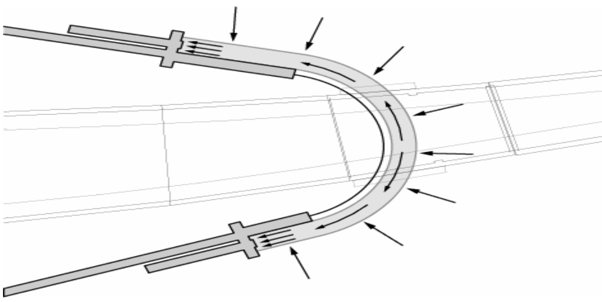

Fig. 2 Top view of the frozen soil body (after Brassinga et al).

3. Brassinga and Oung, in their paper *'Structural behavior of a collar construction made of frozen soils in a deep excavation'* have described the results of laboratory tests on frozen soil samples, and a two dimensional FEM to determine the forces acting on a frozen soil retaining wall, which appeared to be the only alternative for the construction of Central Metro Station at Rotterdam under given circumstances. One of the important considerations was the effect of time on strength and deformation characteristics of different soil types. A two dimensional FEM was used to calculate the bending moments and the axial and tangential forces during different stages of excavation.

This very interesting paper would have become all the more useful, had some instrumentation been provided in the wall and its performance monitored with respect to time. The computed results could then be compared with those actually observed.

4. In their paper *'New Hood Catharijne: a 5-level challenging underground construction'* which is of great relevance to the urban developmental projects, ***A.E.C.vanderStoel, Vink, Kluft and Nijs*** have described the geotechnical investigations carried out for the construction of one of the largest and the deepest car parking garages in Netherlands along with a shopping mall, entertainment area and a canal.

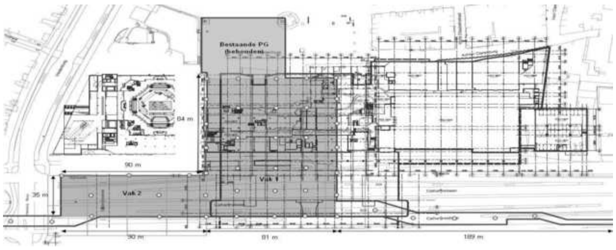

Figure 3. Proposed car parking and an artist's impression of the finished project (after Stoel et al).

Since the proposed building is surrounded by other high rise buildings and an existing car park and the construction is proposed to take place with pre-stressed pre-fabricated walls placed in increment-bentonite slurry walls, FEM analysis was carried out simulating the sequence of construction. The design of piers carrying very heavy loads were done using the code based on previous results and the FEM. The ground water flow was modeled using a 3D code and it was made sure that no changes in ground water levels of any consequence will take place. The authors have demonstrated hoe with the use of modern techniques and collaboration of experts in different fields, complicated geotechnical problems can be resolved.

It would be of interest to see when the actual construction takes place and whether the predicted movements and ground water levels match with those computed.

3 EXPERIMENTAL SIMULATION IN THE LABORATORY

1. Shahin, Nakahara and Nagata in their paper *Behavior of ground and existing structures due to circular tunneling* have described the relationship between surface settlement and the volume loss due to shallow tunneling. In a new experimental set up they have simulated the excavation of a circular tunnel, simulated building loads, measured earth pressures, surface settlements, its horizontal position etc., and used a FEM to analyze the results. They have found that volume loss is less significant than the crown drift for estimating the surface settlement troughs and the earth pressure distribution.

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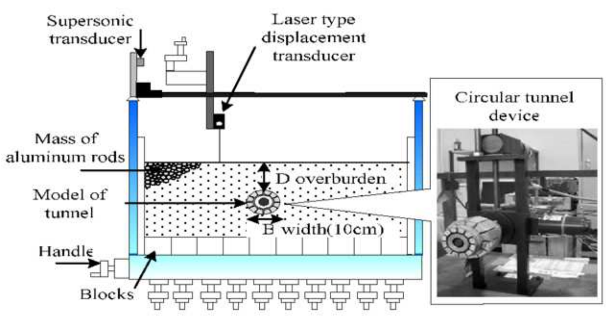
This is an important finding and needs to be verified in the field. Whereas it may not be possible to find a solution to all the possible situations arising in the field, some quantification of parameters would be desirable.



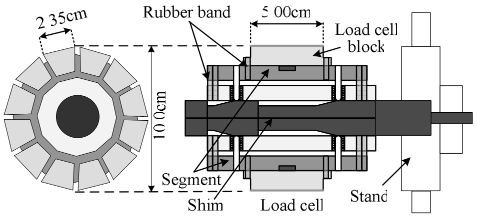


Figure 4. Schematic diagram of device for tunneling (after Shahin et al).

2. In their paper *Seismic analysis of shallow tunnels by dynamic centrifuge tests and finite elements,* ***Bilotta, Lanzano, Russo, Silvestri and Madabhushi*** describe the centrifuge tests carried out on a circular aluminium tunnel in an attempt to calibrate the results of numerical studies with a reliable experimental set up. It is an interesting paper because it is difficult to conduct experiments for dynamic situations.
However, which of the two techniques i.e. the experimental set up or the numerical model should form the benchmark is an issue which could be debated.

3. In their paper *Model tests and numerical analysis on the evaluation of long-term stability of existing tunnel,* ***Sekine, Zhang, Tasaka, Kurose and Ohmori*** have conducted two type of tests on physical models – failure tests and creep tests – using gypsum and diatom whose behavior is similar to sedimentary rocks. At the same time an elasto-visco-plastic model of the tunnel with strain softening has been studied in a numerical model in which the effect of intermediate principal stresses have been considered. It is concluded that FEM analysis with a suitable constitutive law can describe the long term behavior of soft rocks, including creep effects, appropriately.
Even though the analysis carried out is two dimensional, there is a very close agreement between the theoretical results and the experimental ones. It would be interesting to see the results of three dimensional analysis and field measurements, if any.

4. *Mechanical behavior of twin tunnels* is a paper by ***Lee, Choi, Shim, Cho and Hong,*** where the authors investigate experimentally the displacements before and after two tunnels are excavated and study the effect of the centre distance and coefficient of earth pressure at rest.

The software used for the analysis is PFC which is normally used to study the crack propagation etc., the results have shown that the induced displacements increase initially till the distance between the centers reaches 2D. The effect of K on displacement and crack propagation has shown results in agreement with the experimental work.

It would be interesting to know how the parameters for the PFC model were chosen, because these are the problems faced in real life.

5. In their paper *Model tests and PIV analysis on failure of behavior of embankment due to injected water* ***Nakata, Murata and Orense*** have described a series of small scale model tests conducted to look at the collapse mechanism of embankment slopes as result of water injection using Particle Image Velocimetry to measure local velocities within soil masses. This resulted in two type of failure patterns, a sudden slip failure and a gradual planar failure. They concluded on its basis that the measurements of displacements and pore water pressure are adequate for predicting slope failure due to injected water.

In this remarkable paper, the techniques which are normally used in the field of fluid mechanics have been successfully deployed for studying the problems of geotechnical engineering.

4 NEW DESIGN METHODS

1. In their paper *Analysis of movements of underground structures from horizontal load,* ***Dimov and Bogushevskaya*** have investigated some of the problems faced by designers when the underground construction transfers load either horizontally or horizontally and vertically.

The equations are derived fundamentally based on the known procedures of the theory of elasticity. The solutions will be useful not only for practical problems but also for the interpretation of tests with flat dilatometers and blade pressuremeters. As indicated by the authors some more work is required to supplement the data and modify the equations, if required.

2. *Design of multiple deep non-circular tunnel linings* is a paper by ***Fotieva, Bulychev, Deev and Firsanov,*** where they have described a method for the design of multiple deep tunnel linings of arbitrary cross sections. The method accounts for the self weight and the underground water pressure. The interaction analysis of the lining and surrounding rock mass is based on the theory of elasticity. In this approach, the mathematical techniques of conformal mapping and complex variables have been used to find solutions for different shapes other than circular. The authors have suggested how the effect of time dependent properties, grouting and earthquakes etc. can be taken into account to make it more versatile.

However the fact remains that the method fundamentally presumes homogeneity and isotropy of the media through which the tunnel is driven and does not take the geological features into account.

3. ***Jovicic and Logar*** in their paper *Design of a deep tunnel in a layer of a normally consolidated clay*, have described the procedure which was used to design a 400 m deep section of the tunnel in weak normally consolidated clays. The model was based on the behavior of such clays when subjected to unloading. The role of the rise of the resulting negative pore pressure on the strength and stiffness of clays for un-drained, consolidation and fully drained conditions is discussed. The full sequence of the construction of a 5 m diameter tunnel is discussed and results presented. Two and three dimensional FEM analyses were used to determine the effect of negative excess pore pressure, the stresses and the convergence etc. A total of eightanalyses with four different overburdens and two sets of properties each were carried out.

It would be of interest to watch the actual performance of the tunnel during and after excavation.

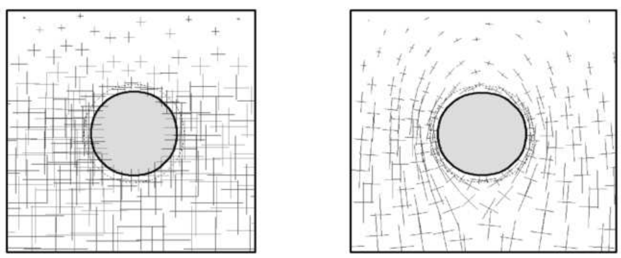


Figure 5. Principal stresses in soil surrounding a tunnel with and without shear strength [after Santos et al].

4. Effect of soil saturation changes on pressure on tunnel linings is a paper by ***Santos, Ledesma and Lloret*** which describes the effect of saturation on mechanical properties of soil and shows that the saturation can lead to reduction in arching and therefore increase in stresses in the tunnel lining. The paper shows how a conventional FEM program can be used for assessing the effect of soil saturation changes on underground structures.

5 NUMERICAL MODELING AND 3 D SIMULATION

1. In the paper '*Stability of circular tunnels in soft ground,*' ***Wilson, Sloan and Abbo*** have carried out FEM analysis of a circular tunnel in soft ground, where the strength varies linearly with the depth. The solution takes into account the ground surcharge, soil unit weight and the non-homogeneous strength of soil varying linearly with depth. Rigid body mechanisms are used to obtain the lower and upper bound solutionsusing semi-analytical methods. The solutions are presented in the form of non-dimensional numbers so that they can be applied for other problems. The results have also been compared with laboratory and centrifuge results. When there is no variation in strength, it becomes a special case of the same problem.

2. In the paper *Shield tunneling – Validation of a complete 3 D numerical simulation on 3 different case studies*, ***Demagh, Emeriault and Kastner*** have presented a numerical simulation of shield tunneling process using the software FLAC 3D. Comparison of results obtained from numerical simulation have been compared with those obtained from actual in-situ measurements from three actual casesand found that there is general agreement, particularly with regard to the simulation of various processes of shield tunneling like excavation, confining pressure, advancement, installation of tunnel lining and grouting of annular voids etc.. It is a very interesting development, because this will enhance the capability of FLAC 3D which is already a very powerful software, is based on finite difference technique, can take large deformations into account and can simulate construction sequence and support systems.

3. Usmani, Nanda and Sharma in their paper *Stress and seepage analysis of underground caverns,* have presented the results of the investigations and analysis carried out for a large cavern for storage of hydrocarbons. The results presented include the stresses, its stability and seepage. Two main concerns around which the design of the cavern revolves are high horizontal stresses and the water tightness required for the sealing of gases. The horizontal stresses appear to be really high and one wonders why the shape of the cavern was not changed to suit the stress orientation.

4. In their paper *Numerical analysis of circular reinforced concrete tunnel lining****Lewandowska and Czajewska*** have described the results of numerical analysis of reinforced concrete lining of four characteristic sections. The data used was from an actual construction site. The results will be used to finalize the tunnel lining and the location of joints to take care of large momentum values. The results show that there is a definite advantage to be gained by using jointed reinforced concrete linings in place of rigid linings.The locations of the joints are also very relevant because most of the times precast concrete panels are used and directions can be oriented suitably.

5. ***Rozenvasser, Symonovych, Tokoveko, Gavrilenko and Shatalov***in their paper *Construction of the Donetsk (Ukraine) Underground Railway on the undermined territories and tectonic faults,*have described the problem of construction of Metro through a terrain having faults and undermined areas, in their paper Construction of Donetsk (Ukraine) Underground Railway on the undermined territories and tectonic faults.A technical solution for the construction through difficult terrain was worked out and implemented.The investigations showed some patterns of rock deformation within the tectonic fault zones, specially when undermining. Within these areas was recorded the abnormal distribution of displacements and deformations, if compared with the undisturbed rock mass. They describe the development of a rigid segment with the application of extruded lining. They also developed a new solution for running tunnels which provided alternation of flexible segments outside the tectonic fault zones, with different patterns of the movement joint behavior; one way pattern for the flexible segments – compression only and two way pattern for the deformation inserts – tension-compression.

6. In their paper ' *A numerical study of a deep excavation in soft clay in Norway – Comparison of 2D and 3D analyses',****Torum, Kirkebo and Athanasiu*** describe a numerical study of a deep excavation through soft sensitive clays (partly quick clay) by cut and cover method in Norway. Excavation has been designed with steel sheet pile walls, ribs of jet grouted piles and steel struts for reducing the deformations. Comparison of 2D and 3D analyses showed that the 2D analysis under-predicts the maximum sheet pile bending moment with approximately 50%. In the 3D analysis, the stress concentrations in the longitudinal direction are captured. They also demonstrated that in this particular case, applying the partial material factor on the shear strength is less safe than applying an equivalent load factor on the structural forces when the soil is not at failure.

6 FIELD MEASUREMENTS FOR SOIL BEHAVIOR

1. In the paper *Settlement of an art relic church caused by the construction of the Metro line*, the authors ***Farkas and Turi*** describe the settlement of a church as the construction of a metro station takes place nearby. The strata is variable, the ground water is shallow (4 to 6 m deep) and the cut and cover station is large (90m X 27.5 m). The effect of excavation on the stability of nearby diaphragm ditch, deviation of the diaphragm wall, settlement due to construction of tunnels nearby and the dynamic effects have been accounted for. The foundation and the surface structure of the church were strengthened and a modern system for monitoring settlements based on four type of monitoring systems installed.

2. In the paper*The problem of controlling the mountain pressure when underground developing of ore deposits,* the authors ***Baimakhan, Takishov, Avdarsolkyzy, Rysbayeva, Altynbekov, Kulmaganbetova, Aliyeva, Salgarayeva and Zakashbayev*** have described a method for determining stresses, deformations and displacements of thick mass under the sagging roof over the worked out space.

Since the solution is based on theoretical considerations, it would be interesting to match it the results of numerical models and actual measurements.

3. Stability of slurry trenches near railway is a paper by Havinga, Tol, Maijers, Bruijn and Jong, where the authors have described the construction of concrete floors and diaphragm walls for taking the railway track down. During the construction phase a nearby temporary track was used for the movement of trains. A trench was excavated and filled with bentonite for the construction of the diaphragm wall. The

stability of the slurry trench was studied under dynamic loads created by passing of trains and causing pore pressure and accelerations to increase, with the help of Finite Element Method. The pore pressures and the accelerations in the subsoil below and beside the railway were measured for two days and when the trains were passing.

This interesting paper shows that unlike the practice in some countries, the design criterion for slurry trenches should be designed for dynamic loads. In this particular case (porous sandy soil) the rise in pore pressure did not match the dynamic loading, but since this effect would depend on the permeability of the material, this aspect needs elaboration.

7 USE OF FIELD MEASUREMENTS FOR PREDICTION

1. Osouli and Hashashin their paper *Predicting excavation performance via inverse analysis,* have used the inverse analysis for learning from local experience and using it for the prediction of soil response in new excavation with similar soil strata. It is based on field measurements in a similar soil strata. Using the measurements of wall deflection and settlements measured on a metro station excavation, they have demonstrated the technique for its use for some other sections of the Metro.

Even though the paper does not give much details about the Neural Network Material modeling used in the analysis, it shows the strength of the technique and the tremendous potential it has. The technique is, in fact, applicable to all geotechnical problems and coupled with advancements like video gauges, laser scanning , total stations or webcams for a more accurate record of structural behavior during loading or unloading, it can be revolutionary, to say the least. The technique will have applications in the field as well as in the laboratory.

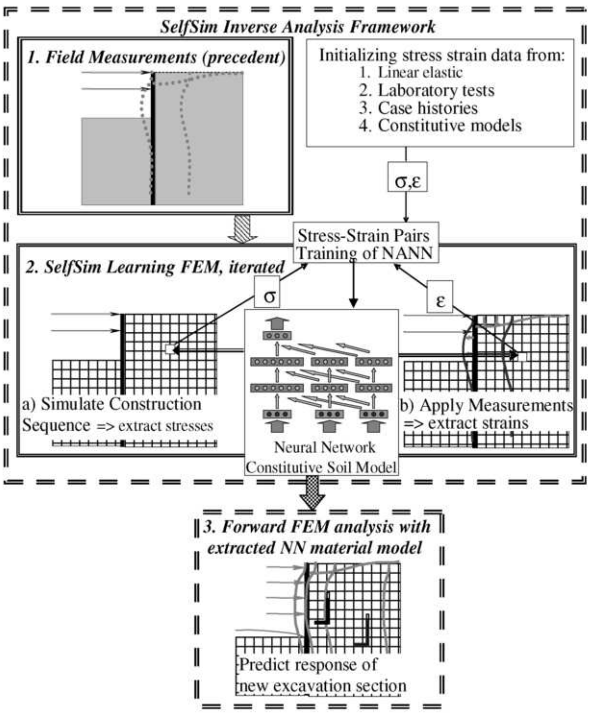


Figure 6. Application of SelfSim inverse analysis framework to predict ground response at a new excavation section or site (after Osouli et al).

2. In their paper *Instrumented field test and soil structure interaction of concrete pipe with high fill,**Vaslestad, Yesuf, Johansen, Wendt and Damtew*** have investigated the earth pressure on deeply buried culverts. Instrumentation of the field test with the induced trench method is described. The method involved installing polystyrene above the rigid culvert in order to reduce the vertical earth pressure. The instrumentation consisted of hydraulic earth pressure and a system for measuring deformation of expanded polystyrene. The measurements have been carried out for a period of 17 years and the interaction of soil pipe and the expanded polystyrene is modeled using a FEM. The results have been presented in the form of a design method.

The paper describes the properties of different materials chosen for the analysis, but it would be desirable to know about selection of some of the other parameters like those dealing with interfaces and the time dependent characteristics of polystyrene compressible layers.

8 OBSERVATIONS

A review shows that a large number of papers in this Session (nearly 70 percent) are based on the studies carried out in the laboratory, and by comparison there is little work done in the field. To some extent, it is to be expected as it is difficult to obtain reliable data from the field. But it is very important to see that the field data corroborates with the laboratory findings for advancing the state of art.

Also it is observed that numerical modeling finds a place almost everywhere. There is hardly any paper which has not used a numerical model. Also it is observed that the commercially available softwares have found acceptance amongst researchers even the hard core ones from the universities, which shows that the dependability of these softwares has increased. The most popular softwares seem to be from Itasca, USA i.e., FLAC 2D, 3D and PFC 2D and Plaxis from Plaxis BV, Netherlands.

As the techniques of analysis get more and more refined, the need for getting the basic data with the same degree of sophistication becomes apparent all the more. In the coming times one would see more and more of laser scanning and webcams for more accurate recording of construction activities. Automated and remote instrumentation to measure the movements from a distance will become common.

At the same time numerical modeling will move in the direction of intelligent self-updating, learning from field measurements every time an iterative cycle is performed. Once we combine the two i.e., reliable data collection and its analysis based on self-learning techniques, the results would be more reliable.

Also on the cards is the integration of heterogeneous data using a geographic information system.The papers for the conference however, did not mention much about it.

9 TOPICS FOR DISCUSSION

In the light of the above, it is suggested that the discussion may proceed on the following lines

1. Developments of techniques in the laboratory for the simulation of underground excavations
2. New techniques of field measurements
3. Advancements in the techniques of numerical modeling for simulation of excavation process (including the excavation by TBMs)

10 PAPERS IN THIS SESSION

1. Osouli, A. and Hashash, Y. M. A. 'Predicting excavation performance via inverse analysis'.
2. Wilson, D. W., Sloan, S. W. and Abbo, A. J. 'Stability of circular tunnels in soft ground'.
3. Demagh, R., Emeriault, F. and Kastner, R. ' Shield tunneling – Validation of a complete 3D numerical simulation on 3 different case studies'.
4. Pitilakis, K., Bandis, S. and Hemeda, S. 'Geotechnical investigations and seismic analysis of underground monuments in Alexandria, Egypt.'
5. Farkas, J. and Turi, D. 'Settlement of an art relic church caused by the construction of the metro line'.
6. Usmani, A., Nanda, A. and Sharma, K. G. ' Stress and seepage analysis of underground rock caverns'
7. Bilotta, Emilio, Lanzano, Giovanni, Russo, Gianpiero, Silvestri, Francesco and Madabhushi, Gopal ' Seismic analyses of shallow tunnels by dynamic centrifuge tests and finite elements'.
8. Shahin, H.M., Nakahara, E. and Nagata, M. ' Behavior of ground and existing structure due to circular tunneling'.
9. Sekine, Y., Zhang, F., Tasaka, Y., Kurose, H. and Ohmori, T. ' Model tests and numerical analysis on the evaluation of long term stability of existing tunnel'.
10. Nakata, Y., Murata, H. and Orense, R. 'Model tests and PIV analysis on failure behavior of embankment due to injected water'.
11. Zhusupbekov, A., Seidmarova, T. and Matsumoto, T. 'Corelation of soil parameters and load displacement curve of piles driven in loam and clay ground in Astana, Kazakhstan'.
12. Baimakhan, R. B., Takishov, A. A., Avdarsolkyzy, S. A., Rysbayeva, G. P., Altynbekov, Sh., Kulmaganbetova, Zh. K., Aliyeva, A.M., Salgarayeva, G. I., Zhakashbayev, B. Zh. 'The problem of controlling the mountain pressure when underground developing of ore deposits'.
13. Lee, S. W., Choi, J. I., Shim, S. H., Cho, G. C. and Hong, E. S. 'Mechanical behavior of twin tunnel'.
14. Havinga, H. R., A.F. van Tol, Maijers, A. H., K. de Bruijn and E. de Jong 'Stability of slurry trenches near railway'
15. Brassinga, H.E. and Oung, O. 'Structural behavior of a collar construction made of frozen soils in a deep excavation'
16. A. E. C. van derStoel, Vink, D., Kluft, D. J. and P. den Nijs 'New HoogCatharijne: a 5-levels challenging underground construction'.
17. Vaslestad, J., Yesuf, G. Y., Johansen, T.H., Wendt, M. and Damtew, T. 'Instrumented field test and soil structure interaction of concrete pipe with high fill'.
18. Torum, E., Kirkebo, S. and Athanasiu, C. 'A numerical study of a deep excavation in soft clay in Norway – comparison of 2D and 3D analyses.'
19. Sieminska-Lewandowska, A. and Mitew-Czajewska, M. 'Numerical analysis of circular reinforced tunnel lining'.
20. Dimov, Leonid A. and Bogushevskaya, Elena M. 'Analysis of movements of underground structures from horizontal load'.
21. Fotieva, N. N., Bulychev, N. S., Deev, P. V. and Firsanov, E. S. 'Design of multiple deep non-circular tunnel linings'.
22. Jovicic, V. and Logar, J. 'Design of a deep tunnel in a layer of a normally consolidated clay'.
23. C. de Santos, Ledesma, A. and Lloret, A. 'Effect of soil saturation changes on pressure o tunnel linings'.
24. Rozenvasser, G. R., Symonovych, V. E., Tokovenko, V. N., Gavrilenko, Yu. N. andShatalov, V. F. 'Construction of the Donetsk (Ukraine) Underground Railway on the undermined territories and tectonic faults'.