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General Report on Technical Session 4B: Deep Excavation, Tunneling and Groundwater controlling

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ABSTRACT
The General Report reviews a total of 27 papers related to deep excavation, tunneling and groundwater controlling form 17th international conference on soil mechanics and geotechnical engineering. A total of 11 papers in the sub-theme of tunneling covers four subjects including ground movement and its effect on adjacent existing structures, ground treatment, hazard and risk management, and face stability. A total of 9 papers in the sub-theme of deep excavation session covers two main aspects of excavation engineering, of which one is design and construction, and the other is performance and new seepage control technology in excavation. A total of 7 papers in the sub-theme of groundwater controlling covers two aspects of groundwater, of which one is groundwater control during underground construction and the other is treatment of contaminated groundwater. In particular, some advances and research topics on safety of tunneling, deep excavations, and groundwater control during excavation in China are introduced.

1 INTRODUCTION

There are 27 papers grouped in the TS4B session. It can be divided into three sub-themes categories: tunneling, deep excavation and groundwater controlling. These papers have been divided into the following subject groups:

Tabel 1 the subithemes and subject groups of TS4B

Sub-themes	Subjects	Number
Tunnelling	Ground movements and effect on existing structure	3 papers
	Ground treatment	3 papers
	Hazard and risk management	3 papers
	Face stability	2 papers
Deep excavation	Design and construction method	7 papers
	Performance and new seepage control technology	2 papers
Groundwater controlling	Groundwater control during construction	5 papers
	Treatment of contaminated groundwater	2 papers

2 TUNNELING

2.1 *Review of papers related to ground movement and effect on existing structure*

Shahin et al. present the model test to investigate the relationship between surface settlement and excavation patterns of circular tunnels for shallow tunnel. The numerical simulation is also performed. Figure 1 shows the apparatus used in the model test. The tunnel device is presented in Figure 2. The volume loss is simulated by tunnel shrinkage towards the centre of tunnel. The maximum shrinkage reaches 4 mm, which is equal to 15.36% of the volume loss. The model tests are conducted for four kinds of overburden ration, *D*/*B* equals 0.5, 1.0, 2.0 and 3.0, where *D* is the depth from the surface to the crown of the tunnel and *B* is external diameter of the model tunnel. Meanwhile, the finite element calculations are carried out using FEMtij–2D with the subloading t_{ij} model. From both model tests and numerical simulations, it is found even for the same volume loss the surface settlement profiles vary with the excavation patterns for shallow tunnelling. Observed and calculated results reveal that the distribution of shear stain and earth pressure are highly dependent on the excavation patterns.

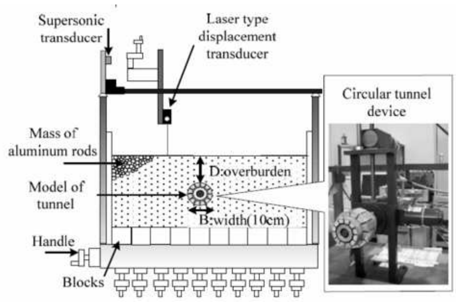

Figure 1. Schematic diagram of 2D tunnel apparatus (Shahin et al)

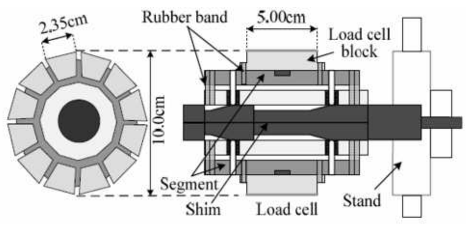

Figure 2. Circular tunnel device (Shahin et al)

The interaction between tunnelling and existing pile-raft is also studied. The existing pile-raft has a very significant influence on the surface settlement troughs. They do not follow the Gaussian distribution curve anymore and the maximum surface settlements offset from the tunnel axis. The shear strains concentrate to the rear piles when *D*/*B*=2.0 and 3.0, while, it concentrates to the front pile with *D*/*B*=1.0. The axial forces and bending moments are changed due to the excavation of the

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tunnel. The distance between pile tip and the tunnel crown has a significant influence on the behaviour of the pile raft.

Phienwej et al. analyze ground and wall movement of the MRT underground station in Bangkok using 2D finite element software Plaxis. The half width of the station is firstly excavated by cut and cover method. Then the other half of the station is enlarged by NATM with up and down tunnels. The bored tunnels are excavated from the cut and cover station. The cross section of the station is presented in Figure 3. In the numerical calculation, the hardening-soil model is adopted for reasonably simulating the unloading behaviour of soils in the case of excavation. The parameters used in the calculation are determined using laboratory and field testing combined with back analysis method. The calculation is performed with a number of steps in accordance with excavation process. One of the calculated surface settlement at the back of the diaphragm wall due to the cut and cover is shown in Figure 4. It is compared with the results from simplified method proposed by Ou and Hsieh (2000). The calculated surface settlements have a very good agreement with the results from Ou and Hsieh (2000) in the primary influence zone. With the excavation of the bored tunnel, the lateral displacements of the left wall decrease due to stress release of the bored tunnel. In contrast, the right wall continues to displace. However, the surface settlement over the bored tunnel increases significantly due to the excavation of the tunnel.

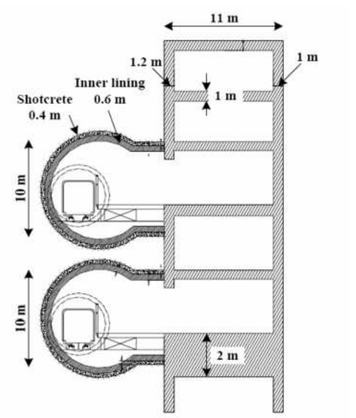


Figure 3. Cross section of Wang Burapha station (Phienwej et al.)

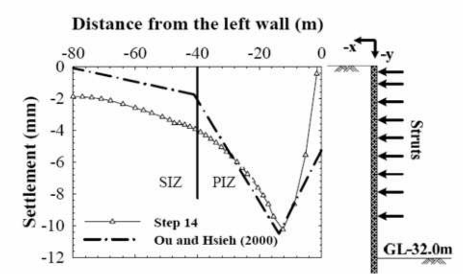


Figure 4. Comparison between FE analysis and simplified method at Step 14 when excavation depth is 32 m (Phienwej et al.)

Papageorgiou et al. present the findings on the relationship between surface settlement and tunnelling parameters using in-situ monitoring data. The tunnel with the external diameter of 9.18 m and the internal diameter of 8.48 m is constructed by EPB machine. Measurement is undertaken along the 300 m long section of the extension of Athens Metro Line 2. The surface settlement, the average tunnelling rate, the backfill volume and chamber pressure are recorded during the tunnel process. However, no relationship is found between the surface settlement and tunnelling parameters. The parametric analysis is undertaken for ψ in a simplified method proposed by Oteo and Sagaseta (1982) and GLI proposed by Chang et al. (2000) with measurements from Athen metro line 2.

2.2 *Review of papers related to ground treatment*

Kirsch and Richer describe ground freezing design under historical structures for tunnelling. The frozen ground is used to keep the stability of the auxiliary tunnel. The City-Tunnel Leipzig consisting of two tubes is constructed below a historical building constructed in 1908 and a modern structure of 1995. The two buildings are separated by a reinforced bored pile wall. Part of the bored pile wall intersects with the western tunnel. Therefore, the lower edge of the bored pile wall needs to be removed prior to tunnelling (sees Figure 5). Removal of the lower part of the pored pile wall below both buildings is accomplished from an auxiliary tunnel. The auxiliary tunnel with a diameter of 3.5 m is excavated by mining technique. The tunnel consists of three parts in accordance with the three freezing stages (see Figure 6). Each stage ends in an enlarged section from where drilling for the next stage is performed. Each ends is sealed by an ice plug to maintain its sealing function against the 10 m water pressure during tunnelling. A sudden change of direction of almost 90° is designed for geometrical necessities. Ground freezing is performed with a total of 120 pipes by liquid nitrogen flowing. The pipes are installed in the horizontal boreholes of 35 m long below ground water table. Numerical simulation of the thermal and mechanical behaviour of the soil is performed beforehand. A total of 180 temperature gauges are installed in the ground to properly control the ice propagation. Control parameters were determined for all temperature gauges by prior numerical analysis and are constantly adapted to real soil-ice behaviour. The tunnelling and surrounding environment are finally guaranteed.

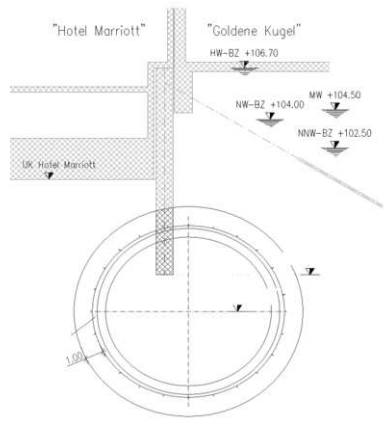


Figure 5. Cross section of the bored pile wall and tunnel (Kirsch and Richer)

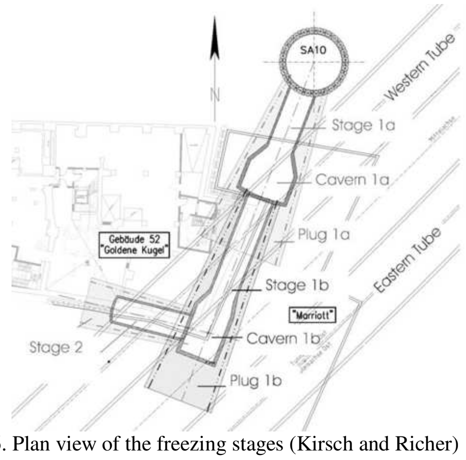


Figure 6. Plan view of the freezing stages (Kirsch and Richer)

Guatteri et al. present the procedure and instrumentation results of the horizontal jet grouting carried out in a prototype tunnel. The HJG is carried out in the fine, non-cohesive and saturated soils, namely silt and very fine sand. The ground treatment by HJG is a full scale test to check the efficiency of the solution. The full scale test is performed in the field with an 18 m wide and 17 m deep square shaft and a 90 m long and 5 m wide access ramp. The shaft is retained by 1.0 m thick diaphragm wall reinforced by metallic beams. The soil behind the diaphragm wall, where the prototype tunnel is excavated later, is improved by Vertical Jet Grouting method with a total thickness of 3.2 m. The proposed treatment at the tunnel section is formed by the 360º HJG columns and the frontal septum at the end of the conical treatment (see Figure 7). The 360º HJG columns are performed by double lines of Ø 0.50 m. The frontal septum is 3.0 m thick and formed by Ø 0.80 m columns. The surface settlement and water tightness are monitored using ten superficial marks (HN) and eleven piezometers. The installation of the instrumentation is shown in Figure 8. The horizontal jet grouting technique is finally proved to be a reasonable solution to keep the stability for tunnelling in saturated sandy soils. The soil treatment inside the chamber should be performed with HJG. The prevented valve equipped with a pressure gauge has to be installed in all the time including drilling and injection stage to control the outflow.

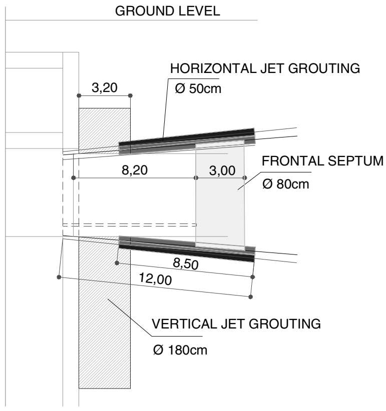


Figure 7. Section view of the treatment scheme (Guatteri et al.)

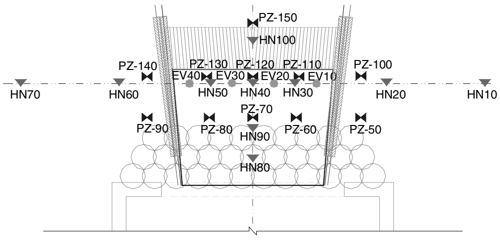


Figure 8. Plan view of the instrumentation (Guatteri et al.)

Takano et al. describe the reinforcing effect of face bolt for NATM tunnelling in terms of the failure patterns and ground behaviour. The tunnel face failure is simulated in laboratory with four cases of model tests by pulling out tunnel model from a sandy ground. Four different condition of tunnel model were prepared including the case of without face bolts and placing face bolts with the length of 0.25*D*, 0.5*D* and 1.0*D*, where *D* is diameter of tunnel model of 20 mm. The overburden ratio of 2.0*D* and the pulling out rate of 0.1mm/sec are kept constant during the test for four cases. The apparatus is shown in Figure 9. The excavation of the tunnel is simulated by pulling out the rod. The tank could be removed from the apparatus and placed on a turntable in an X-ray CT scanner for scanning. The scanning is undertaken at pulling out length of 0 mm (initial state), 1 mm, 2 mm, 5 mm and 10 mm, respectively. The model ground is scanned every 1.0 mm from the bottom of tunnel model to the ground surface and a total of 70 cross sectional images are obtained. Then the failure zone and patterns are obtained combined the cross section images, as shown in Figure 10. It is found from the model tests that the length of face bolts deeply affects to the ground settlement because the width of failure zone can be reduced by face bolts at the crown and failure zone developed above the crown can be narrow. In the case of large scale of face failure, the length of 0.5*D* is enough to keep the face stability. The bolting effect is confirmed by the centrifuge model tests with 2 cases in terms of surface settlement and displacement around tunnel face.

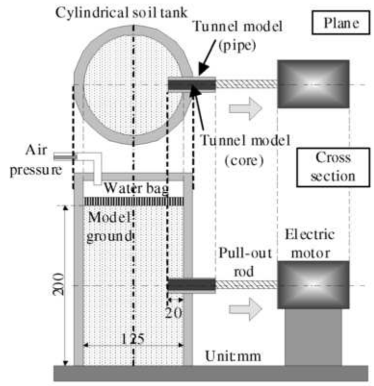


Figure 9. Tunnel pull-out model test apparatus (Takano et al.)

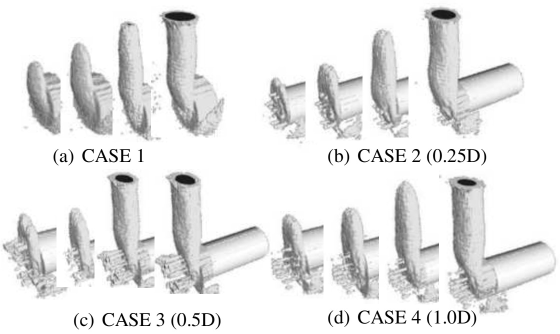


Figure 10. Three – dimensional image of failure zone (Takano et al.)

2.3 *Review of papers related to hazard and risk management*

Mayer et al. present some new approaches for TBM tunnel design. The first approach is the consideration of tunnel joints to optimize the numerical models to simulate the failure mechanisms of tunnel lining. The second one is to predict the tunnel lining damage during the construction process using the proposed look-up tables. The longitudinal and circumferential joints are both considered in the simulation and exhibition non-linear behaviour. The longitudinal joints are assumed as the concrete hinge, which could resist the rotation and thus cause moments. The rotational stiffness is taken as a constant as long as the joints are closed and decreased when the longitudinal joints are opening. The tunnel joints could be simulated by two ways in numerical simulation. The first way is using the discrete coupling element to represent the "cam and pocket" of the segments. The second way is using special continuum element to describe the friction force between segments. The numerical simulations are then employed to deliver the look-up table to evaluate the design risk. The calculated values are normalized by the lower threshold in the look-up table. The threshold values are obtained from the specifications of EC2. Three risk levels are designed for the look-up table, namely low risk, intermediate risk and high risk. The risk of lining safety during the construction process is evaluated by the look-up table.

Chin and Chao describe the fundamentals of engineering risk management and its application in underground construction. Risk is defined as the combination of uncertainties and consequence of risk events. Risk management is a systematic approach in underground construction and usually includes risk policy, risk assessment, risk response and risk control. The application of risk management in Taiwan Taoyuan International Airport MRT system is presented. The DOT shield tunnelling is adopted in the project. The alignment of the bored tunnel intersects with the foundation of pier P64 that is composed of nine bored piles with diameter of 3m and centre to centre distance of 4.5m. The 9 bored piles are removed prior to the tunnel excavation. The underpinning method is adopted to transfer the loads of the viaduct superstructure to a temporary support steel frame and new foundations built of diaphragm wall. The risk identifications are undertaken by event tree during pile construction shown in Figure 11. The risk analysis during demolition of obstacle piles is shown in Figure 12 by event tree. The risk rank in this stage is third. Risk mitigation measures is developed when the risk rank is greater than third level and detailed presented in the paper. Risk monitoring and control are adopted to track the identified and unidentified risks.

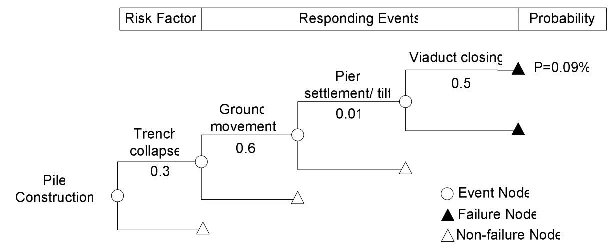


Figure 11. Event tree analysis for pile construction (Chin and Chao)

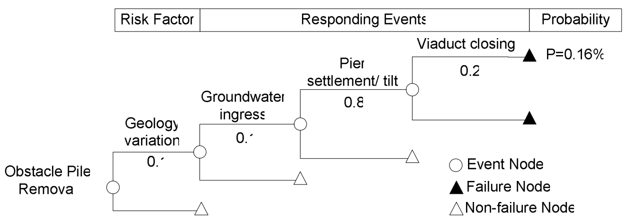


Figure 12. Event tree analysis for obstacle removal (Chin and Chao)

Wightman and Tattersall describe the tunnel failure caused by flooding in Hong Kong. The tunnel of 3.8 m diameter is constructed by TBM of an open face, which passes through a previously grouted zone in reclamation fill about 26 m below ground level within Hung Hom Bay. Gas ground investigation at the site indicates that there is significant dissolved gas in the groundwater. The tunnel and access cofferdam are flooded by sudden flood 11 minutes after the gas alarm is triggered. The sudden flood is attributed to soil liquefaction produced by gases exsolving from underground water. It is concluded that liquefaction of soils caused by rapidly exsolving of gas is very possible. The movement of water and expanding gas result in soil piping and soil inter particle loss of contact leading to density reduction and loss of shear strength. As groundwater seeps through the soil towards a tunnel free air surface, the gas undergoes a gradual pressure reduction with the formation of gas bubbles which migrate and erupt from the soil causing loss of ground through piping erosion, as shown in Figure 13, Figure 14 and Figure 15. Thus, the tunnel failure model could explain the mechanism for the inundation, the behaviour of gases under pressure in groundwater and the problems associated with methane generation.

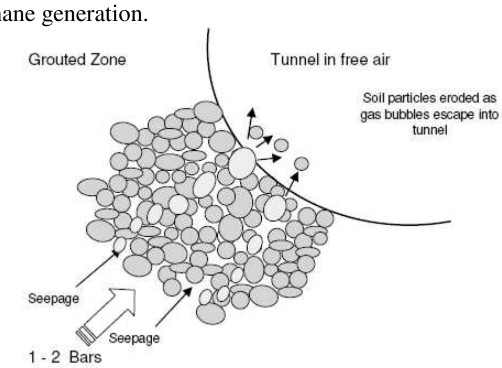


Figure 13. Soil Erosion and formation of soil piping (Wightman and Tattersall)

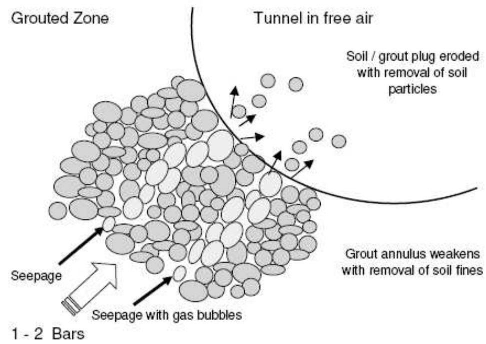


Figure 14. Soil pipes elongate along the seepage paths with the affect becoming more pronounced as seepage rates increase (Wightman and Tattersall)

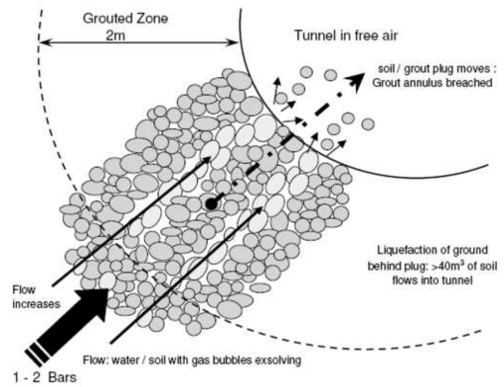


Figure 15. Soil / grout plug fails leaving a hole <1 m^2 (Wightman and Tattersall)

2.4 *Review of papers related to face stability*

Mihalis et al. present a new controlling parameter of tunnel stability factor to determine the support pressure *P* for shallow tunnel. The Tunnel Stability Factor (*TSF*) is defined as $TSF = \sigma_{cm} / (\gamma H^a D^{1-a})$, where, $\sigma_{cm}$and γ are the strength and specific unit weight of the rock mass around the tunnel, *H* is the height of overburden soil and *D* is the equivalent diameter of the underground opening. The strength is obtained by $\sigma_{cm} = 2c / \tan(45^\circ + \varphi/2)$, where *c* and φ are the cohesion and internal friction angel of the rock mass respectively. In order to built the relationship between the support pressure *P* at tunnel face and the *TSF*, the parametric analysis is performed by combining the following cases: (1) tunnel diameter *D*= 4m, 6m, 8m, 10m. (2) overburden height *H*=10m, 12.5m, 15m, 17.5m 20m. (3) rock cohesion *c*=5kPa, 10kPa, 15kPa, 20kPa and internal friction angel φ= 25° and 30°. (4) the support pressure *P* is calculated for the safety factors of 1.0, 1.1, 1.2, 1.3 and 1.4. With the parametric analysis, the relationship curves are obtained between *P/c* and *TSF* for each safety factor. The support pressure *P* could be determined by curves fitting and defined by the equation of $P/c = A(TFS)^{-B}$, where the parameters *A* and *B* could be determined by curves fitting. Thus, the support pressure *P* could be determined in the preliminary design stage.

Placzek presents the main principles of tunneling under compressed air. The principles for the application of compressed air usually should consider the following conditions such as what marginal conditions tunneling under compressed air is possible, what determines air permeability, how the required air quantities can be calculated, what measures can be taken when high air losses are to be expected, what stability analyses have to be carried out and what risks exist despite all precautions. The precondition for the application of compressed air is the water permeability of soils. The limit of applicability is concluded based on the soil permeability. Besides, the air permeability of the soil has a notable effect on the quantity of air flow through the soil. The air permeability of soil is generally derived from the water permeability although it could be determined by experimental means. The required volume of compressed air during tunneling could be calculated by the equation of $QL = QA + QM + QS$ [m³ / min], where, *QA* is air loss through the heading face, *QM* presents air loss through the tunnel casing and *QS* means air loss as a result of locking operations etc. However, it may not be accurately assessed because of safety margin. Possible measures, such as soil injections and skillful planning of excavation, should be taken to reduce the air loss. Safety against out-blow should be verified prior to the tunneling. Finally, the risk must be considered whenever working with compressed air. The risk may arise from increased fire risk, a sudden breakdown of the air flow as well as accumulation of compressed air. The health risks for the miners who have to work under compressed air must be considered.

2.5 *Safety issue relating to tunnelling in china*

China is now rising on the springtide of tunnel construction in accordance to the rapid development of MRT system in urban area. Most of the MRT are constructed underground by TBM tunneling. EPB (earth pressure balance) and SPB (slurry pressure balance) shield machine are most often adopted in urban area. At present, the total length of MRT is more than 600 km distributed in about 10 cities including Beijing, Shanghai, and Guangzhou. Up to now, there are totally 17 cities have obtained the official sanction to develop MRT system. The total length of the MRT will reach 1856 km in 17 cities until the year 2015. Besides, the municipal tunnels such as cable tunnels are also constructed by TBM. The following tunneling related issues are extensively studied and a lot of researchers are devoted to this topic in China.

1) Tunnel stability. The difficulties for tunnel stability mainly arise from the enlarging of the tunnel diameter. The largest tunnel with the diameter of 15.43m was constructed cross Yangtze river by two slurry pressure balance TBM in Shanghai, China. For large tunnels, the failure mechanism and critical slurry pressure become the key issue for face stability because the partial out-flow or global collapse will occur when the slurry pressure is too low or too high (Li and Zhang, 2008). Besides, the tunnel stability should be given more consideration when launching from and arriving in the shaft especially in soft soils with rich underground water.

2) Ground movement and its effect on the surrounding facilities of piles and existing tunnels. Tunnel construction is increasingly carried out in congested urban area. The influence of tunneling on the adjacent foundations, existing tunnels and piples et al. should be predicted during the design process. For example, the cable tunnel constructed for Shanghai Expro 2010 intersected with Shanghai metro tunnels of Line 1, line 2, line 4, line 6, line 7, line 8, line 9, line 10 and will intersect with line 13 and line 14 in the future. Thus, how to reasonably assess the effect of tunneling on the ground movement and adjacent facilities is still remain questionable. The weak disturbance controlling technology has been applied during tunneling specially in congested area. This technology is carried out by adjusting the tunneling technical parameters such as face support pressure, grouting pressure and volume, excavation rate et al. with the guiding of in-situ monitoring, experiential and numerical predictions (Ge et al. 2000).

3) Effect of deep excavation on adjacent operation tunnel. The exploiture of real estate along the MRT leads to many deep excavations performed near the existing tunnels. At present, The response of the existing tunnel is usually predicted by numerical modeling, in-situ monitoring and centrifuge model test in terms of tunnel displacement, tunnel convergence and variation of internal force. However, it is not easy to evaluate the effect of deep excavation on the safety of existing tunnel because of the complexity of the present state of the existing tunnel. Thus the risk management method is introduced to qualitatively assess the effect (Huang et al. 2006).

4) Lining behavior of DOT tunnel. DOT tunnel has been adopted in Shanghai for his saving in underground space, cost and construction duration. The lining behavior of DOT tunnel is different from that of the single circular shield tunnel (SCST) considering its special characteristics. Shen et al. (2009) proposed a numerical model to simulate the lining behavior of DOT during the construction.

5) Ground treatment by freezing method. Most of the cross-passages between tunnels are constructed with the support of artificial frozen soils in Shanghai. The physical and mechanical properties, temperature field theory and in-situ monitoring technology of artificially frozen soils have been focused based on the case studied in Shanghai (Hu et al. 2008, 2009).

6) Long-term performance of tunnel. The excessive surface settlement and tunnel leakage are the often observed long-term exhibition of the tunnel. The long-term behavior of the tunnel is greatly affected by the train vibration, adjacent engineering activities including dewatering and geological conditions. Zhang et al (2008) developed a new tunnel model to simulate the tunnel response with long-term differential settlement along the longitude direction of the tunnel.

7) Risk management. The main characteristic of tunneling is the uncertainty. The risk is inevitable for tunneling. The risk management has been extensively employed for underground engineering in China. The dynamic risk management method was proposed to track the risk during the tunneling. The first guidelines of risk management for tunneling and underground construction were completed in 2007 (MHURD, 2007).

3 DEEP EXCAVATIONS

3.1 Review of papers related to excavation design and construciton method

Justo and Oteo present a numerical analysis of the construction of the Puerta de Jerez underground station. The project was built under a two-storey underground car park. The station has three floors under the car park. One TBM tunnel had been bored below the car park before the construction of the station. Figure 16 shows a simplified geotechnical profile throughout the station.A closure wall was installed around the constructed tunnels in order to avoid damage to the parking and neighbouring buildings due to tunnel construction. In addition, jet-grouting screens were built around the station. Diaphragm walls and pile walls were used as retaining structure. The authors implemented two-dimensional finite element analysis using Plaxis 2D for simulating the whole construction process. The Hardening Soil model was used to model the behaviour of the soils. The authors compared field observed data and numerical results. Although measured and calculated displacements were not followed perfect agreement, it was enough to guide the construction process.

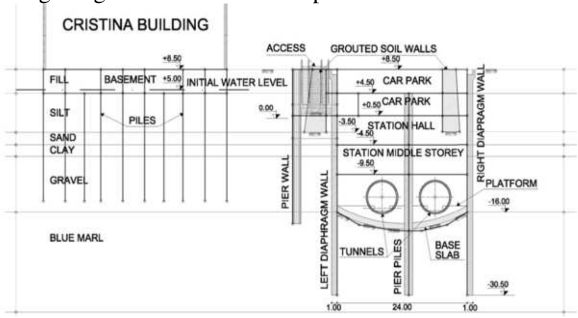


Figure 16 Simulated section through the station and Cristina building

Mazo et al. describe the geotechnical properties of the soils in Seville city, made several conclusions on geotechnical problems in the urban area based on the research performed for the works of Seville Metro. The soil properties were firstly completely described by the authors. Then the construction systems used in the construction of Line 1 of the Seville Metro were introduced. Geotechnical problems in the city centre zone included stability of the excavations, possible affectation of the general water table, movements caused by the excavations and their possible repercussion on buildings or utilities nearby, and difficulties of passing the Canal de Alfonso XIII. A series of soil treatments were performed to resolve some of these issues. The authors reported that the surface settlement on the axis of the first tunnel was large, as show in Figure 17. However, once injection of the gap with mortar was fine tuned, the subsidence was small.

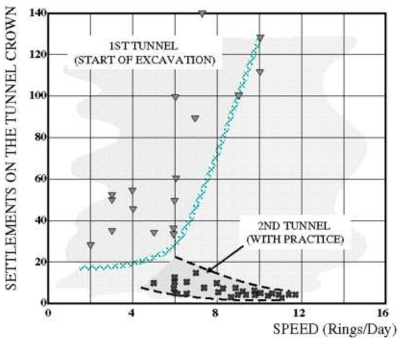


Figure 17 Settlements originated by tunnel excavation at Republica Argentina Ave. (Mazo et al.)

Mešić et al. present a case study to illustrate a deep excavation design. The site is located at a passage through high compressible sediments of the Ljubljana Moors at a southern part and somewhat better gravel and clayey alluvium of the Ljubljana field at a northern part. The authors presented a completed design scheme of the project. The excavation was retained by a 1.0 m thick and 27 m deep diaphragm wall, which in turn was braced by three levels structure slabs. The excavation procedure was modeled by Plaxis 2D, 8.6. The ground behavior was modeled by the Harding Soil model. Simulation of lowering the groundwater level was carried out by MODFLOW-2000. Figure 18 shows the groundwater level as a consequence of pumping from wells at the entire area of the excavation. The authors summarized that a great attention should be paid to deformations of soil mass behind the excavation area and retaining wall itself. However, no field observation data and measurements was discussed in the paper.

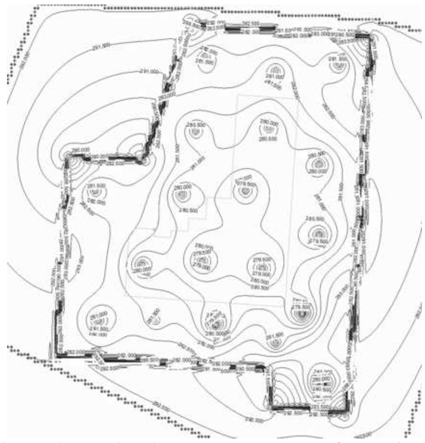


Figure 18 Groundwater level as a consequence of pumping from wells at the entire area of the excavation (Mešić et al.)

Rønning et al. report a tunnel which is planned through a populated area in the city cross through soft sensitive clay (partly quick clay) based on cut-and-cover method. Maximum excavation depth in soft and sensitive clay was approximately 20 m. To support the excavation, the design scheme comprised steel sheet pile walls with supporting ribs of jet-grouted ribs below the excavation level and steel struts in maximum 4 levels. The paper presented the main geotechnical challenges of the project and the designed solutions for the support. The design of jet-grouted ribs as support between steel sheet pile walls was discussed. In addition, the authors employed two-dimensional and three-dimensional finite element analysis. However, the authors did not provide any field observation data.

Sze and Ho present the application of steelworks adopted in deep excavations in Hong Kong. Common sections and installing method were introduced for temporary steel retaining walls such as sheet pile wall, soldier pile wall and pipe pile wall. The most common steel shoring systems were introduced. The authors highlight key features of steel supporting systems based on a series of case studies. Some key features and issues related to the steel embedded walls and shoring system were noted. These included bending stiffness, ground movement owing to wall installation, structure design of the steelworks, pre-loading of struts, connection details of shoring, and temporary steel embedded wall as permanent structure. They also provided some empirical soil stiffness correlated to SPT N value based on back analysis. Figure 19 shows an example of back-analysis for the HKPU case. This paper provides an excellent reference to industrial practitioners and researchers.

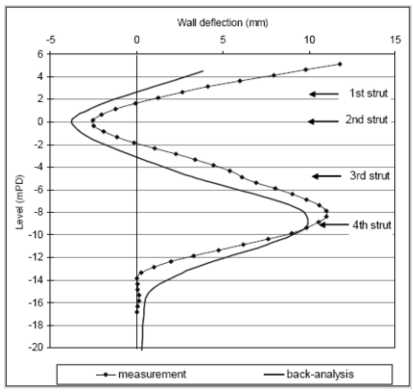


Figure 19 Back-analysis of HKPU case (Sze and Ho)

Bezuijen et al. report the application of corrective grouting underneath a piled foundation in layers of sand and silty sand that were partly disturbed due to ground loss through a nearby diaphragm wall. The corrective grouting led to significant increase of the CPT values of the layers injected. Although the buildings are successfully lifted and stabilized, it was found that the efficiency of the corrective grouting was very low. Furthermore, ongoing settlements after the corrective grouting campaign, lead to a further decrease of the efficiency. The pressure losses in the injection system were tested separately and appeared to be significant compared to the injection pressures. The buildings were relatively stiff due to temporary stabilizingtimber cross beams, so the result of one single injection on the deformation could not be found.

Massonnet introduces jet grouting to support excavation. The author presents a technical method, which can offer numerous possibilities of application. A jet grouting column gives a good control of the treated zone and a decrease in the permeability. Numerous realizations using this technique demonstrated its interest especially in zones which were difficult to access.

3.2 *Review of papers related to performance and new seepage control technology*

Hettler and Triantafyllidis point out that although the numerical analysis made much progress in the last years and it is nowadays pooible to partly model some of the construction procedures itself, there is still a complete theory missing for most of the effects. They investigated a number of case studies about prefomance of deformation caused by construction procedures such as vibrated piles and casting pipes for grouting, jet grouting, bored pile walls and anchor boring. In the case of the Debis excavation, installation of the so called vibrated RI-piles caused very large additional displacement of the wall, as shown in Figure 20.

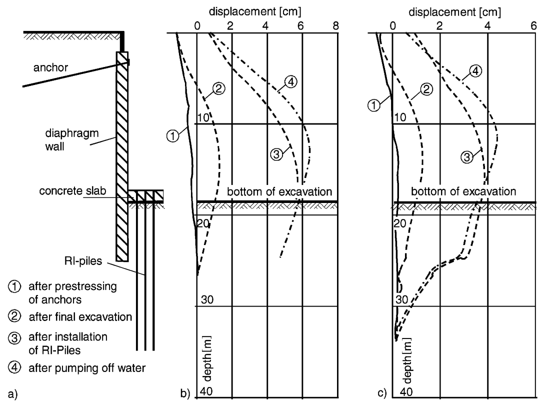


Figure 20 Debis-excavation at Potsdamer Platz: a) cross section of excavation b) displacements in cross section MV 1 c) displacements in cross section MV 2 (Hettler and Triantafyllidis)

They also found that while constructing a jet grouting girder system at the base of an excavation supported by a diaphragm wall, an unexpected heave at the surface and displacements of the wall against the soil side were observed. The installation of grouted anchors may also cause damages in adjacent buildings particularly for multilevel anchored walls showing high density of anchor placement. The authors pointed out that there are still many problems to solve how to describe the entire construction processes.

Inazumi and Kimura present an on-site verification for installation and permeability of H-jointed steel pipe sheet piles (SPSPs) with H-H joints. H-jointed SPSPs with an H-H joint are considered to be effective in structures such as waste landfill shore protection or retaining walls, where high grade water cut-off has to be assured. Figure 21 presents a general application of H-jointed SPSP with H-H joints to waste landfill shore protection. In general, while using H-jointed SPSPs for water cut-off applications, it is necessary to treat the water permeable joints for water cut-off treatment, and the method of filling mortar etc. in the installed interlocking joints is adopted for this purpose.

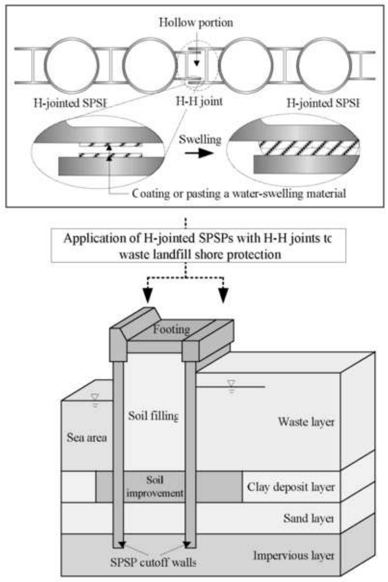


Figure 21 General application of H-jointed SPSP with H-H joints to waste landfill shore protection (Inazumi and Kimura)

In this paper, field installation and permeability tests are conducted for H-jointed SPSPs with H-H joints for their first application in the field. They found that no rotation or twisting of parts of H-jointed SPSPs with highly rigid H-H joints occurred unless some additional operation was performed at the time of installation. This made it possible to install the H-jointed SPSPs with an H-H joint with high accuracy. On-site interlocking performance of H-jointed SPSPs with an H-H joint was confirmed from the fact that it has enabled the reliable cleaning of soil and sand from inside of the joints and there is no collision at the joints. Permeability tests showed that H-jointed SPSPs with an H-H joint is expected to show a hydraulic conductivity of the order of 1×10^{-8} cm/s even at the site.

3.3 *Deep excavations in china*

1) New features of deep excavations in China. Numerous deep excavation projects for high-rise buildings and subway transportation networks have been executed in China during the past two decades. Wang et al. (2005) summarized some new features of the overall trend of excavations. Firstly, size of excavations tends to go larger and larger. Excavations with area of 10,000 m^2 to 50,000 m^2 are commonly encountered. Figure 22 shows a picture of the largest excavation in China - the Shanghai Hongqiao Transport Hub Project. It covers an extremely large excavation area of about 580,000 m^2. Secondly, excavations are getting deeper and deeper. Very deep excavations with depth of 20 m to 30 m become common. There are also many extremely deep excavations with depth larger than 30 m. Figure 23 shows a picture of the construction of the Shanghai 500 kV World Expo Underground Transmission and Substation. The excavation depth of this project was 34 m and it was constructed by top-down method. Thirdly, more and more deep excavations are constructed in close proximity to existing properties including buildings, subway stations, metro tunnels, embankments and underground pipelines. Figure 24 shows the typical situations of excavations adjacent to these properties (Li et al. 2008). With the imposing

of more and more challenging new features of deep excavations, geotechnical engineers in China have no choice but to transform themselves into an adequately trained, well-experienced and highly competent entities. As a result, many new design method and retaining systems are adopted to achieve demanding and stringent objectives. Table 2 lists a few cases which are benchmarks of deep excavations in China. Their successful completion is an index of the technology level and quality of construction industry.

Figure 22 Site of the Shanghai Hongqiao Transport Hub Project with an excavation area of about 580,000 m^2

Figure 23 An aerial view of the Shanghai 500 kV World Expo Underground Transmission and Substation, with an excavation depth of 34 m

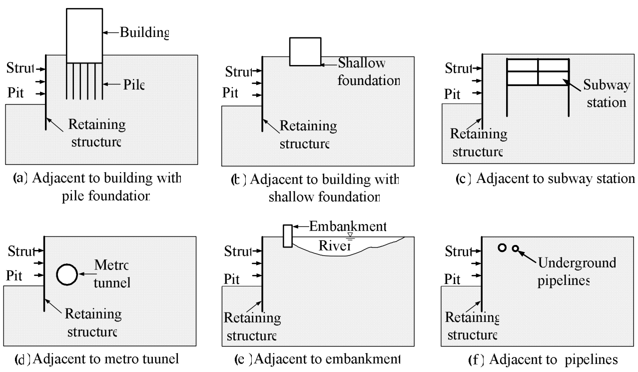


Figure 24 Sketch maps of typical situations of excavations adjacent to properties (Li et al, 2008)

Table 2 Some representive excavation projects in China

No.	Name	Area (m^2)	Depth (m)	Characteristics
1	ChangFeng Commercial Mart	22,000	17.55-24	Adjacent to Metro Line 2 and Line 3, construted by top-down method
2	Zhongsheng Commercial Center	50,000	13.3	Excavated using bottom-up method in the central part and top-down method in the peripheral part
3	Shanghai Hongqiao Transport Hub	580,000	9-29	Compositive project with many project units
4	National Grand Theatre in Beijing	65,000	26-32.5	Complicate groundwater condition and sensitive environment
5	Tianjin 117 Mansion	100,000	18.7-33.2	Compositive project with many project units
6	Shanghai 500 kV World Expo Underground Transmission and Substation	13,000	34	Close to many buildings, cylindrical excavation constructed by top-down method
7	Shengda Plaza	7000	17.05-22.25	Adjacent to Metro Line 4 and Line 9
8	Rememdiation of Collappsed Tunnel of Metro Line 4 in Shanghai	5,000	38-40.9	Complicate obstacles caused by the former collapse, excavation in aquifer I
9	Foundation Pit of Runyang Yangtze Bridge	3500	50	Extremely deep and complicate groundwater condition

2) Performance of deep excavations. The concept of performance-based design has been adopted for deep excavations in Shanghai since the 90's of the last century. In the performance-based design, a thorough understanding of the characteristics of wall deformation and ground movement is very important. As field performance is a collective reflection of various factors involved in a real excavation, experience from the field performance of previous deep excavations provides a useful guide for new deep excavations.

Two basic approaches can be used to study the field performance of deep excavations. One is based on individual case and the other is based on a large number of cased histories. There are a large number of papers and monographs (for example Zhao et al. 1996; Li 1996; and Wang 2007) studying individual cases of deep excavation in great detail based on extensive and comprehensive field monitoring data. There are also some studies involving the performance of deep excavations based on data collected from a large number of case histories. Wang et al. (2007) setup a database of 31 case histories of wall deformation due to deep excavations constructed by top-down method in Shanghai soft deposit. Figure 25 shows the relationship between maximum wall displacement and excavation depth. The maximum lateral displacement of the retaining wall ranges from 0.1%H to 0.6%H, and its mean value is only about 0.25%H, where H is the excavation depth. Xu et al. (2008) setup a database of 93 case histories of deep excavations retained by diaphragm wall and constructed by bottom-up method in Shanghai soft deposit. The maximum lateral displacement of wall ranges from 0.1%H to 1.0%H, and its mean value is about 0.42%H. Xu et al. (2009) also setup a database of 80 case histories of deep excavations retained by bored pile wall and constructed by bottom-up method in Shanghai. The work done by Wang et al. (2007), Xu et al. (2008), and Xu et al. (2009) can be seen as a continuation of the work done by Peck (1969), Mana and Clough (1981), Clough and O'Rourke (1990), Ou et al. (1993), Wong et al. (1997), Long (2001), and Leung and Ng (2007). Charts and figures obtained by these studies not only are benefit to engineers to carry out their designs and for numerical modelers to calibrate their models and model procedures, but also are useful for compiling local codes in the field of deep excavation.

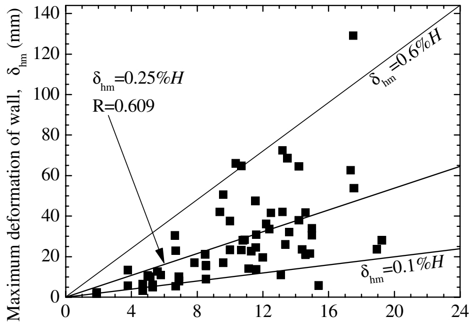


Figure 25 Maximum wall deformation versus excavation depth for deep excavations constructed by top-down method in Shanghai (Wang et al., 2007)

3) Deformation control of deep excavations adjacent to sensitive environment in soft soils. The key aspect of design and construction of deep excavation in sensitive environments is to control deformation of retaining structures and mitigate responses of soils mass around the excavation. However, it is not an easy job to control deformation of deep excavation in saturated soft soil condition as creep effect of soils mass plays a critical role in soil deformation. The deformation of retaining structure and soils mass around the excavation relates to many important facetors such as the volume of excavation, duration without struts due to creep effect, and sequence of the excavation. Liu et al. (1999) suggested excavation procedure taking into account the rational planning and sequence of the excavation, including the lifts, plots, symmetry, time, and bracing. This so called "Time and Space Effect" excavation method is an empirical method developed in Shanghai. Hu et al. (1999) gave an example of this excavation method. As shown in Figure 26 and Figure 27, the steps in the excavation procedure are as follows: (1) excavating the soil in long strip area I1; (2) pouring the reinforced concrete bracing corresponding to the unloading space; (3) excavating the soil in area II1 and installing the corresponding bracing promptly; (4) excavating the soil in area III1; and (5) continuing steps 1–4 for the second, third, and fourth lifts until the design depth of the excavation is achieved. It has been proved that the "Time and Space Effect" excavation method is efficient for deformation control of deep excavations in Shanghai soft soil. However, quantitative prediction of this excavation method needs further investigation.

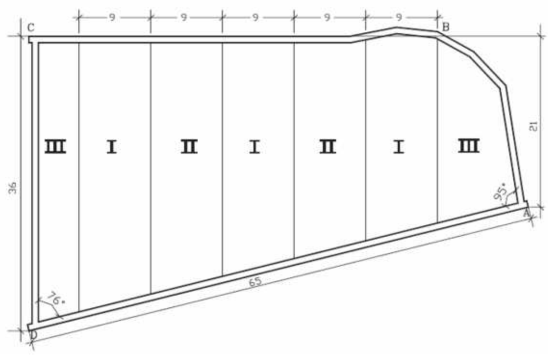


Figure 26 Plan of the construction sequence for the deep excavation at Shanghai New World Commercial City Complex. (Hu et al, 1999)

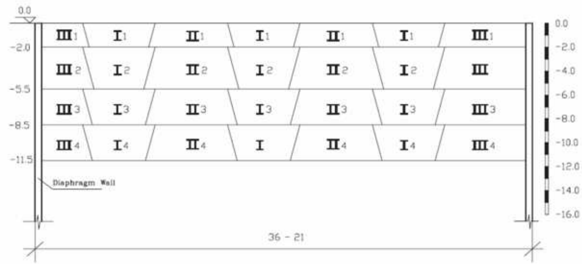


Figure 27 Profile of the construction sequence for the deep excavation at Shanghai New World Commercial City Complex. (Hu et al, 1999)

4) Prediction of the deformation of deep excavations by FEM. Numerical modeling is now becoming a routine part of deep excavation design and this offers considerable benefits to geotechnical engineers. Two dimensional and three-dimensional finite element analysis has been adopted to predict deformation of wall and ground response. However, the results are not always satisfactory as finite element prediction contain uncertainties related to soil properties, supporting system details and construction procedures. It is noted that the constitutive model should be carefully selected in a FEM analysis. Potts (2000) pointed out that linear elastic analyses are entirely inappropriate in modelling deep excavation and can be misleading. Linear-elastic perfectly plastic constitutive models do limit the tensile stresses in the soil and the active and passive pressures that can develop. However, they generally give poor predictions of both the extent and the distribution of ground movements adjacent to the wall. In order to have an accurate representation of both wall deformation and the distribution of settlement of soil behind the wall, small strain models such as the Simpson Brick model (Simpson 1992), MIT-E3 (Whittle and Kavvadas 1994), and the HS-Small model (Benz 2007) should be used. Nevertheless, determination of the parameters of these models usually requires high quality experiments which are not available to most engineers. Back-analysis of previous excavations can provide a reference for determining soil parameters. In order to obtain reasonable analysis results, other important factors should also be considered in a FEM analysis. This include determination of the analysis method (drained analysis, undrained analysis or coupled analysis), modelling of the interface between the soil and the structure, applying proper boundary condition, modelling the initial ground condition at the site, modelling the installation of the retaining wall, and reasonable modelling of the circles of excavation and support installation.

4 GROUNDWATER CONTROLING

4.1 *Review of papers related to groundwater control during construction*

Groundwater control is the most significant aspect during underground construction in the ueban environment. Statiscal inveistigation shows that about 70% construction failure is related to the inappropriate treatment of groundwater. Five papers in the session are related to the groundwater control during underground construction.

Wudtke and Witt present an approach of theoretical analysis on hydraulic heave through the consideration of the resistances of cohesion of soil. Powrie and Preene ever researched the dewatering systerms in fine soils (Powrie and Preene 1994, Preene and Powrie 1994). This paper is concernted to the excvation in cohesive soil. The hydraulic heave in non-cohesive soil and conhesive soil is shown in Figure 28. The approach considered a simple limit static condition as shown in Figure 29. In fact the process of soil deformation in a pre-failure state of a cohesive soil is much complex. Realistic changes in effective stress and pore water pressure have to be taken into account to display the limit state. The soil resistance activated in cohesive soil is determined by the surface forces of clay aggregates.

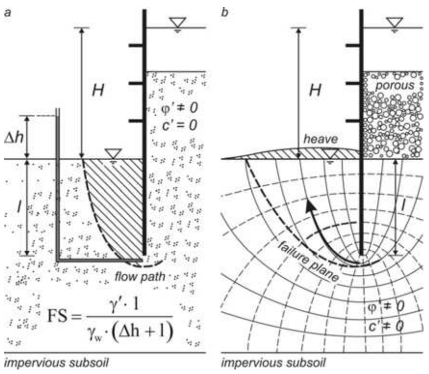


Figure 28 Hydraulic heave in: a – non cohesive soil, b – cohesive soil (Wudtke and Witt)

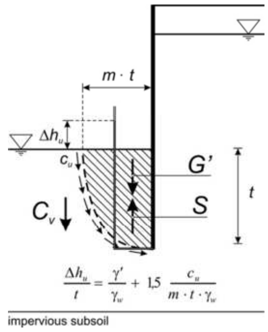


Figure 29 Hydraulic heave as wedge failure (Wudtke and Witt)

Roberts and Botha present a practical design and operation of a large dewatering system in Dubai. This project commenced with excavation over 420,000 m^2 by 25 m depth. Dewatering was carried out using a perimeter ring of deep wells. The actual well layout is given in Figure 30. A numerical model is used to generate groundwater level contour plots for various scenarios and an example is shown in Figure 31. Roberts ever researched the active pumping techniques of wellpoints, deepwells and ejector wells which are used on tunnel to lower pore water pressures (Roberts and Preene 1994, Roberts et al. 2007). This article is a representative case study of one such large scale long term temporary works of dewatering scheme and can be used for reference by other projects.

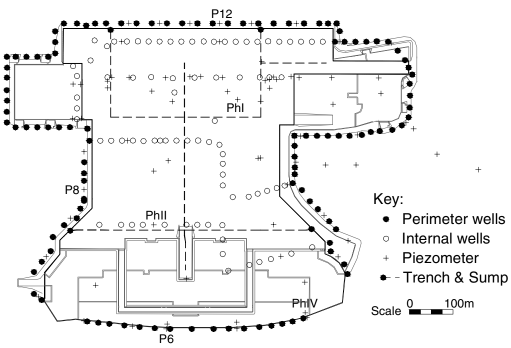


Figure 30 Dewatering well and piezometer 'as built' layout (Roberts et al., 2009)

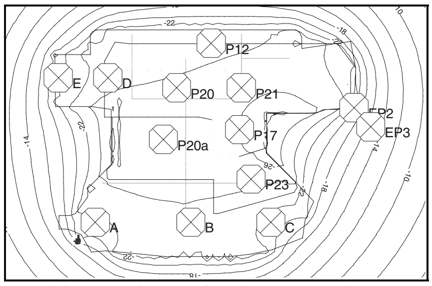


Figure 31 Model groundwater level contours 31 December 2003 (Roberts et al.)

Perau et al. present an approach to relax pore-water pressure by design relief boreholes at the bottom of excavations. Figure 32 shows Terzaghi's classical seepage situation and seepage situation with relief boreholes. They think that Terzaghi's assumption of a rectangular failure body is only applicable to the case of non-cohesive soils and a simple folw-field geometry but not work for systems with cohesive soil and manipulated groundwater flow fields. Figure 33 shows the failure mechanisms with and without relief boreholes. The applied relief boreholes improve the flow field significantly so that the verification in this case is near to a successful result while in cases of missing relief boreholes the verification is far away from it. It is helpful to apply relief boreholes to improve the geohydraulic situation beneath the bottom of an excavation. The relief boreholes need to have a sufficiently wide diameter and a certain depth.

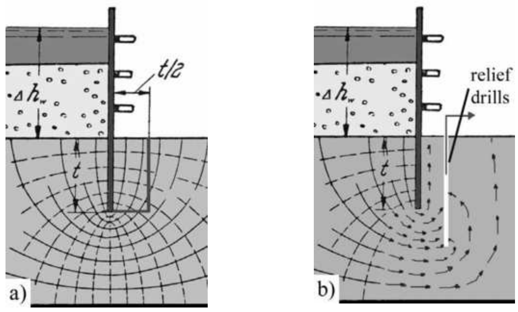


Figure 32 a) Terzaghi's failure body for verification against heave (non cohesive soil, classical seepage situation) b) situation with cohesive soil and seepage affected by relief boreholes (Perau et al.)

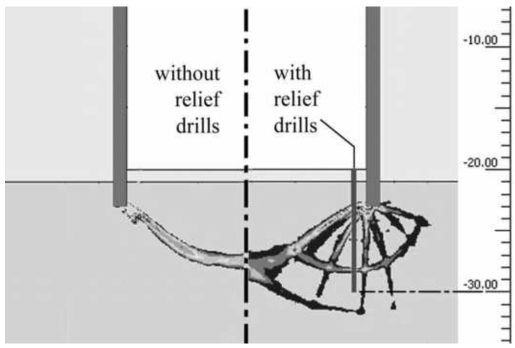


Figure 33 Failure mechanisms beneath the bottom of the excavation (ϕ_k'=25°, c_k' = 20 kN/m², $\sigma'_{tension}$ = 0) without relief boreholes (left hand) and with relief boreholes, t_E = 10 m (right hand) (Perau et al.)

Thumann et al. present two case histories to illustrate the knowledge of the local groundwater regime in case of unexpected events such as watertightness of frozen collar construction and diaphragm wall leakage incident. 3D groundwater model has been developed to determine the effect of dewatering activities and the actual hydraulic resistance of the diaphram wall. Modelling of diaphragm wall hydraulic parameters is shown in Figure 34. The freeze-up of the collar construction is based on the on-line measurements of the groundwater pressures at both sides of the wall. The combination of temperature measurements and use of drainage wells is important to minimize the flow of the groundwater along and across the almost frozen wall. Closure and repair of a sudden gap in the diaphragm wall is made possible by the installation of additional drainage wells and extensive on-line monitoring.

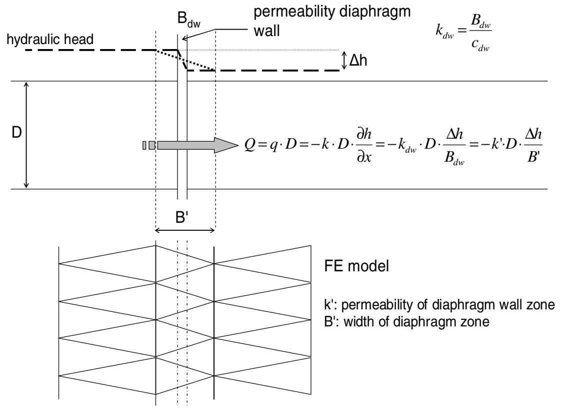


Figure 34 Modeling of diaphragm wall hydraulic parameters in the MicroFem code (Thumann et al.)

Kibria et al. present an unconventional seepage control approach for a substructure with their local experiences. This paper introduces the implementation of lime injection program along the exterior walls of the substructure by a project case. Lime injection can be carried out to the affected area, and the internal treatment at inner side of the walls should also be carried out.

4.2 *Review of papers related to treatment of contaminated groundwater*

Two papers in this section are related to the treatment of contaminated groundwater. ***Jirasko and Vanicek*** focus on the interaction of groundwater regime with remediation method of permeable reactive barriers (PRB). The principle of PRB method is shown in Figure 35. The parametric study containing 51 numerical models of different shapes and dimensions of PRB were done and the backwater in front of PRB, decrease of groundwater level behind the PRB, flow rate through reactive gate, pore water velocity in gate, and residential time in reactive medium were observed.

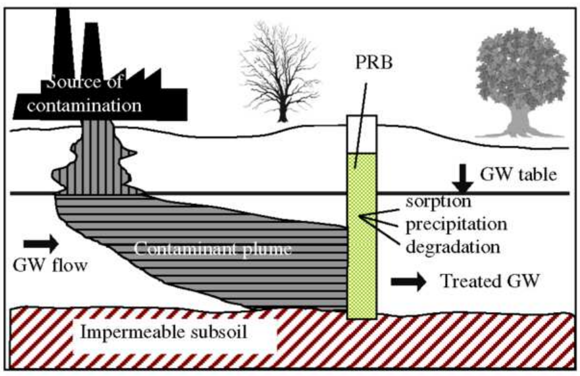


Figure 35 Principle of groundwater remediation by PRB method (Jirasko and Vanicek).

Nobre and Nobre present a risk-based remediation approach at a contaminated site impacted with chlorinated organics. Figure 36 explains the definition of risk zones according to the percentile selected for the probability density function solution. The risk-based approach demanded the assessment of contaminant exposure pathways as well as groundwater mass transport analysis, taking into account the intrinsic degradation pathways and other natural attenuation mechanisms. The risk analysis results indicate that vinyl chloride is responsible for the highest calculated risk at the site.

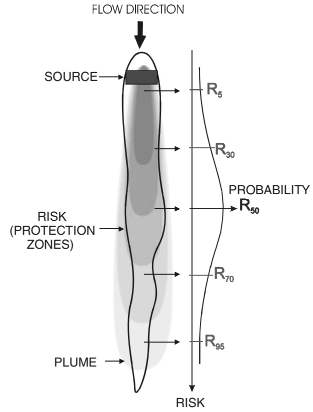


Figure 36 Schematic risk zones according to confidence intervals (Nobre and Nobre)

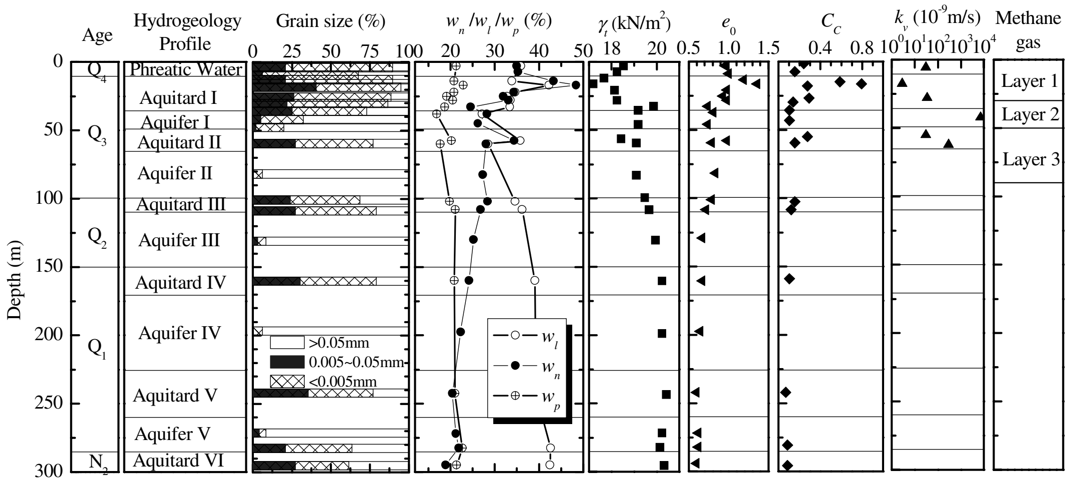
4.3 Groundwater related geohazards during construction in china

The soft deposit of Shanghai is rich in groundwater with an aquitards over aquifer one another, which is simply called multi-aquifer-aquitard system (MAAS) (Xu et al., 2009a). Figure 37 shows an illustrative soil profile and mechanical properties in Shanghai. The buried depth of foundation soil layers related to construction are generally less than 100 m. These sediments are soft silty clay in aquitards and silty to fine sand in aquifers (Xu et al., 2008; 2009a).

There are many excavation projects are constructing in Shanghai. Some representive projects are tabulated in Table 1. Underground excavations and dewatering maybe change geological environment. There are following geohazards during deep excavation which needs to be research further:

1) Impact on surroundings due to drawn of groundwater head in confined aquifer: Drawdown of groundwater level in confined aquifer will cause the increase of effective stress of soil strata over the aquifer. Thus, the soft clay will be consolidated and settlement will occur on groundsurface. The impacts include the range and magnitude of settlment and groundwater depression due to dewatering. To predict these impacts, the appropriate methods and correct evaluation of parameters are required (Robets et al., 2007; Shen et al., 2006a, 2006b). In order to alleviate the impact on surroundings, some countermeasures, e.g. reduction of pumping time, should be conducted (Shen et al., 2006a). Although there are some theoretical and practical prediction methods were estabilished by Powrie and Preen (1994), Preen and Powrie (1994) , Roberts and Preen (1994), and Roberts et al. (2007). However, engineering practice shows that it is difficult to directly apply these methods in the Chinese cases. The difficulties include: i) evaluation of parameters of hydraulic conductivity and stiffness of soft clayey soil, ii) identification of dewatering-induced settlement from the total settlement both due to groundwater level lowering and excavation (Shen et al. 2006a).

Therefore, further research topics include i) correct evaluation on the parameters of permeability of aquifers and compressibility of the soil strata over the aquifer, ii) field observation on drawdown cone and the dewatering-induced settlement during excavation works.



Note: N_2=Pliocene; Q_1=Lower Pleistocene; Q_2=Middle Pleistocene; Q_3=Upper Pleistocene; Q_4=Holocene; w_n =Water content; w_p=plastic limit; w_l =liguid limit; γ_t = unit weight; e_0 = void ratio; C_C=compressive index; k_v = hydraulic conductivity in vertical dirction

Figure 37 An illustrative geotechnical profile and soil properties in Shanghai (Xu et al. 2009a)

2) Cut-off of groundwater by retaining structure. During excavation, the retaining structure such as diaphragm was used to cut off groundwater in aquifer besides the earth retaining and prevention of basal heaving. In Shanghai, in order to reduce the settlement of surrounding ground surface during pumping of groundwater from confined aquifer, retaining structures are generally design to cut off the confined aquifer fully or partially, as shown in Figure 38. The full cutoff of aquifer is an effective way and there is very less impact on surroundings (Figure 11a). However, in most cases, full cutoff is not economic and partial cut-off is generally used as shown in Figure 11b. The insert depth of the retaining wall in confined aquifer is determined by the following factors: i) basal heaving prevention (Wudtke and Witt, 2009; Perau et al., 2009); ii) drawdown of groundwater head of confined aquifer and the settlement outside the pit. The relationship among insertion depth of retaining wall, drawdown of water head, and settlement should investigated in details in the future.

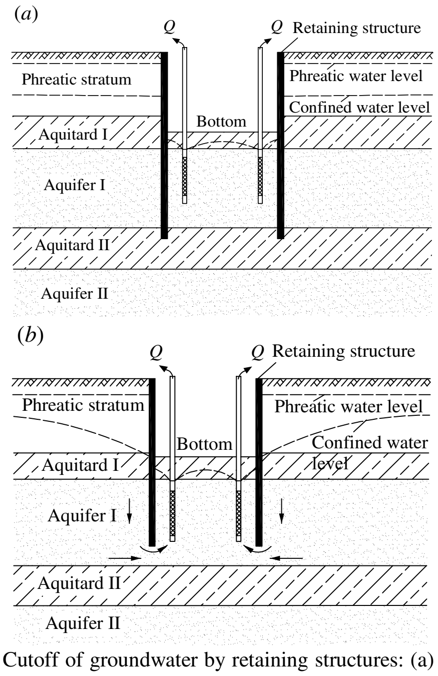


Figure 38 Cutoff of groundwater by retaining structures: (a) full cutoff, (b) partial cutoff (Miao et al, 2009).

3) Another aspect of the geohazards related to groundwater is the quicksand hazard in Aquifer I (AqI). In Shanghai, when the excavation till to (or over) AqI, the bottom of excavated pit or the joint of diaphragm wall should be sealed using jet-grouting technology, e.g., chemical churning pile (CCP) method and/or triple rode method. Since in jet-grouting construction, the cement slurry was jetted into ground under high pressure, when jet-grouting is conducted in AqI, in most case, it is very difficult to form uniform columns with high quality as that in the clayey soil (Shen et al., 2009b). In order to solve this problem, Shen et al. (2009a) developed a new technology called Twin-Jet, in which cement slurry and accelerating agent such as water-glass is jetted into ground and is quickly mixed with sandy soil. Consequently, gel shaped column can be formed within several seconds. However, the mechanisms of separation of cement and sand and quick gelling must to be further elucidated.

4) Melting hazards of freezing soil. In Shanghai, when excavation work is conducted in sand layer (AqI) such as bypass tunnel and entrance and departure of shield machine, artificial freezing is employed. However, sometimes freezing soil may be melted during construction, which may lead to quicksand hazards. In Shanghai Metro line 4 accident occurred in 2003 due to the melting of frozen soil (Yu and Zhu 2008; Xu et al. 2009b). This human-induced disaster occurred during the construction of bypass tunnel connection between two shield tunnels. The soil layer at this site is a fine sand layer with a 40 m high confined head. The melting of frozen soil caused quicksand in the confined aquifer and large amount of soil flowed into the tunnels, which resulted in the collapse of tunnel at a length of about 210 m and the inclination and collapse of buildings over the tunnel (Yu and Zhu 2008). Therefore, monitoring on the state of freezing soil becomes very significant during freezing construction as presented by Thumann et al. (2009).

Although in this report the related topics on groundwater are presented in details in Shanghai, other coastal cities such as Tianjin, Guangzhou, Hangzhou, are also rich of groundwater with higher seepage capacity than that in Shanghai (Xu et al., 2008; 2009b). These local characterisations of groundwater with its effect on underground construction must be investigated one by one in the future.

4 SUMMARIES

The TS4B session contains a wide range of papers on the topics of tunnelling, deep excavation and groundwater controlling. Most of the papers are of value to the readers, and are highly recommend to the readers the original papers for more details. Basing on the papers, recent advance and hot spotted problems in China, the following comments or discussions are proposed for this session:

Ground movements and its effect on existing structure due to tunnelling are given more consideration in congested urban area. Ground treatment is a very useful mean to keep the safety of tunnel and surrounding environment. Hazard is often encountered due to the uncertainties in underground construction, and risk management is an effective way to deal with the uncertainties. Face stability is of importance special for shallow SPB tunnel with large diameter. Further research or discussions are proposed for TBM tunnel as following: 1) effect of tunnelling on adjacent facilities; 2) effect of tunnel leakage on the performance of tunnel; 3) risk management.

Excavation is a hot spotted problem in urban development. With the imposing of more and more challenging new features of deep excavations in an urban environment, design and construction of deep excavations has become one of the most challenging tasks for geotechnical engineers. Performance-based design of excavation is a trend for engineering practice. Further Researches in the future are as follows: 1) performance of deep excavations; 2) mechanism of soil-structure interaction; 3) deformation control method and evaluation of its effect; 4) criteria of deformation control; 5) prediction of displacemtent of the wall and soil mass, and 6) effect of deep excavations on surrounding environment.

Groundwater control is important in underground construction. It is well known that the substructure and groundwater influence each other. To avoid the occurrence of boiling and quicksand, when excavation is conducted over confined aquifer, dewatering in the confined aquifer should be adopted. It is important to choose appropriate dewatering approach according to local engineering experiences. It is also necessary to research the effect on environment due to dewatering. Further Researches in the future are as follows: 1) evaluation of impact on surroundings induced by dewatering; 2) the effect of retaining structure on groundwater seepage; 3) delayed dewatering in aquifer; and 4) effective jet-grouting to improve the bottom of excavated pit or the joint of diaphragm wall.

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