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Bored tunnelling – TBM and shield tunnelling

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ABSTRACT: This general report reviews and examines 27 papers submitted to the session on TBM (tunnel boring machine) and Shield Tunnelling, as a risk management system.

1 INTRODUCTION

The design code used for geotechnical structures is to be written based upon the performance of the structures in service described in Eurocode 7 (Simpson and Driscoll, 1998). A limit state design is one of the procedures based upon the performance of structures. The design strategy for underground structures such as in tunnelling and braced excavation should also follow this system. A performance-based design system is basically equivalent to a risk management system. Actually, two of the papers submitted to this session describe the practical examples of the application of a risk management system to the assessment of the influences of shield tunnelling on superstructures.

2 RISK MANAGEMENT SYSTEM

The risk management cycle is shown in Figure 1. It consists of the following four stages:
1) Listing of risk factors
2) Risk analyses

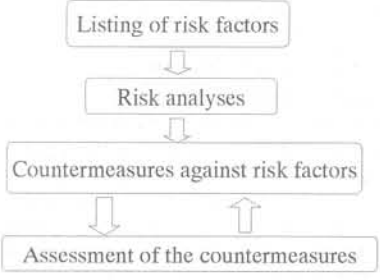

Figure 1. Risk Management Cycle

3) Countermeasures against risk factors
4) Assessment of the countermeasures

Table 1 summarizes the papers submitted to this session from the viewpoint of the risk management system.

3 TBM AND SHIELD TUNNELLING AS A RISK MANAGEMENT SYSTEM

3.1 *Application of the risk management system to tunnelling*

First, the practical examples of the risk management approach to shield tunnelling problems are introduced, so that one can understand the complete procedure of applying the risk management system.

Netzel and Kaalberg present a good example of the application of the risk management system to damage assessment on superstructures due to TBM tunnelling. The procedures that demonstrate the contents of the system are as follows:

1) The risk factor adopted in this project is the ground settlement due to TBM tunnelling.

2) Risk analysis of the damage to superstructures due to the ground movement from tunnelling is conducted by 2-D or 3-D finite element simulations. A damage classification system is defined using the strain and cracks in the walls of the structures.

3) The countermeasures against damage risk are as follows. The alignment, design and tunnelling boring technique can be optimized in order to minimize the damage caused by the differential ground settlement. Protection techniques (mitigating measures, underpinning) can be used to reduce the effect of TBM tunnelling on the surroundings, as demolition of structures is prohibited in Amsterdam.

4) Risk assessment shall be followed by conducting a cost-benefit analysis of the countermeasures adopted.

Oteo, Arnaiz, Trabada, Melis and Mendana present a report on the application of the risk management system to shield tunnelling in Madrid, Spain. The risk issue is the surface settlement due to tunnelling. The risk analysis is carried out by the semi-empirical Madrid model, which is similar to the Peck-Schmidt method. The countermeasure against the risk is the compensation grouting. Assessment of the countermeasure is described in terms of the reduction of settlement, cost and work performance time.

This system can guarantee the performance of the ground and superstructures during tunnelling and post construction stage.

3.2 *Risk and countermeasures prior to and during construction*

Aristaghes and Blanchet introduce the monitoring system for TBM tunnelling. The key risk issue adopted in this study is the TBM performance during construction. The sensor signals for TBM performance were statistically analyzed and used for the collapse risk indicator. However, the practical data were not fully given.

Bakker, Leenderste, Jovanovic and van Oosterhout and Bakker, de Boet and Admiraal present companion papers that introduce the recent large-diameter shield tunnelling projects in the Netherlands. Monitoring was conducted in the two cases of shield tunnelling in soft ground that focused on the following three issues:

1) Processes related to the tunnel boring machine, i.e., the cutter wheel performance, the hydraulic jacks operation and the grouting pressure and volume.

2) Geotechnical information, i.e., the ground movement and the pore water pressure behaviour.

3) Structural behaviour of tunnel lining, i.e., the deformation and damage of tunnel lining.

The structural behaviour of tunnel lining was adopted as a key risk factor in these papers, and numerical analyses of lining damage were conducted.

Benmebarek, Kastner and Ollier show a successful example of reducing settlement due to shield tunnelling. The risk issue is to reduce the ground displacement due to slurry shield tunneling. A systematic injection system for tail void was adopted as a countermeasure in this case.

Chang, Chen and Wang show the relationships between surface settlement and construction factors, i.e., excavation soil, chamber pressure and grout volume. The risk issue is the settlement behaviour due to tunnelling. The risk issue is analyzed statistically.

Cooper and Chapman show the results of monitoring the movement of an existing underground tunnel obtained during the construction of new railway tunnels that pass just beneath an existing tunnel. The key risk issue discussed in their paper is the effect of the NATM driven tunnelling on the existing structure. The settlement curve, rotation and distortion of the existing tunnel were analyzed. A method of its prediction is suggested.

Hashimoto, Hayakawa, Mizuhara and Konda investigate successive surface settlement due to shield tunnelling. The risk issue described in this paper is also the surface settlement due to the tunnelling. The risk analysis is carried out using many case records of shield tunnelling conducted in the last 20 years in Japan. The countermeasure against this risk is the control of the maximum deformation during the passage of the shield–tunnelling machine.

Kuwano, Takahashi, Honda and Miki show centrifuge model tests on the effects of soil nailing on the overall stability of clay ground with different over-consolidation ratios. The risk issue is to increase the tunnelling stability and decrease the overall deformation of the ground around the tunnel. The countermeasure against this issue is the application of a soil nailing method around the tunnel. The assessment of the soil nailing was conducted from the observed ground displacement.

In the paper by Lee, Shen, Liu and Bai, the key risk issue due to shield tunnelling in Shanghai is also the surface settlement. In order to evaluate the settlement-related factors, the authors use the novel parameter, which demonstrates the actual construction process of shield tunnelling, i.e., earth pressure in the chamber, grouting volume and over cutting. The full publication of their paper is found in the special issue of Soils and Foundations.

Marshall and Milligan report the systematic field measurement results of pipe jacking (internal diameter 1.5m, driven length 260m, average depth axis 6.4m) in soft silty clay ground. The risk factors are the pipe jack driving performance and the ground deformation. The acquired results will assist engineers in preparing countermeasures for designing the driving machine capacity and predicting the ground deformation.

Mihalis and Kavvadas introduce the subject of TBM tunnelling in a difficult soil condition, Athens schist formation. Also in this paper, the key issue is the tunnel face stability and the ground displacement due to tunnelling. The countermeasure adopted is the soil improvement using jet grouting. The assessment of the jet grouting effectiveness will be conducted from the economic viewpoint.

Samuel, Mair, Lu, Chudleigh, Addenbrooke and

Table 1 Paper review from the viewpoint of risk management cycle

Authors	Risk (Pre ,during and post construction)	Risk analysis	Countermeasure	Assessment of countermeasure
Netzel et al (Netherlands)	Surface settlement	2-D, 3-D FEM	Alignment, Underpinning	*(undefined)
Oteo et al (Spain)	Surface settlement	Semi-empirical Madrid method	Compensation grouting	Settlement reduction
Aristaghes et al (France)	TBM performance during construction	Statistical analysis of signals	*	*
Bakker et al (Netherlands)	Structural behaviour of tunnel lining	Numerical analysis	*	*
Benmebarek et al (Algeria)	Surface settlement	Experimental site observation	Backfill grouting	*
Chang et al (Taiwan)	Surface settlement	Statistical analysis of observation	*	*
Cooper et al (UK)	Effect of tunnelling on the structures	Field observation	*	*
Hashimoto et al (Japan)	Surface settlement	Case records	Deformation control	*
Kuwano et al (Japan)	Tunnel stability and ground deformation	Centrifuge experiment	Soil nailing	Centrifuge experiment
Lee et al (HK)	Surface settlement	Statistical analysis of observation	*	*
Marshall et al (UK)	Driving performance and ground deformation	*	*	*
Mihalis et al (Greece)	Tunnel stability and ground deformation	Field observation	Jet grouting	*
Samuel et al (UK)	Effect of tunnelling on the structures	2-D FEM	Construction control	*
Shao et al (USA)	Surface settlement	Field observation	Construction control	*
Shen et al (Taiwan)	Geologic condition	*	Tunnelling method selection	*
Van der Stoel et al (Netherlands)	Surface settlement	*	Near pile injection	*
Zhu et al (China)	Structural behaviour of tunnel lining	Numerical analysis	*	*
Beth et al (France)	Surface settlement	Field observation	Compensation grouting	Field observation
Harris et al (UK)	Effect of tunnelling on the structures	Field observation	Compensation grouting	Field observation
Lee et al (UK)	Segmental lining damage	Field observation	Compensation grouting	*
Sugiyama et al (Japan)	Surface settlement	Field observation	Compensation grouting	Cost reduction by 20%
Gourvenec et al (UK)	Post construction ground loading	Field observation	*	*
Katelaars et al (Netherlands)	Environmental effect due to excavated soil	*	Re-use of excavated soil	*
Prinzl et al (Austria)	Structural behaviour of tunnel lining	Numerical analysis	Performance criteria	*
Sager et al (Germany)	Geotechnical condition and machine driving	*	Slurry machine and sonic probe	*
Yamada et al (Japan)	Tunnel stability and ground deformation	Model tests and 2-D FEM	MJS method	2-D FEM

Readings report the effects of boring a new tunnel under a masonry tunnel. The risk issue is the effect of new tunnelling on the existing old masonry tunnel. The risk analysis is carried out by the sophisticated 2-D coupled finite element method, taking into account the construction stages of the masonry tunnel. The analysis enabled the crossing by the new tunnel to be carried out with confidence. The instrumentation and survey showed that the predictions were met at a high level of accuracy.

Shao, Macari, Xia and Ye demonstrate extensive field measurement from a large-sized (diameter = 11.3 m) semi-open shield tunnelling project. The risk issue in this project is the ground surface settlement due to tunnelling. The countermeasure against settlement is the control of construction parameters such as the frontal face earth pressure, the amount of excavated soil, the machine advancement speed and the amount and quality of the grouting to the tail void. These are exactly the important construction parameters for shield tunnelling in soft ground. The movement or the postural position of shield machine during driving is also a crucial factor particularly in soft clay ground. The information reported from Lee et al during this symposium is valuable for evaluating machine movement. The assessment of the countermeasures will be conducted from the cost and benefit viewpoint.

Shen, Tsai, Hsieh and Chu introduce countermeasures adopted for tunnelling against adverse geologic conditions due to tectonic action in Taiwan. In this paper, the geological survey is one of the listing methods for documenting risk factors. The countermeasure against geologic conditions is the selection of tunnelling method, i.e. the drill and blast method, use of full-face tunnelling machine or the reinforcement of the tunnel face by shotcrete.

Van der Stoel and van Tol describe a full-scale test program of injection to protect piled superstructures, i.e., old masonry houses in Amsterdam, from the settlement due to shield tunnelling in soft ground. The risk factor is the surface settlement from the tunnelling. The countermeasure against settlement is the injection into the near pile. Preliminary test results were reported in the paper.

Zhu, Ding, Hashimoto, Nagaya and Tamura describe the 2-D finite element method, which obtains the structural behaviour of the tunnel lining and the ground displacement. The key risk issue is the acting earth pressure and internal forces of tunnel lining during construction. The authors introduce the actual events that occur during shield tunnelling into their method, i.e., the effects of gap closing between soil and lining, the grouting pressure distribution and the grout hardening process.

3.3 *Assessment of compensation grouting as a countermeasure during construction*

Compensation grouting has been frequently used for protecting superstructures against ground displacement due to underground construction in the UK and other countries. The companion papers on the application of compensation grouting in underground construction are presented. The compensation grouting itself is the countermeasure against the risk factor of surface settlement due to underground construction.

Beth, Carayol and Lavene report the implementation of compensation grouting for TBM tunnelling in soft ground in Puerto Rico. The risk issue is the surface settlement due to tunnelling, and the countermeasure is compensation grouting. The assessment of the countermeasure is carried out by examining the observed surface settlement. It can be concluded from the measurement results of the surface settlement due to tunnelling reported by Hashimoto et al in this symposium that the successive settlement becomes large in the case of soft clay ground due to the disturbance of soft clay. As compensation grouting can easily disturb soft soil, long-term observation of surface settlement will be required in this project.

Harris, Mair, Burland and Standing demonstrate a system for controlling the tilting of tower superstructures due to tunnelling and large-scale excavation. The key risk issue is the effect on the superstructure due to underground construction. The countermeasure adopted is compensation grouting and its real-time control using filed measurement results. The assessment of the countermeasure resulted in successful protection of an important superstructure.

Lee, Dasari, Bolton, Soga, Sugiyama, Ano, Hagiwara and Nomoto report the effect of compensation grouting on segmental tunnel lining using field measurement records. The assessment of countermeasures was carried out from the viewpoint of the damage to the segmental lining and the superstructures due to compensation grouting.

Sugiyama, Nomoto, Nomoto, Ano, Hagiwara, Mair, Bolton and Soga discuss field measurement records on surface displacement due to tunnelling and compensation grouting. Compensation grouting was carried out to compensate for ground loss and stress relief by tunnel excavation, when it was needed, based on the monitoring results. The soil improvement costs (including compensation grouting) for the project are reported to have been reduced by 20 percent compared with the expected costs.

3.4 *Miscellaneous risks and assessment at post-construction*

Gourvenec, Bolton, Soga, Gui, Mair, Edmonds, Chudleigh and Butler report on field investigations of long-term ground loading on an old tunnel in London clay. The risk issue is the post-construction long-term ground loading on tunnel linings, which is the necessary viewpoint of the risk management system for underground construction. The in-situ pressure meter test data and the pore water pressure distribution around an old cast iron lined tunnel were obtained. The risk analysis will be carried out using the in-situ data and laboratory test data. If necessary, countermeasures against that risk will be undertaken.

Ketelaars and Saathof report on the re-use of soil from bored tunnels. The key risk issue selected in this paper is the environmental effect due to tunnelling. Around 1 million m^3 per year will be excavated in TBM drives in the Netherlands. In Japan, 10 million m^3 per year will be expected to be excavated, including tunnelling and braced excavation. This is potentially a crucial environmental issue, so the cost of the re-use of the excavated soil must be analyzed.

Printzl and Gomes introduce an interesting situation in Bangkok, Thailand, where the shield machines will drive through the cut and cover station boxes after the installation of the diaphragm walls at different stages of excavation. In addition, a temporary tunnel lining will be removed after the excavation inside the station is finalized. The risk issue is the structural elements of the temporary tunnel lining. The excavation inside the station will cause a continuous change in the ground stresses around the tunnels. Vertical loads will decrease whilst the horizontal loads will increase with the passive earth pressure. The numerical analyses of the temporary tunnel lining were carried out to assure successful performance criteria.

Sager and Herrenknecht introduce the design and development process of the large-diameter slurry shield machine. The risk issues described in this paper with regard to the type selection of TBM are as follows:

1) Control of large ground water pressure
2) Access to the excavation chamber under high pressure by using divers
3) Minimization of wear
4) Consequent optimization of the flow of material at the cutter head and in the excavation chamber
5) Optimization of the logistical systems

The countermeasure is the adoption of the slurry shield machine with a sonic probing system. The assessment of the countermeasure will be conducted by the actual use of this slurry shield tunnelling system.

Yamada, Sugimoto, Nishio and Kayukawa demonstrate the development of the 4-centered slurry shield driving method. The risk issues are the tunnel stability of the new type shield tunneling machine and the effects of shield tunnelling on the neighboring underground structures. The risk analyses were conducted by model tests and 2-D finite element simulation. The countermeasure against the latter risk is the MJS method, i.e., the horizontal jet grouting method. The countermeasure assessment was done by the 2-D finite element simulation.

4 CONCLUDING REMARKS

This report reviews and examines 27 papers submitted to the session on TBM (tunnel boring machine) and Shield Tunnelling, as a risk management system. A wide range of topics concerned with the TBM and shield tunnelling are expected to be covered from the unified viewpoint of the risk management system. This risk management system will be analyzed by assessing the various countermeasures proposed. Some of the papers concluded with a description of the preparation of the countermeasure and failed to provide information with regard to its assessment. In these cases, a cost-benefit analysis of the countermeasure will need to be conducted to obtain a complete assessment.

The full assessment of the risk due to tunnelling will help ensure the successful installation of underground structures prior to, during and post construction. This is the most reasonable performance-based design system for underground structures.

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