

**GEO Technical Guidance Note No. 25 (TGN25)
Geotechnical Risk Management for Tunnel Works**

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1. SCOPE

- 1.1 This Technical Guidance Note (TGN) provides guidance on geotechnical risk management in relation to tunnel works. It does not cover immersed tube tunnels, box culverts, submarine outfalls and underground pipes for drains, sewers and water mains. Any feedback on this TGN should be directed to the Chief Geotechnical Engineer/Mainland East.

2. TECHNICAL POLICY

- 2.1 The technical guidelines contained in this TGN were agreed by GEO's Geotechnical Control Conference (GCC) in November 2005.

3. RELATED DOCUMENTS

- 3.1 Barton, N. & Grimstad, E. (1994). The Q-System following twenty years of application in NMT support selection. *Proceedings of the 43rd Geomechanic Colloquy*, Salzburg, Felsbasu, 6/94, pp 428-436. (Re-printed in the course notes on Design Methods for Jointed Rock by Dr N. Barton produced by the Department of Civil and Structural Engineering, Hong Kong Polytechnic University, 24-26 March 1997).
- 3.2 Barton, N. (2004). Risk and risk reduction in TBM rock tunnelling. *Proceedings of the ISRM International Symposium: Third Asian Rock Mechanics Symposium*, Kyoto, Japan, pp 29-38.
- 3.3 Burland, J. B., Standing, J. R. & Jardine, F. M. (Ed.) (2001). *Building Response to Tunnelling - Case Studies from Construction of the Jubilee Line Extension, London. Volume 1: Projects and Methods. Volume 2: Case Studies*. CIRIA Report No. SP200, CIRIA, London.
- 3.4 BSI (2001). *BS 6164:2001 Code of Practice for Safety in Tunnelling in the Construction Industry*. British Standards Institution, London, 124p.
- 3.5 BTS/ICE (2004). *Tunnel Lining Design Guide*. British Tunnelling Society and Institution of Civil Engineers, London, 184p.
- 3.6 BD (2005). *Code of Practice for Site Supervision 2005*. Buildings Department, Hong Kong, 99p.
- 3.7 Clayton, C. R. I. (2001). *Managing Geotechnical Risk - Improving Productivity in UK Building and Construction*. Institution of Civil Engineers, London, 80p.
- 3.8 Essex, R. J. (Ed.) (2007). *Geotechnical Baseline Reports for Construction: Suggested Guidelines*. American Society of Civil Engineers, Reston, USA, 62p.
- 3.9 Eskesen, S.D., Tengborg, P., Kampmann, J., Veicherts, T.H. (2004). Guidelines for tunneling risk management: International Tunnelling Association, Working Group No. 2. *Tunnelling and Underground Space Technology*, vol. 19, No. 3, pp 217-237.

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- 3.10 ETWB (2004). *Impossibility/Unforeseen Ground Conditions/Utility Interference (Environment, Transport and Works Bureau Technical Circular (Works) No. 17/2004)*. Environment, Transport and Works Bureau, Government Secretariat, Hong Kong.
- 3.11 ETWB (2005a). *Implementation of Systematic Risk Management in Public Works Projects (Environment, Transport and Works Bureau Technical Circular (Works) No. 6/2005)*. Environment, Transport and Works Bureau, Government Secretariat, Hong Kong.
- 3.12 ETWB (2005b). *Geotechnical Control for Tunnel Works (Environment, Transport and Works Bureau Technical Circular (Works) No. 15/2005)*. Environment, Transport and Works Bureau, Government Secretariat, Hong Kong.
- 3.13 GEO (2005). *Site Investigation for Tunnel Works*. Technical Guidance Note No. 24 (TGN 24). Geotechnical Engineering Office, Hong Kong, 8p.
- 3.14 GEO (2009). *Catalogue of Notable Tunnel Failure Case Histories (up to December 2008)*. Geotechnical Engineering Office, Hong Kong.
(<http://www.cedd.gov.hk/eng/publications/reference/doc/HK%20NotableTunnel%20Cat.pdf>)
- 3.15 ITA (2009). *General Report on Conventional Tunnelling Method*. International Tunnelling and Underground Space Association.
(<http://www.ita-aites.org/cms/ita-aites-home/latest-news-detail/datum/2009/05/13/ita-report-online-copie-1.html>)
- 3.16 ITIG (2006). *A Code of Practice for Risk Management of Tunnel Works*. The International Tunnelling Insurance Group (in association with the Munich Re Group), 37p.
- 3.17 Muir Wood, A. M. (1990). The Observational Method revisited. *Proceedings of 10th Southeast Asian Geotechnical Conference*, Taipei, vol. 2, pp 37-42.
- 3.18 Munich Re Group (2004). *Underground Transportation Systems - Chances and Risks from the Reinsurer's Point of View*. Münchener Rückversicherungs-Gesellschaft, Germany, 64p.
(<http://www.munichre.com/en/publications/default.aspx>)
- 3.19 Nicholson, D., Tse, C. M. & Penny, C. (1999). *The Observational Method in Ground Engineering: Principles and Applications*. CIRIA Report No. 185, CIRIA, London, 214p.
- 3.20 Peck, R. B. (1969). Advantages and limitations of the Observational Method in applied soil mechanics. *Géotechnique*, vol. 19, no. 2, pp 171-187.
- 3.21 Powderham, A. J. (1994). An overview of the observational method: development in cut and cover and bored tunnelling projects. *Géotechnique*, vol. 44, no. 4, pp 619-636.

(Note: ETWB TC(W)s and PNAPs that are referred to in this TGN can be found from the website of the Development Bureau (DEVB) (website: <http://www.devb-wb.gov.hk/>) and the Buildings Department (website: <http://www.bd.gov.hk>) respectively. Only those directly relevant to the subject of geotechnical risk management are referenced above. All references

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can be found in the Civil Engineering Library of the Civil Engineering and Development Department, which is open to the public, or from the websites indicated.)

4. DEFINITIONS

- 4.1 Geotechnical Risk Assessment – The process of identifying geotechnical hazards and risks, evaluating their potential consequences and likelihood of occurrence, together with strategies for preventative and contingent action.
- 4.2 Geotechnical Risk Management – The overall systematic process of geotechnical risk assessment, and risk mitigation and control.
- 4.3 Hazard – An event which has the potential to impact on matters relating to a project which could give rise to undesirable consequences.
- 4.4 Risk – Combination of the probability of an event occurring and its consequence for project objectives.
- 4.5 Tunnel Works – Tunnels, shafts, caverns and associated underground facilities, however constructed.

5. TECHNICAL RECOMMENDATIONS

5.1 GENERAL

- 5.1.1 There have been serious failures in tunnel construction worldwide (see case histories in GEO (2009)). These have resulted in fatalities, damage to property and other socio-economic consequences. Most of these are due to inadequacies in the management of geotechnical risks.
- 5.1.2 The risk management approach is now widely adopted to control risks in construction projects. Codes and technical guidance have been published on safety in tunnelling and risk management of tunnel works, for example, BSI (2001), the Code of Practice by the ITIG (2006) and Eskesen et al (2004). Clayton (2001) describes a risk-based approach for controlling ground-related uncertainties in construction projects. Essex (2007) gives guidance on the preparation of Geotechnical Baseline Reports which are used as the geotechnical baseline for allocation of financial risks in contracts with underground construction. Project managers are advised to take account of the provisions of these codes of practice and technical guidance that are appropriate to Hong Kong in undertaking their work.
- 5.1.3 In Hong Kong, private projects involving tunnel works are subject to geotechnical control under the Buildings Ordinance (BO), in which "building" is defined to include "cavern or any underground space adapted or constructed for occupation or use for any purpose including its associated access tunnels and access shafts".
- 5.1.4 For government projects, the DEVB has issued policy documents on project risk management, with respect to physical impossibilities and unforeseen ground conditions (ETWB, 2004) and

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on systematic risk management which is applicable to public works projects with cost estimates exceeding HK\$200M (ETWB, 2005a). DEVB has also issued ETWB TC(W) No. 15/2005 (ETWB, 2005b), which states the policy and procedures for geotechnical control of planning, design and construction for government tunnel works.

- 5.1.5 The land and technical requirements for protection and maintenance of permanent tunnel works including those during operation and maintenance should be considered in both the project planning and design stages. Provisions for protection of major railway and sewage tunnels are given in relevant ETWB TC(W)s (e.g. ETWB TC(W) Nos. 19/2002, 28/2003, 33/2003 and 2/2005) and PNAPs (e.g. PNAP Nos. 77, 165 and 279). For some tunnels, e.g. drainage tunnels and tunnels with a drained lining design, long-term monitoring requirements and performance criteria will also need to be specified.
- 5.1.6 The geotechnical control provisions in the BO and the ETWB TC(W) No. 15/2005 are intended to protect public safety. The Geotechnical Engineering Office (GEO) has a role in implementing these geotechnical control provisions.

5.2 AIMS AND PRINCIPLES

- 5.2.1 One of the aims of geotechnical risk management in tunnel works is the overriding need to ensure that the works do not adversely affect public safety or infrastructure (including buildings, structures, roads, slopes, landfills, tunnels, water mains, gas mains, sewerage/drainage rising mains or other sensitive facilities and members of the public).
- 5.2.2 Geotechnical risk management should be an integral part of the overall project risk management, and be an integral consideration in the planning, design, procurement and construction of all tunnel works. It is the responsibility of the client, with due advice from the project manager and an experienced geotechnical professional, to ensure that adequate resources are provided for the management of geotechnical risks in the construction of such works. The implementation details should take into account the level of risk to life and property.
- 5.2.3 Geotechnical risk management should be undertaken from the start of every project. It is a cyclical process that continues throughout the duration of the project, with all the activities being reviewed and the assessment updated on a regular basis. The client should ensure that qualified professionals with relevant geotechnical and tunnelling experience are employed in the project risk assessment/management team. Insurance of the risk does not remove the need or reduce the responsibility for the client to ensure safety is properly managed.
- 5.2.4 The project manager and the geotechnical professional responsible for risk management should continually review the geotechnical risks and ensure that such risks are properly managed. At the project planning stage the risk assessment might indicate no obvious public safety concern. However, at that stage the design and/or construction method is not known with certainty, and there is often inadequate information on geology/hydrogeology and conditions of the sensitive receivers to establish the magnitude of the geotechnical risks. Hence, continual review is essential.

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5.2.5 Some geotechnical risks are design- or construction method-related. Consequently, evaluation of the tunnel alignment/layout design and construction methods is an important step in managing the geotechnical risks, in that exclusion of particular layout designs or construction methods could avoid specific risks. In some cases, the project/contract may need to exclude layouts, designs or construction methods that are not acceptable based on risk management considerations.

5.2.6 In major public works projects, the project manager is required to prepare a Risk Management Plan (ETWB, 2005a) covering the risk management strategy/activities, responsibilities and items of risks in the project risk register. A similar approach is also adopted in some major private projects (e.g. railways).

5.3 GEOTECHNICAL HAZARD IDENTIFICATION AND RISK ASSESSMENT

5.3.1 Geotechnical Risk Assessment (GRA) is the process of identifying the geotechnical hazards and associated risks posed by the proposed tunnel alignment and works and methods of construction, evaluating their potential consequences and likelihood of occurrence, both during construction and in the long term, together with strategies as appropriate for preventive and contingent actions.

5.3.2 In order to assess the levels of geotechnical risks, the geotechnical hazards, construction methods and the sensitive receivers that are present and relevant to the proposed tunnel alignment and works should first be identified. Some typical examples of geotechnical hazards and construction method-related risks in tunnel construction are given in Annex TGN25 A1.

5.3.3 All geotechnical hazards affecting a project, the design- and construction method-related risks, and evaluation of these items of risks should be recorded in the overall project risk register. Individual items of risk should be assigned to designated “risk owners”, and the risk acceptance criteria should be established. Typical format of a risk register can be found in Clayton (2001) and ETWB (2005a).

5.3.4 Site investigation, including a comprehensive desk study, site reconnaissance, a carefully designed project-specific ground investigation and a condition survey of the sensitive receivers, is an essential element in identifying geotechnical risks (GEO, 2005). In Hong Kong, it is a requirement to include a Preliminary Geotechnical Appraisal in the Technical Feasibility Studies (for public works projects) or a Geotechnical Assessment (for private projects, see PNAP No. 78) incorporating an engineering interpretation of the results of the desk study, site reconnaissance and any preliminary ground investigation available. This allows an early identification of the geotechnical hazards and risks and the possible methods of mitigation. The adequacy of ground investigation to locate the soil/rock interface and corestone-bearing ground as well as problematic ground (e.g. marble cavities) where ground treatment is needed prior to excavation should be carefully evaluated, both before tender and during construction.

5.3.5 Determination of the relative ranking of each geotechnical risk should be carried out using semi-quantitative or qualitative risk assessment techniques. This enables the prioritisation of geotechnical risks for mitigation and the identification of geotechnical risks that already meet practicably achievable and tolerable levels and can be accepted without the need for active mitigation.

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- 5.3.6 A staged assessment approach, comprising preliminary, secondary and final detailed evaluation stages, has been recommended by Burland et al (2001) for evaluating the effects of tunnel works on adjacent facilities such as buildings, structures and utility services.
- 5.3.7 As part of the GRA, stability and impact assessments should be carried out. These should include calculations and analyses to demonstrate that the proposed works will be stable and will not cause adverse impact to sensitive receivers, both during construction and in the long term. Particular attention should be given to brittle facilities and areas of ground that could collapse in a brittle manner. The cumulative impact on the sensitive receivers due to the proposed works and nearby projects (e.g. cumulative settlement) should be assessed. The assessments should also examine the adequacy of the criteria proposed to protect the permanent tunnel works in the operational and maintenance stages.
- 5.3.8 The documentation of the results of the GRA process should include a statement of the scope of the proposed works and the anticipated or proposed construction methods, equipment and procedures (Method Statement); an assessment of constructability of the works; the risk acceptance criteria and their basis; the sensitive receivers (including members of the public) and their vulnerability; an assessment of the magnitudes of the potential impacts posed by the works on the ground and their effects on life and property (see Annex TGN25 A1), taking into account the interpreted geotechnical conditions and any geotechnical hazards and risks and failure mechanisms and triggers identified; and an assessment of gaps or deficiencies in the site investigation data and an evaluation of their significance for the GRA, the design and other aspects of the project.
- 5.3.9 The results of the GRA should also include Geotechnical Risk Mitigation Plans (see Section 5.4), including any additional ground investigation field/laboratory work and condition survey and monitoring required prior to construction, in order to reduce uncertainties sufficiently for effective risk management.

5.4 GEOTECHNICAL RISK MITIGATION PLANNING

- 5.4.1 The purpose of geotechnical risk mitigation planning is to identify and implement cost-effective actions that will eliminate the identified geotechnical risks or to reduce them to practicably achievable and tolerable levels. With this information, particular mitigation options can be selected where the risk levels cannot be accepted and specific action identified. For example, at the project planning stage, where project constraints allow, the tunnel alignment should be selected to avoid construction close to existing foundation piles and areas of difficult ground that require costly geotechnical risk mitigation works. For TBM tunnelling, the locations of intervention for maintenance of TBM and the ground treatment and other risk control measures required for intervention should be planned taking into account problematic ground.
- 5.4.2 Mitigation actions during construction should be recorded in Geotechnical Risk Mitigation Plans (GRMP), which are formal instructions to the designated risk owners to undertake preventive and precautionary measures for particular geotechnical risks. Tracking of the GRMP is required to monitor the status of risk management activities and to determine whether risk mitigation has been undertaken and is effective. The actions under the GRMP have to be continually reviewed for effectiveness until the geotechnical risks are deemed to have been

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removed or reduced to tolerable levels. GRMPs should include risk control limits, actions needed when the limits are reached and the action parties.

- 5.4.3 The human resource requirements for managing geotechnical risks and the responsibilities that the risk owners have toward the risk management process need to be defined. The risk owners should be responsible for ensuring that the items of geotechnical risks assigned to them are adequately managed, with the action taken and the basis of decisions made documented.
- 5.4.4 Qualified geotechnical professionals with relevant tunnel works experience should be employed to carry out the geotechnical risk identification, the GRA reviews, and the preparation and updating of the risk register and the GRMP. The experience and responsibility level of such persons should be commensurate with the potential consequences of the decisions to be made, especially where there are public safety implications. The person responsible should review the design and provide input on the decision to commence the excavation, and should be given the authority to instruct measures to be undertaken on site immediately when ground or groundwater conditions worse than those assumed in the GRA or the design are encountered.
- 5.4.5 The project manager should, with the assistance of the geotechnical professional responsible for risk management, prepare a Site Supervision Plan (SSP). The typical contents of a SSP covering the geotechnical aspects of government and private projects are given in Appendix A of ETWB (2005b) and the Code of Practice for Site Supervision 2005 (BD, 2005) respectively.
- 5.4.6 Where the geotechnical risks have public safety implications, there should always be technical auditing of the standard of the GRA and implementation of risk mitigation actions at all critical stages of design and construction. The auditors should be qualified geotechnical professionals with adequate relevant experience. It is good safety management practice for the client of the project to directly engage the auditors to ensure independence from the project management staff, designer, contractor and the site supervision team, so that public safety considerations will be given due weight relative to contract programme and financial considerations. For complex designs, the client should consider to appoint qualified professionals independent of the designer to carry out a detailed checking of the design.
- 5.4.7 The Observational Method (OM) has the potential to achieve saving of time and money in projects involving tunnel works without compromising safety. Nicholson et al (1999) describe the OM as a continuous, managed, integrated process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction. All these aspects have to be demonstrably robust. The OM should not be used where there is insufficient time to implement the planned design modification or emergency plans, e.g. brittle collapse. Peck (1969) discusses the advantages and limitations of the OM and recommends its conditions of use, which should be observed in implementation. Muir Wood (1990) and Powderham (1994) revisit Peck's initial work to add to the thinking on the use of the OM in tunnelling.
- 5.4.8 The OM involves preparing the design covering the most probable ground conditions (i.e. the design condition most likely to occur in practice), with allowance made for the possibility that the most unfavourable ground conditions (i.e. the worst conditions, including groundwater conditions, or the worst credible set of geotechnical parameters that the designer considers might occur in practice) will occur. A suite of designs should be prepared and incorporated in

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the design documentation for possible implementation depending on the encountered ground conditions.

- 5.4.9 The implementation of the OM requires robust inspection and monitoring and geotechnical site supervision to be put in place, as critical design decisions have to be made on site in a timely manner to manage the geotechnical risks. When the OM is to be used, the designer should incorporate suitable provisions in the design and contract documentation for implementation of the inspection, monitoring and review programme and contingency plans, and recommend requirements for geotechnical site supervision by qualified professionals.

5.5 RECORDING, MONITORING, REVIEWING AND RISK COMMUNICATION

- 5.5.1 Appropriate geotechnical instrumentation should be installed to monitor the critical parameters required for risk control, verification of significant design assumptions and reviewing of the performance of the temporary and permanent works. These could include groundwater pressures, ground movements and vibrations, and the distortions, displacements and vibrations of adjacent facilities caused by the works. In addition, the affected facilities should be inspected, and representative baseline conditions and the method of interpreting the acceptability of deviations from the baseline established well before construction commences. Guidance on monitoring for tunnelling is given in ITA (2009).
- 5.5.2 A reporting system should also be put in place to ensure effective communication of risk mitigation actions. Where the response values are reached or abnormal response is observed, then the pre-defined contingency or remedial action needs to be taken in a timely manner. There should be a mechanism for reviewing the opportunity to reduce instrumentation and the frequency of monitoring where appropriate.
- 5.5.3 The geotechnical risk management process does not take place in isolation from other project activities. Communication of risk information and consultation with the project participants responsible for other areas of project implementation, as well as the major stakeholders including the concerned public, are two-way processes that should be proactively undertaken and should continue throughout the duration of the project.
- 5.5.4 The geotechnical risk management process should take place at all levels of the project organisation. Geotechnical risks should be reported to a central point to achieve an overview of the whole project in risk terms. This can be achieved by requiring particular service providers (typically consultants and contractors) to report on the status of a risk management/mitigation activity and its effectiveness.

6. ANNEXES

- 6.1 TGN25 A1 – Typical Examples of Geotechnical Hazards and Risks in Tunnel Construction

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TYPICAL EXAMPLES OF GEOTECHNICAL HAZARDS AND RISKS IN TUNNEL CONSTRUCTION ^(Note 1)

Examples of Geotechnical Hazards	Risk Treatment Options
Variable rockhead and mixed ground conditions	Avoid/reduce the risk, e.g. by selecting a suitable tunnel alignment based on adequate site investigation
Presence of buried obstructions or voids (e.g. corestones, boulders, disused piles, old seawalls, cavities in karst and other artifacts)	
Presence of foundations and other subsurface installations	Reduce the risk, e.g. by specifying or selecting appropriate tunnelling method(s) with adequate additional site investigation during construction
Presence of permeable zones that may be subject to high groundwater pressure or that may convey large quantities of inflow	
Presence of weak or compressible ground (e.g. weak/fractured zones, faults, fissures, clay-coated discontinuities, granular soils and soft/compressible soils). Ground under very high or very low insitu stress	
Presence of explosive or poisonous gas (e.g. methane) or other aggressive chemicals	Treat the risk, e.g. by specifying appropriate ground support (e.g. precast segmental linings with back grouting), ground strengthening, groundwater control and containment measures, and implementing preventive or protective works
Salinity of groundwater	
Contaminated ground, e.g. due to ingress of leachate from landfill	

Examples of Construction Method-related Risks	Associated Tunnelling Method ^(Note 2)
Excessive ground settlement/lateral displacement due to ground loss (including rock falls within the tunnel, tunnel face collapse and loss of soil into surrounding voids) or inadequate ground support caused by unsuitable tunnel construction method/equipment/control measures	All methods
Excessive ground settlement/lateral displacement due to groundwater inflow/drawdown caused by inadequate tunnel construction method (e.g. pre-grouting not carried out in difficult ground), or inadequate ground treatment or groundwater control or inadequate consideration of changes in ground stresses or groundwater regime	All methods
Excessive ground vibration	All methods that use vibratory equipment, or that could induce ground vibration such as D&B
Ejection of rock and protective material (e.g. blast door) at the tunnel portal or areas with a thin ground cover, due to explosion and/or gas pressures	D&B ^(Note 2)
Blow out or ground heave for tunnelling under high compressed air or slurry or grouting pressure	All methods that create pressure in the ground, e.g. compressed air or slurry TBM ^(Note 3) and grouting

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Notes:

1. The typical examples of geotechnical hazards and risks listed above serve as reference only and are not exhaustive. Adverse impact on life or property and losses are often not ascribable to one single cause. There are often several combined factors that lead to adverse consequence and a loss event (Barton, 2004; Munich Re Group, 2004). Designers should exercise their engineering judgement in evaluating all possible geotechnical risks in relation to their projects.
2. Common tunnelling methods include use of the cut & cover method, Tunnel Boring Machine (TBM), drill & blast (D&B) method including use of mechanical excavation techniques (ITA, 2009), the Norwegian Method of Tunnelling (provision of support to the rock mass based on the NGI Q-system (Barton & Grimstad, 1994)) and soft ground tunnelling techniques (which include use of the New Austrian Tunnelling Method, ground treatment such as grouting or ground freezing, and groundwater control such as use of recharge wells). BTS/ICE (2004) provides technical guidance for the design of structural linings for all manner of driven tunnels and shafts to be constructed in most types of ground conditions.
3. TBM can be adopted for tunnels in rock (with or without shield) or in soil or mixed ground (with shield supported by earth pressure balancing, slurry or compressed air). A competent professional engineer with relevant experience, with the assistance of a qualified geotechnical professional, should prepare the specification of the TBM and the associated risk control requirements. In the above table, the guidance applicable to TBM also applies to micro-tunnelling (including horizontal directional drilling) and pipe-jacking methods.