Tunnelling in Difficult Ground: How the Geotechnical Baseline Report Helps

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ABSTRACT

ABSTRACT: The design of tunnels and their subsequent construction can involve a high level of risk, especially with respect to unforeseen ground conditions or constructability issues. The management of such risks is essential and critical, and for the Tsuen Wan Drainage Tunnel (TWDT) was implemented by the inclusion of the Geotechnical Baseline Report (GBR) into Tender Documentation. The GBR included characterization of the geotechnical parameters and the geological conditions, in such a manner so as to allow the definition of an appropriate construction methodology, and optimal excavation and support techniques. This paper describes how the ground condition risk was managed on this Project utilising a custom-built Double Shield Tunnel Boring Machine (TBM), highlighting the use of detailed geotechnical characterisation as the primary driver for offsetting risk from unforeseen or changing ground conditions during tunnelling.

1 INTRODUCTION

1.1 The Use of the Geotechnical Characterization in Offsetting Risk

The design of underground works has traditionally followed a deterministic approach, based on indirect management of the potential risks through a series of predetermined project decisions. In reality however both the design and construction phases are imbued with a certain degree of uncertainty, particularly with respect to the nature of the characteristics and their spatial variation, the behaviour of the rock mass and the level of knowledge of these factors acquired during the different stages of the Project.

Geotechnical characterisation for mechanized TBM tunnelling is of paramount importance, due to the low adaptability of such methods to changing ground conditions that are often inherent in linear underground excavations. Although TBMs are widely used, such is not a risk-free technology. Encountering geological and hydrogeological conditions different from those foreseen at the design stage may result in problems and risk, which may have significant effects on the program and safety, if such are not properly managed.

The basic concept of the GBR is to establish a realistic, common basis for all the contractors to use in preparing their bids and subsequently a basis for evaluating any contractor claims for differing site conditions that developed during construction (U.S. National Committee on Tunnelling Technology, 1974). Therefore, the GBR shall be considered the baseline to define and evaluate the risk tolerance and the vulnerability of the Project, and to develop a managing scheme to address the foreseen risks (ITA, 2002). Furthermore, the GBR shall be considered complimentary to the allocation of responsibilities for managing and mitigating such risks, including the residual risk, and to increase the probability to be sheltered from economic lost and damages (Kovary, 2002).

Given the above factors, promoting the use of a detailed geotechnical and geological characterisation, as one of the primary drivers for offsetting risk from unforeseen or changing ground conditions, during the tunnelling operations, is considered essential to ensure the proper and efficient management of the risk.

1.2 Targets and Residual Risk

A main task of geotechnical design is to achieve the economic optimisation of the construction, taking into account the ground conditions, in particular the safety, the long term stability and environmental requirements. The variability of the geological conditions, including the structural geology, ground parameters and stress and ground water conditions requires that a consistent and specific procedure be used in the design process. The key influences governing the geotechnical design are the ground conditions and ground behaviour.

Thus, a certain degree of uncertainty and therefore a level of risk are not completely avoidable despite the experience, the time, and the costs incurred (Carol, 1992). In fact, the level of knowledge of geological parameters, which may well constitute the principal source of project risks, may be limited by the nature of the characteristics of the medium and the spatial variation and behavioural pattern of the rock mass (i.e. the geological asset). Furthermore, limitations in site investigation during the construction phase, must also be considered, especially when such could interrupt the tunnel advance.

1.3 The GBR

Detailed geological, geotechnical and hydrogeological characterisation, along the length of the TWDT alignment was undertaken, in the form of a GBR and a Geotechnical Data Report (GDR).This established the baseline ground conditions for the Contractor to take into account during the Tender and Contractor Design process, and these reports represented a contractual statement of the subsurface conditions be anticipated to be encountered during the construction of the tunnel.

The provision of such a detailed characterisation from the onset of project enables the Contractor to have a deeper understanding of the project, to be better able to optimise construction methods and techniques and to formulate a more detailed and informed Risk Analysis. The economic benefits, to both the Contractor and the Employer, are also baselined (Kovari, 2002).

1.4 Application of the GBR

The GBR describes the anticipated ground conditions with which the tunnel and associated structures will be constructed, and based on such the Contractor, and his Designer, can produce an effective design, formulate his construction methods and techniques and formulate an informed Risk Analysis and develop a comprehensive Risk Management Plan. The GBR details and describes the geotechnical and geological rock mass and material characteristics including rock mass and material strength, abrasivity, drillability and cuttability. It also details and describes the anticipated hydrogeology, in order that the control of groundwater, both in terms of drawdown, and the effects of such on existing buildings and structures (EBS) and features, and water inflow into the tunnel, can be ascertained. This is particularly pertinent for those areas of particular concern highlighted e.g. in the fault zones and areas of low rock cover. All of the above are relevant to the choice of the excavation technique, the type of TBM to be used and, the management of the design and construction, particularly with reference to efficiency and productivity which could be achieved.

2 THE TSUEN WAN DRAINAGE TUNNEL

2.1 Project Description

The existing drainage facilities in the Tsuen Wan and Kwai Chung areas were constructed over 30 years ago. Those do not now have sufficient spare capacity to handle the additional stormwater run-off arising from the continuing urbanization of these and surrounding areas, resulting in greater risk of damaging flooding, particularly during severe weather conditions. The TWDT will operate by intercepting excess stormwater from the upland catchment areas and conveying such to direct discharge to the sea.

2.2 Project Characteristics and Geology

The TWDT has been designed as a 6.5m internal diameter, circular profile tunnel, with a 7m excavation diameter, and a length of approximately 5.1km. It is concrete-lined with a 3,500m undrained length.

The tunnel was driven through predominantly extremely strong and abrasive, fresh rock (tuffs and granodiorites of the Tsuen Wan Volcanic Group) with a variety of cross-cutting dykes (including basalt, rhyolite, fine-grained granite, and quartz). The tunnel alignment also traversed a number of faults and fault zones, generally consisting of blocky and highly fractured rock, and with a variety of mixed soil and rock conditions (e.g., from highly to completely decomposed rock, to mixed soils with corestones and residual soil). The effects of these ground conditions were exacerbated by the close proximity of the tunnel to existing major infrastructure (existing Water and Railway Tunnels) and locations with shallow overburden.

2.3 Project Requirements

Severe constraints and specific requirements were imposed in order to minimise the impact of the construction to the public and on the environment, such as the adoption of a ground treatment programme for the stabilization of the tunnel excavation (it was expected that mechanical excavation may have to be carried out together with progressive installation of initial supports, in areas of poor ground, to best suit the extant ground conditions) and to mitigate against potential ground movement and water draw-down. In particular, pre-excavation grouting was carried out at specific locations, including the Fault Zones as identified in the GBR, and at the locations of sensitive ground level installations, such as existing Water Supplies Department facilities. Criteria for the control of groundwater inflow were specified in the Contract Documents.

2.4 Excavation Methodology and Choice of TBM

The anticipated geotechnical conditions, in conjunction with the course of the route and the tunnel gradient, represented the decisive pre-requisites for the selection of the tunnelling method. By taking into account the tunnel shape and cross-section, its length and the geotechnical conditions, and the available technology, the most suitable tunnelling machine could be procured. When selecting appropriate tunnelling technology, the environmental compatibility of the tunnelling methods must also be taken into consideration. A project-related analysis was however essential and represented the main basis for the approach (ITA-AITES WG14. Recommendations and Guidelines for Tunnel Boring Machines, 2000),.

Among the various environmentally-related hazards (natural and anthropic types) and construction equipment related hazards, the principal TWDT construction hazards were identified and distinguished into two main categories - geological hazards and induced geotechnical hazards related to the excavation behaviour of the rock mass. A similar approach was followed in listing the construction equipment-related hazards, and the main mitigation measures were determined in order to contain the construction risk to an acceptable level.

The objective of this evaluation was to ensure an appropriate machine choice, considering the possible hazards involved. A brief example evaluation is presented in Table 1, where a rate value of applicability (o = difficult application, oo = applicable, ooo = ideal field of application) has been assessed for each TBM type considered suitable for this Project.

Table 1: Evaluation of the Influence of Tunnelling Hazards in the TBM-type Selection

Tunnelling Hazards	TBM TYPE		
	OPEN	SINGLE SHIELDED	DOUBLE SHIELDED
Abrasive/Hard rock	000	0	00
Rockfall, rock wedge instability (overbreak)	0	00	00
Caving ground	0	00	00
Water inrush	000	00	00

The outcome of the evaluation indicated the adoption of a Double Shield TBM (DSTBM) and such requirement was included in the Contract. In fact, in lieu of an average lower production, double shield TBM has the advantage of the provision of radial grippers, and longitudinal thrust rams pushing off the tunnel lining (depending on the geological condition encountered), and therefore was bettered-suited for the heterogeneous ground conditions present.

The added advantage of the DSTBM is that boring can proceed utilising the grippers, whilst the lining ring is being erected.

The circular profile was chosen to facilitate mechanized tunnelling and to improve the efficiency, productivity and cost-effectiveness of the construction. The adoption of segmental concreted lining improved the hydraulic performance of the tunnel increasing its capacity, with the precast segments augmented by the mechanical efficiency of the TBM facilities

3 THE GBR OUTLINE

3.1 Site Investigation and Laboratory Tests

An extensive ground investigation programme was undertaken for the TWDT, comprising ground investigation field work by drilling and trial pit excavation, with associated field and laboratory testing, and installation of piezometers, for the purpose of assessing the ground conditions (BS 5930:1999). The methodology, scope and layout of the ground investigation works were fully detailed in the GDR. A brief summary of the site investigation and laboratory tests is presented in Table 2.

Table 2: Summary of Boreholes, Site Investigation and Laboratory Testing

Boreholes	Vertical (m)	Inclined (m)	Total
No. boreholes	56	23	79
Borehole length	3505	2356	5861
Rock core obtained	3093	2079	5172
Lugeon Tests (rock mass permeability)			228
Core bulk density			46
Cerchar Abrasivity Index (standard fracture surface)			60
Vp			38
Tensile strength			55
Point Load Test			394
UCS			204
E_{Young}			94

3.2 Fault Zones

The GBR detailed anticipated fault zones on the tunnel alignment, giving indications as to their possible extent, and the ground conditions likely to be experienced. The faults detailed in the GBR, included those where very closely-jointed rock mass could be expected, and particularly focused on seams of soil-like material (fault gouge) which could potentially contain water under high pressure and therefore be prone to loosening, ravelling, flowing and collapse, in the absence of effective support and ground treatment.

Fifteen fault zones were identified, along with approx. 430m of tunnel where severe ground conditions could be expected to affect tunnel progress. Particular emphasis was placed on the encroaching of the fault zone at the eastern portal (Wo Yi Hop Intake) where an extensive fault, >120m was expected, with associated adverse ground conditions, due to fractured, weakened and severe rock decomposition indicated.

3.3 Critical Conditions and Possible Consequences

The following critical ground conditions were highlighted:

i) Possible fracture zones with increased permeability in saturated conditions; which could imply high pressure water inflows with consequent instability of the tunnel face and/or difficulties in the operations in the tunnel. Occurrence of high pressure water inflow must be considered during excavation, with possible washing-out of the soil/rock matrix and crown instability;

ii) Occurrence of fault zones characterized by gouge bearing fault rocks; in the case of large fault zones, this could lead to difficulties during excavation, and to possible severe caving although “Squeezing” conditions were not considered likely;

iii) Occurrence of high strength rock mass at the decametre – hectometre scale; such could severely hamper the TBM performance or even require by-passing the TBM, to excavate by drill and blast (in case of significant length of the sector to be excavated within).

Based on the GBR, specific requirements were included in the Contract with respect to the TBM type (double shield TBM) and to pre- and post-grouting treatment, in order to address the stabilisation of the tunnel excavation and to mitigate against water draw-down and potential ground movement.

3.3.1 Abrasive and Strong Rock Occurrence

Abrasive rock is a significant factor in tool and cutterhead wear, and to the design of the excavation and in the design of the TBM. In the case of hard rock, the compressive and tensile strength strongly influenced the applicability and productivity of the TBM. For all TBM types, the machine architecture, the installed power at the cutterhead, and the choice and design of the cutting tools and cutterhead, are conditional upon the strength of the ground, particularly for single shielded TBMs, which are sensitive to high strength because of the thrust reaction force through the rams, reacting against the tunnel lining.

The expected wear can be countered by the use of boring or extraction additives, and protection or reinforcement to sensitive TBM parts. In all cases it is essential that cutting tools can be quickly and safely removed, and replaced from within the excavation chamber.

Cutter wear prediction can be made using the "Rock Mass Excavability Index" (RME) (Bieniawski, 2006). As well as the basic purpose of evaluating rock mass excavability, in terms of TBM performance, RME can be correlated to cutter consumption per excavated cubic metre; assumption valid for rock with UCS values of intact rock >45MPa (Bieniawski, 2009). The results are presented considering three levels of variation of CAI (CERCHAR Abrasivity Index) (i.e. CAI>3, 1.5<CAI>3, and CAI<1.5).

From the GBR Data and analysis, CAI>3 should be chosen in order to evaluate cutter consumption during construction; e.g. for location, Chainage 3150-2380, where 65<RME<80 was expected, the changed cutters/excavated m^3 was expected to vary from 0.005 to 0.001, with such corresponding to 540-1400 changed cutters for this location. Substituting as-built records into the proposed formula, the results show a better performance in the maximum cutter consumption (0.01138), significantly improved from the prdicted (0.0139) which was confirmed by the total average cutter replacement (586) which is close to the predictable lower limit (544) for the same tunnel section (Bieniawski, 2009).

Whilst this exercise indicates an appropriate choice of cutter wear, the shape and dimension was made by the contractor, whilst its reliability confirms the accuracy of the GBR data.

3.3.2 Caving Ground and Water Table Drawdown Control by Ground Pre-treatment and Probing Ahead

The GBR anticipated caving ground and water-table drawndown hazard at fault and shear zones, where ground conditions indicated the possibility of very low self-support. The nature of this hazard strongly influenced the choice of TBM and its characteristics (e.g. precluding the application of an open TBM). In fact, the project's requirements regarding the ground pre-treatment ahead of the excavation face, where fault occurrence was expected, demanded that systematic probe-drilling be carried out, which had a significant effect on TBM progress. Therefore the adoption of a double shield TBM was determined, despite its average lower progress, in lieu of an open TBM, with the added advantage that a it also ensured safer working conditions, and more flexibility in adapting to changing ground conditions.

Probing ahead was a fundamental operation enabling the Contractor, and the Designer, to locate potential critical conditions ahead of the tunnel face. During probe-drilling the main drilling parameters (advance speed, torque and thrust at least) were recorded and correlated with the expected geology and with the TBM performance parameters. Normal practice required the installation of high-performance drilling equipment, positioned within the TBM shield allowing advance drilling around the cutterhead (within 4º degree minimum to the tunnel wall, after Garshol K.F., 1997) and through the cutterhead (see Figure 1).

If probe-drilling did not reveal detrimental conditions, normal TBM procedures were applied. However, if detrimental conditions were detected, appropriate ground treatment (pre-grouting and pre-drainage) was carried out.

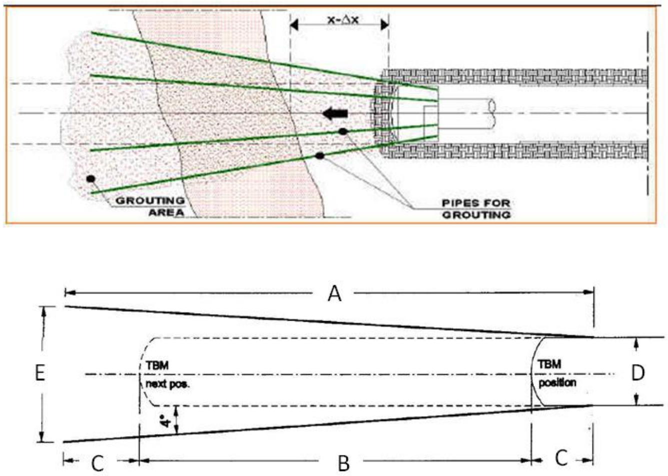

Figure 1: Illustration of grouting/drainage in advance of TBM excavation

3.3.3 Ground Treatments Typologies and Criteria of Application in TWDT

The efficiency and effectiveness of the ground treatment was strictly related to the geotechnical characteristics, and to the geometry of the ground to be treated. Therefore, the GBR was essential for proper design of the mix design, the injection pattern and grouting technique.

Ground treatment is normally carried out by pressure grouting, comprising drilled boreholes of suitable diameter, length and direction, aided by packers and grouting pipes, into which pre-prepared grout, at variable pressure, is pumped, with a view to achieving a consolidation of the ground ahead, and improving the long-term self-support of poor ground and rock conditions, and to reduce rock mass permeability. Ground treatment relies on the injection of cement grouts, with stabilizers or admixtures (common cement, microfine cement) as necessary or chemical grouts (resins and gels) and/or combinations of them both. Such grouting is additional to standard tunnel support measures, such as ground reinforcement, fiber glass dowels, self-drilling anchors and steel pipes canopies and ribs.

Due to the limited available work-space, ground treatment from within the tunnel is often a critical activity owing to high cost (e.g. average cost of tunnel face time is worth normally more than over 2,000USD$/hr). Grouting is time-consuming and therefore whenever possible, advanced ground pre-treatment, from the surface, where such is feasible and cost-effective can be considered.

In-situ permeability tests are normally performed to assess the most suitable mix design, and detailed site investigation is carried out to determine such.. Nevertheless cement-based grouts still remain the most effective, and affordable, and a wide range of microfine cements are now available on the market, if a high penetration rate is required. However chemical grouts may still be required to deal with those joints where cement grout cannot reach. The penetration distance for a given volume, depends on the viscosity and pressure used and therefore the effectiveness of chemical grouts, consisting of only liquid components, is higher because they have 'viscosity' but not cohesion, and minimal friction.

The effectiveness of grouting in tunnelling can be enhanced by implementing stages of the treatment, and grouting behind the tunnel face (post-grouting) can be considered a supplement to pre-grouting. However the use of post-grouting only is far less effective and efficient and the total cost to achieve targets can be 2-10 times higher than if associated with pre-grouting (Garshol, 2003).

Permeability tests were used to define the cut-off criteria to apply during grouting (e.g. grouting pressure, volume and grout-setting time) and to define the most suitable equipment and material.

In this project stringent requirements were introduced for the stabilisation of the tunnel excavation and as mitigation against potential ground movement and water drawn down, particularly in the fault zones, where pre-excavation grouting was required for ground stabilisation and groundwater exclusion from the tunnel ahead of the excavation face. Additional criteria were also set for groundwater control into the tunnel, both in the short and the long terms, and to avoid any adverse impact on existing structures and features, with such criteria assessed based on the water inflow measured into the probe hole (ph) and the excavated sections of the tunnel (tu), considering three levels of variation of water inflow i) lt/min/25m ph>10, ii) lt/min/25m tu>10, iii) lt/min/100m tu>35.

3.4 Monitoring

In order to record the influence of the tunnelling works, a specific monitoring system is necessary, and such should include procedures for prompt data collection and interpretation, as well as communication, to control in-ground deformation and surface movement, to validate proposed consolidation and support measures and to control the tunnel alignment. Alert, Alarm and Action (AAA) limits should therefore defined for the overall set of monitored parameters, to cover critical scenarios and in order to control residual risks.

Certain monitoring requirements were identified and specified in the Employer's Requirements indicating the minimum zone of influence, and highlighting particular existing structures and features, which had to be included in any monitoring system, and specific AAA limits and vibration values were given. The monitoring included the performance of the TBM to form the tunnel to the required shape and alignment, with tolerance limits specified.

Based on the GBR hydrogeological and piezometric data, specific criteria were introduced to control underground water drawdown in order to avoid any adverse impact on existing structures, resulting from water inflow to the tunnel and specified the action to be taken

A brief summary of the monitoring values and water draw-down criteria, are given in Tables 3 and 4, respectively.

Table 3: Summary of Monitoring Limits for EBS structures during the execution of the TWDT

EBS Type	Ground Movement Monitoring (mm)			Vibration Monitoring (Prolonged Vibration)	
	Alert	Action	Alarm	PPV (mm/s)	Amplitude (mm)
Buildings	8	12	15	15	0.2
Water retains structures	3	4	5	13	0.1
Existing Tunnels	3	4	5	13	0.1
All other EBS including Buried Utilities	25	40	50	25	0.2
TWDT Tunnel (Segmental lining)	Ovalisation (%)	Deviation (horizontal) (mm)	Deviation (vertical) (mm)	PPV (mm/s)	Amplitude (mm)
	1^	75	75	50	0.6*

Note: ^ BTS (2000); * BS7385 - Maximum displacement allowable = 0.6mm (frequency range lower than 4Hz)

Table 4: Summary of the Water Drawdown Control Criteria during the execution of the TWDT

Criteria	Description	Total water discharge (lt/min/m)
1	Discharge greater than, after completion of 25m length probe hole	10
2	General inflow greater than, for the excavated section within25m of the current face	20
3	Inflows of more than, over any 100m length (shorter excavated section to be calculated on pro-rata basis), or a concentrated inflow at any particular location	35 2

Should any of the "criteria" be exceeded pre-excavation and/or post-excavation grouting was required and no further excavation, at the particular developed face, could proceed until the grouting had achieved the criteria.

Regardless of inflows met the first criteria in the proximity of the existing waterworks facilities, pre-grouting was required.

The Project also required the implementation of a Tunnel Data Management System (TDMS), which was web-based, a digital database of real-time construction information including relevant construction information, as well as ground movement and instrumentation records.

3 CONCLUSION

In order to mitigate the risks inherent in the construction of TWDT, a detailed GBR was implemented, and the detailed geological and geotechnical data was considered the primary driver for offsetting such risks from unforeseen or changing ground conditions during the construction phase.

Furthermore, additional necessary precautions and relevant to the Construction Phase were included into the Tender Documentation, including:

- ✓ To adopt the proper method of excavation, which serves as a primary countermeasure for limiting instability and collapse.
- ✓ To set up a strict control of the secondary countermeasures for limiting the eventual instability.
- ✓ To set up an alarm system that is activated when threshold values are exceeded or not met.
- ✓ To elaborate the method statements to ensure the correct use of the construction methodology, and such shall also include the actions and the information procedures to face anomalous events.
- ✓ To create follow-up team (composed of the Construction Management and Representatives of the Contractor) to verify the systematic interface of the key parameters and the process of design, construction, monitoring, and design modifications.
- ✓ To develop project interfaces at the levels of design, monitoring, and analyses. Real time access to the system was be given to all the involved Parties.

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REFERENCES

Bieniawski, Z.T., Celada, B., Galera, J.M. and Alvarez, M.(2006). "Rock Mass Excavability (RME) Index". Proc. ITA World Tunnel Congress, Seoul, Korea.

Bieniawski, Z.T., Celada, B., Galera, J.M. and Tardaguila, I. (2009). "Prediction of cutter wear using RME". Proc. ITA World Tunnel Congress, Budapest, Hungary.

BS 5930:1999. Code of practice for site investigations

Carter, T.G. (1992). "Prediction and uncertainties in geological engineering and rock mass characterization assessment". Proc. 4th International Rock Mechanics and Rock Engineering Conference - Paper 1, Turin, Italy.

Garshol, K.F.(1999). "Use of pre-injection and spiling in front of hard rock TBM excavation". Proc. 10th Australian Tunnelling Conference, Melbourne, Victoria, Australia.

Garshol, K.F.(2003). "Pre-excavation grouting in rock tunneling". MBT International Underground Construction Group, Switzerland.

ITA-AITES(2000). "Recommendations and Guidelines for Tunnel Boring Machines (TBMs). Working Group No.14. Mechanized Tunnelling, International Tunnelling Association.

ITA(2002). "Guidelines for Tunnelling Risks Management". Working Group No.2, International Tunnelling Association.

Kovari, K. (2002). "La sicurezza del sistema nel campo della costruzione di gallerie in aree urbane – L'esempio della galleria Zimmemberg". Gallerie e grandi opera sotterranee XXIV n.68 – Dicembre, 31-46, Patron Editore, Bologna, Italy.

U.S. National Committee on Tunneling Technology of the National Academy of Science (1974). "Better Contracting for Underground Construction". Report No. DOT-TST-76-48. Recommendation 2.