

Risk assessment steps and challenges in rock tunnel projects

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ABSTRACT

The construction of underground structures is directly linked to the geological context, the characteristics of the ground, its behavior, and its evolution. Despite all the efforts made to recognize ground by means of boreholes, geophysical surveys and in situ and laboratory tests, knowledge of the ground condition always involves a degree of uncertainty which can have serious consequences on the construction, as much for the contractor who carries out the work as for the owner who finances it. Geotechnical risk assessment is a process that must be repeated at all stages of the project from the feasibility study to its construction and exploitation. In this paper, the sources of risk, generally linked to ground conditions, their assessment and the methodology used to evaluate the risk of one of the major tunnel projects in Quebec are presented. The challenges encountered during each phase of assessment and treatments proposed to be used during construction are discussed.

RÉSUMÉ

Le contexte géologique, les caractéristiques des sols et du roc, ainsi que leur comportement anticipé, représentent un enjeu primordial dans tout projet de construction en souterrain. Malgré les efforts déployés pour la réalisation des études géotechniques approfondies, il reste toujours des inconnus et des imprévus qui peuvent mener à des conséquences catastrophiques tant pour l'entrepreneur que pour le client-proprétaire. L'évaluation du risque géotechnique lié au sous-sol est un processus complexe et évolutif qui doit être mis-à-jour à toutes les étapes de l'avancement du projet. Le présent article présente une méthode d'évaluation qualitative de risque qui s'appuie sur un exemple d'évaluation effectué sur un important projet de tunnel au Québec. Les défis rencontrés à chacune des étapes du projet ainsi que les traitements proposés visant la réduction du risque sont également discutés.

1 INTRODUCTION

Risk management in a tunnel project generally implicates various aspects such as geological, technical, mechanical, financial or political. The decisions made will have consequences on the costs and schedule of the project. Risk assessment is the formalized process of identifying hazards and evaluating their probability of occurrence and their consequence on the overall project. Mitigation strategies are a part of the process in order to call for appropriate preventative actions. A risk register must be maintained for the duration of the project since it has to be continuously updated as the project evolves and as mitigation measures are applied to reduce the risk at various stages.

The case study uses a method to assess the risk based on the ground conditions during the initial tunnel design phases by a geotechnical team hired by the owner of the project. The project consists of constructing a future public transportation tunnel in hard rock using a TBM. We will see how the initial risk assessment of ground conditions, if done early in the project, has a potential to improve the project outcome and the capability of modifying the design without major supplementary costs. The risk assessment for ground conditions covers only one aspect of the process of risk management, but it is critical that the project owner evaluates if it falls within risk acceptance criteria. The close

implication of the tunnel design team during the investigation and the concurrent interpretation of the data throughout the field work are an integral part of the investigative process by reducing the areas of uncertainties.

2 OVERVIEW OF RISK PRINCIPLES, GUIDELINES AND CODES

Several methods can be used to assess the risk in an underground project. The chosen method depends principally on the type of geology and the mechanical excavation methods used to execute the works. The better-known methods of risk assessment in tunnel projects are based on systematic risk management techniques using the same principles. The risk level, or severity, is calculated or estimated based on parameters used in the risk matrix. The frequency or likelihood in which the hazard (or danger) will occur and its consequence, from insignificant to disastrous, that can affect the project. The risk is then classified as negligible to unacceptable

In the case study presented in this paper, the owner had already prioritized an excavation method, based on the particularities of the project. In order to adequately assess the risk based on ground conditions, the team examined several options on how to assess this type of risk. Amongst the many publications consulted, two important works by

Table 1. An example of a 5-class Risk Matrix as proposed ITA, 2004

Frequency	Consequence				
	Disastrous	Severe	Serious	Considerable	Insignificant
Very likely	Unacceptable	Unacceptable	Unacceptable	Unwanted	Unwanted
Likely	Unacceptable	Unacceptable	Unwanted	Unwanted	Acceptable
Occasional	Unacceptable	Unwanted	Unwanted	Acceptable	Acceptable
Unlikely	Unwanted	Unwanted	Acceptable	Acceptable	Negligible
Very unlikely	Unwanted	Acceptable ^a	Acceptable	Negligible	Negligible

^a Depending on the wording of the risk objectives it may be argued that risk reduction shall be considered for all risks with a consequence assessed to be “severe”, and thus be classified as “unwanted” risks even for a very low assessed frequency.

international tunnelling associations and one by insurers were considered in this study. They are briefly described in the following sub-sections.

2.1 ITA / AITES

The International Tunnelling Association published the **Guidelines for Tunnelling Risk Management** in 2004, following too many front-page articles featuring spectacular tunnel collapses in the 1990s. Initiated in 1999 by the ITA Working Group No.2, the Guidelines «gives guidance to all those who have to prepare the overall scheme for the identification and management of risks in tunnelling and underground projects. This guideline provides owners and consultants with a method recommended by the tunnelling industry for best practice of risk assessment. It goes through all the stages of risk management throughout the entire project, from its early design phase to the tendering and contract negotiation phase to construction phase.

The qualitative risk assessment should be carried out during the early design stage and be focussed on the identification of potential hazards to the construction activities. The timing of this assessment should be such that major changes to the design are still possible. The assessment includes hazard identification, classification of the identified hazard, identification of risk mitigation measures, and details of the risk in a risk register. It insists that the owner must establish a risk policy as a first step, in which the risk acceptance criteria are set.

The hazard identification for the qualitative risk assessment is split between general and specific hazards. Frequency of occurrence and extent of consequences for each identified hazard form the base of the risk classification. The **Guidelines** classifies the frequency in a 5-class matrix varying from very unlikely to very likely. The consequence classification also contains 5 classes, going from insignificant to disastrous. The resulting product will define if the risk is negligible, acceptable, unwanted, or unacceptable. An example of this risk matrix is shown in Table 1.

2.2 ITIG

Tunnel collapses and other costly incidents have raised concerns amongst insurance companies, as the frequency and size of claims have been escalating to the point where insurance companies have considered to stop offering insurance in the tunnelling sector, or have increased terms

and restricted cover. In trying to tackle the issues around insuring tunnel projects, the International Tunnelling Insurers Group (ITIG) produced a **Code of Practice for Risk Management of Tunnel Works** (2012), with the objective to promote and secure best practice for the minimalisation of risks associated with the design and construction of tunnels, caverns, shafts and associated underground structures to reduce the probability of loss and the size of claims. The scope of the **Code** applies to all phases of the project.

The insurer’s industry point of view is useful because this method insists on the competence of all parties. Moreover, promotes risk assessments at each stage, provides transparency through by recording each risk into a risk register in which risk allocation is given to the most appropriate party responsible for the control and management of an identified risk. This process also ensures that each responsible party, made up of specialists in their respective fields, identifies the hazards, proposes mitigation measures, and plans pro-active actions to reduce the risk to a level as low as reasonably practicable (ALARP), a common principle to most risk assessment methods.

In the same manner as other risk management guides, the notion of risk is a function of the consequence/severity of a hazard and the likelihood of its occurrence, while a «hazard» is defined as an event that has the potential to impact on matters relating to a project, including third parties. The Risk Assessment Matrix is also based on a 5-class of likelihood and severity of consequences, as illustrated in Table 2, in which the risk is classified as High, Moderate or Low.

Table 2. An example of Risk Assessment Matrix (after ITIG, *Code of Practice for Risk Management of Tunnel Works* 2012).

		Severity Score				
		1	2	3	4	5
Likelihood Score	1	L	L	L	M	H
	2	L	L	M	M	H
	3	L	M	M	H	H
	4	M	M	H	H	H
	5	M	H	H	H	H

Of particular interest to the specific task of assessing the risk based on ground conditions, the **Code** insists on the quality of the geotechnical investigations and proposes a list of parameters that must be included in the studies and their assessments and evaluations be taken into account. These include the **geology** (as a global term which includes hydrogeology, soil and rock characteristics and properties, and the potential presence of gases), tunnelling methodologies appropriate to the nature of the ground and its environment, ground and groundwater treatment measures, ground movements and settlements and their impact on a Third Party. The second aspect is **environmental** considerations (dust, noise, vibrations, traffic, plants, presence of hazardous chemicals and pollutants), temporary and permanent ground support systems and other related costs, type of contract and particular factors for the proposed project location, geology and environment.

At the Contract Procurement stage, the **Code** states that when prepared by (or on behalf of) the owner (or the insurer's client), the Geotechnical Baseline Report (often a GBR) shall be issued to tenderers as integral and formative information on which tenders shall be based and the owner shall take full responsibility for the information so issued. The **Code** also suggests that each tenderer submit their own (risk) assessment of Ground Reference Conditions, the requirements of which shall be defined and fully described in the Contract Documentation. This also provides the owner with an insight on the competency and understanding of the ground conditions and associated risks on the part of tenderer or his team.

At the design stage, the **Code** proposes that the design process for temporary works that support the grounds during construction shall be treated as for permanent works. The design team shall ensure that the site investigation is planned and designed to obtain ground and groundwater information and geotechnical properties appropriate for the construction of the tunnel works while recognising the likely tunnelling methods that may be employed during construction and prepare a geotechnical assessment that evaluates the geological and geotechnical information available. Where appropriate, and as part of risk management, the design team shall detail excavation/support sequences and identify appropriate monitoring measures for the range of anticipated ground and groundwater conditions and shall also include for the provision of contingency measures. These measures should be pre-planned before the beginning of the tunnel works

2.3 AFTES

A major contribution for guiding us in providing our client (the owner) with a risk assessment based on ground conditions is proposed by the *Association Française des tunnels et de l'espace souterrain* (AFTES) published in 2012, which deals specifically with risks caused by hazards and uncertainties. The work titled **Recommandation sur la caractérisation des incertitudes et des risques géologiques, hydrogéologiques et géotechniques** is a collection of reflective thinking of risks and hazards with regards to everything sub-surface and its potential adverse

effect on underground works and other type of works conditioned by the risks associated with adverse ground conditions. The **Recommandation** is a thorough piece of work based on the principle that the primary risk before all construction projects can begin concerns geological and geotechnical «uncertainties». The objective is to bring and share a common methodology for assessing the risks specific to ground condition and leave the contract management risks to other parties.

The methodology is based on a three-step process that includes :

- A retrospective analysis of all the results of the geotechnical investigations (factual data), an analysis of its reliability and an listing of all remaining uncertainties;
- An appreciation of the risks associated with those uncertainties. This process includes risk identification and its qualitative or quantitative evaluation;
- Risk mitigation and control measures by reducing its likelihood or the area of uncertainty and/or reducing its consequences.

The AFTES method forms a comprehensive document that explains the terminology and details each phase of the assessment work by identifying a large variety of potential hazards (geological, hydrogeological, geotechnical), their sources, and insists on the quality of geotechnical investigations and most importantly, on the reliability of the information obtained, which can add to the uncertainties. In its methods, the **Recommandation** favors the elaboration of a geological model as a graphic representation of the uncertainties.

The risk register includes the use of mitigation measures at all stages of the process in order to reduce the risk to its lowest level of practicability, the end result being a residual risk. This way, the owner can go forward with a somewhat reduced risk while being informed of the associated costs of mitigation and control measures before the beginning of the works. As shown in Table 3, the risk matrix is a 4-class evaluation, for both the likelihood (vraisemblance) and the consequences (conséquences).

Table 3. Risk Assessment Matrix (after AFTES, 2012).

Matrice des risques					
Vraisemblance	Possible	4	8	12	16
	Peu probable	3	6	9	12
	Très peu probable	2	4	6	8
	Improbable	1	2	3	4
		Faibles	Moyennes	Fortes	Très fortes
Conséquences					

The assessment expresses the level of risk with a numerical score, as shown in Table 4. By proposing risk mitigation measures, the risk level can be reduced to improve the workability of the project to an acceptable level. Further risk-reducing measures can be added along the progression the tunnel works if needed. This way, they will have been pre-planned and budgeted for.

Table 4. Comprehensive qualitative assessment according to the initial risk level score suggesting the use of mitigation measures to obtain a lowered residual level of risk. (AFTES, 2012).

Indice NR (Niveau de risque)	Qualification indicative du niveau de risque à adapter en fonction de chaque projet	
NR < 2	Risque négligeable / Mineur	Aucune action requise, les facteurs de risque doivent faire l'objet d'un suivi spécifique par le biais de procédures adaptées.
2 < NR < 5	Risque significatif (mais a priori acceptable)	La construction peut débuter, les facteurs de risque doivent faire l'objet d'un suivi spécifique par le biais de procédures adaptées et le projet doit éventuellement être complété par une série de mesures prédéfinies pouvant faire l'objet d'adaptations durant la phase d'exécution.
5 < NR < 10	Risque important (à surveiller)	La construction ne peut pas débuter avant que le risque soit réduit ou annulé. Des solutions sont possibles sans changement important du projet.
NR > 10	Risque inacceptable	La construction ne peut pas débuter avant que le risque soit réduit ou annulé. Si le risque ne peut être maîtrisé, il est possible que le projet soit abandonné ou modifié.

The AFTES method carefully reminds the owner that the risk matrix is only one indicator that can be used in the final decision of going ahead or not. Or at least, it may help in re-thinking the right type of contract or technique for executing the works. The following sections present the principal hazards suggested by the AFTES methodology, some of which are demonstrated by the case study.

3. IDENTIFICATION OF THE RISK

Three categories of geotechnical risks (as proposed by AFTES) have been considered for the risk assessment of the project:

- The **innaccuracies**: they are a source of risk related to an identifiable marginal error in the position of a geological contact for example or an inaccurate description related to the homogeneity of a soil or rock type;
- The **hazards** : They also can be identified during the investigations which could cause major changes in the design or the position and depth of the works for example. The risk associated to known hazards (faults, poor quality rock), can often be reduced by targeted complementary investigation or mitigation measures;
- The **incidentals, unexpected or unpredictable** are those related to unforeseen events that could not have been anticipated even by competent geotechnical teams and that can significantly impact the good progress of the works.

The risk identification requires an analysis of the uncertainties with regards to their effect on the expected results. In other words, all hazards include a certain risk, but it does not necessarily affect the end result. Therefore, the process of risk identification mainly takes into account the geotechnical risks which can cause unwanted consequences. It analyses the causes and sources of risk, evaluates their likelihood and consequences and allows for the choice of risk-reducing strategies. The owner can then evaluate if the residual risks are acceptable when compared to his set of acceptance criteria for the project.

4. SOURCES OF RISK

The risk assessment based on ground conditions must take into account a variety of hazards and uncertainties related to the geological condition of the soil and the rock and its structural features. Hydrogeological hazards are equally important as they can rapidly flood the entire project or cause major ground settlement above the underground works. In the same range, a misunderstanding of the geotechnical parameters of the soils or the rock mass or the presence of uncertainties resulting in an excessive variability of the parameters. This can cause a tunnel collapse or have other devastating consequences. Three major sources of risk are considered for this case study including, Geological risk, Hydrogeological risk, and Geotechnical risk. In the following sections, the detail of each source will be presented.

5. APPLICATION OF A RISK ASSESSMENT METHOD (CASE STUDY)

The project consists of approximately six (6) kilometres of tunnel, several new stations, and seven auxiliary structures mid-way between stations, used for ventilation and for pumping infiltration water during its exploitation. The tunnel will be excavated by TBM (Tunnel Boring Machine) and pre-cast concrete lining will be installed as final lining. The project intersects different geological formations and faults through the very crowded urban environment.

5.1. Geotechnical Investigations

Several phases of investigation were carried out. The first stage (pre-feasibility) comprised approximately twenty boreholes and limited in-situ and laboratory testing. Potential dangers were however identified in the second stage, which included another twenty-five boreholes and a wider variety of testing for rock-mass characteristics, geocamera survey and seismic survey in areas with stratigraphic anomalies or questionable topographical features. At this stage, some geotechnical and geological constraints and limitations were identified which called for a third phase of investigation including a detailed program of boreholes and testing. At this stage, the tunnel alignment and depth were almost designed, but room was

left for change during the investigative process. The location of the boreholes was closing wide spaces and targeting identified uncertainties in order to collect answers. Contingencies were provided to include a few more boreholes and tests to provide clarification of geological interpretation. In total, approximately 120 boreholes have been carried out through the project alignment during the three phases of investigation.

All of the factual (Geotechnical Data Reports) data were used to prepare the Geotechnical Baseline Reports (GBR).

5.2. Geological Conditions of the Project

A good understanding of geological condition helps to better recognize the major and minor risks through out the tunnel alignment. The geology of the site consists of nearly flat-lying limestone bedrock with minor thinly-bedded shale in a gently folded structure. However, a few regional faults with lesser-known secondary faults and glacioteconic features were recently discovered. All this added a little complexity and challenge to the geological interpretation. The major joint set is related the limestone bedding with dip of nearly zero to 6-7 degrees, unless the bedding is affected by a fault. 20 degree. There are also vertical and subvertical joints which intersect the tunnel alignments and create different wedges which can slide in blocks and create instability problems for the tunnel, depending on the intersection angles. The tunnel is also affected by rock slices movements (glacioteconics) and wide openings filled with till. These zones, if intersected by the TBM, can potentially contribute significant water infiltration. The overburden in one particular glacioteconic zone along the project has a thickness of up to 18m which is a challenge for tunneling project. The numerous changes in the nature of rocks or its lithological aspects along the project, as two Formations with multiple sedimentary facies are to be encountered throughout the length of the project, require a careful adaptation or modification of the TBM excavation parameters. Some sections will present a regular limestone bedding, but others will be intensely intruded by igneous dykes. The more argillaceous facies, if not excavated adequately can slow the progress of the excavation. The presence of natural gas in the boreholes at the tunnel elevation or its below during the excavation phase, is also a significant risk to evaluate and prepare for.

5.3. Qualitative risk assessment

A team of a geologist, a hydrogeological, and a rock mechanics engineer were given the mandate to do the risk assessment for this major subway project.

Based on the client suggestion, the AFTES methodology has been used. In the following sections, the several steps of risk assessment carried out for this project will be presented in detail.

5.3.1. Determination of the sources of risks

The three categories of source of risk have been considered and studied in details for their occurrence in the case study. For each category, the main sources of risk were identified based on ground conditions:

Geological Sources

- The presence of heterogeneous or lenticular soil missed by the borehole investigations
- The presence of hard cobbles and boulders in till, affecting the excavation rate
- Heterogeneity of a rock mass caused by intrusive rocks cutting a regular sedimentary formation
- Selective softening of dykes and sills producing zones of weakness in the rock mass
- Variations in the quantity of argillaceous rock which softens and weathers rapidly during and after excavation depending on the method of excavation
- The presence of folds, faults, and other discontinuities affecting the rock mass (ductile to brittle deformation)
- Sudden changes in bedrock gradients
- The presence of non-cohesive fill material inside discontinuities caused by post-glacial isostasy or volcanic ash layers within hard rock
- The presence of natural gas in the rock Formations
- The presence of unfavorable jointing conditions in the rock mass causing the wedging out of blocks
- The presence of karsts or large dissolution features

Hydrogeological Sources

- The hydraulic characteristics of the rock mass and its permeability which is directly influenced by the index of fracture of the rock
- The anisotropy of the rock, causing differential permeability
- The hydraulique head
- The groundwater quality: contaminated groundwater can be very hazardous to workers and cause early degeneration of tunnel parts and equipment
- Physico-chemical parameters of the groundwater (pH, agressivity, potential for the formation of ochre
- Ground settlement caused by lowering of the groundwater table during excavation, which can affect third party properties et infrastructure
- Flow of infiltration water (surface and groundwater) and its effect on excavation
- The environmental aspect of the groundwater, and the local perturbation of the natural water level caused by existing underground infrastructure.
- The presence of contaminated soils and/or contaminated groundwater.

Geotechnical Sources

- Uncertainties due to wide variations in the geomechanical rock parameters (UCS,

Table 5. Definitions of the parameters used in the risk register for this case study

DEFINITIONS

RISK TYPE	1- Geological 2- Hydrogeological 3- Geotechnical
SOURCE IDENTIFICATION	ROC (hardness, resistance, lithological variation, contacts, argillaceous content, expected behaviour during excavation), DISCONTINUITIES (fissures, fractures - with or without discontinuities -joint sets - opening - FAULTS - stratigraphic anomalies, etc)
LIKELIHOOD	Very likely, likely, unlikely, very unlikely. The percentage is a fairly wide estimate of the likelihood (asked by the client) interpreted from the available data and previous experience and does not reflect a calculated statistical value
CONSEQUENCE	Rather than a frequency, a description of the type of consequence is given and the way it could affect the cost or the scheduling of the project, followed by an qualitative level of severity - marginal - moderate - serious - severe
RISK LEVEL	The risk matrix result: the product of the likelihood and the consequence of each hazard
PREVENTATIVE MEASURES	The mitigation and control measures planned to be executed before or during the tunnel works
DETECTION METHOD	The use of a method of detection prior or during tunnel works, such as a horizontal borehole initiated at the TBM cutterhead and or a form of instrumentation (also as preventative measures)
RESIDUAL RISK LEVEL	The risk level AFTER preventative treatment
CURATIVE MEASURES	Planned additional measures, instruments, equipment to be implemented in order to further reduce the consequences in the eventuality of an unwanted event

Table 6. Example of a risk register created for the case study.

Risque No.	Type (1-2-3)	Identification	Source du risque	Vraisemblance*		Lieu (PK à PK)	Conséquence	Niveau de risque	Traitement préventif	Risque résiduel	Méthode de détection	Traitement curatif
				Probabilité	%							
+01	1	Occurrence de gaz dans 2 forages, V3-46 (fin T2) et PT-02	Présence de gaz dans le roc	Possible	50-90%	T2 à 40+680 ou +	Risque d'explosion si non ventilé	Elevé	Monitoring, ventilation, mesures de détection	Moyen	Monitorer 4 gaz	Programme de prévention des risques, ventilation
+02	1-2	Présence de lits de shale fracturé - joints horizontaux ouverts avec remplissage silto-argileux à la voûte	Matériel non cohésif dans joints ouverts parallèles au litage	Possible	50-70%	40+700 à 40+900	Affaissements mineurs au niveau de la voûte - venues d'eau significatives possibles	Moyen	Observation continue de la voûte, forage à l'avancement	Moyen	Forage à l'avancement	
+03	1-2	Présence de lits de shale fracturé - joints horizontaux ouverts avec remplissage silto-argileux à la voûte	Matériel non cohésif dans joints ouverts parallèles au litage	Possible	50-70%	41+ 055 à 41+400	Surtelements au niveau inférieur et radier	Faible				
+04	1	Présence d'un lit de shale fracturé avec remplissage silto-argileux à la voûte	Matériel non cohésif dans un joint ouvert parallèle au litage	Possible	50-70%	41+400 à 41+420	Affaissements mineurs au niveau de la voûte - venues d'eau possibles	Moyen	Observation continue de la voûte -	Moyen	Survi topographique en surface (bassements éventuels)	
+05	1-2	Fractures et pression artérienne dans forage à 35 m de l'axe du tunnel, sous le niveau de la voûte	Fractures ouvertes dans un des forages	Peu probable	20-50%	41+620 à 41+600	Venues d'eau probables	Faible	Observation des signes précurseurs à l'avancement	Faible		
+06	3	Indétermination ou variabilité des paramètres géotechniques	Nombre d'essais insuffisants (imitations)	Possible	20-40%		Inertitude sur la définition de la résistance du massif au creusement	Moyen				
+07	3	Indétermination de discontinuité dans le roc et les blocs instables	La distance entre les forages et l'orientation de joints par rapport au tunnel	Possible	40-60%		Inertitude sur la position de joints verticaux et horizontaux entre les forages	Elevé	Forage à l'avancement	Moyen	Géologue au chantier, forage dans la face, mesures d'instruments, analyses des paramètres de forage pendant l'avancement	Programme de prévention des risques
+08	3	Indétermination d'excavabilité du roc	Les essais ne sont pas réalisés	Possible	NA		Tunnelier avec titre de coupe avec outils non adéquats, le changement des outils plus fréquent et la puissance de la machine insuffisante	Moyen				
+09	2	Potentiel d'eau souterraine (nappe du roc) contaminée au solvant TCE	Présence de contamination au TCE dans l'eau souterraine dans un puits à proximité (40 m) du tronçon ouest de T3 près de l'arrivée à la future station V14u	Possible	30-70%	40+900 à 40+940	Infiltration d'eau contaminée dans les excavations, danger entre autres pour la santé des travailleurs et dommages aux équipements	Moyen à élevé	Forages et aménagement de puits complémentaires en cours -	Moyen à élevé	Analyses de l'eau souterraine	Traitement de l'eau in situ ou balancement de la nappe par pompage et traitement ex-situ

5.3.4 Risk Register and mitigation options

The cross-section along the tunnel made the production of the risk registers an easier task, as far as the identification of the risks is concerned. On the register, the hazards are numbered, classified according to their type. Then the risk and its source are identified and is localized along the tunnel. Thereafter, each risk is assessed using criteria of likelihood and consequence before mitigation measures suggested and re-assessed afterwards. The parameters used in the register were defined at follows (Table 5).

A risk register was also prepared for each tunnel segment represented by the cross-section of Figure 1 as

shown in Table 6. A risk assessment report was prepared, with detailed methodology and definitions of the concepts of risk based on AFTES method. A 4-class matrix such as that presented in the AFTES methodology have been used in which left the task of quantifying the risk to the client's risk management specialists, along with the other categories of risks.

Early (pre-planned) mitigation measures were proposed for each risk outlined, resulting in a re-evaluated residual risk level. Further control measures, applicable to each identified risk, to be considered at time of construction were also presented in another table accompanying the risk register for each tunnel segment.

6. DISCUSSION

It is important to emphasize that the choice of method and parameters used for assessing risks on ground conditions is not unique but varies with the amount of data available and the client's expectation, as well as his risk tolerance criteria. In the example given above for the risk assessment, there was a challenge for the team to quantify the risk because it is difficult to associate the percentage to each risk occurrence when assessing each risk individually. The probability associated to each risk (percentage of occurrence) is more meaningful when each risk can be compared to the other risk in different categories. Moreover, the probability of each risk depends on accuracy and availability of geological, hydrogeological, and geotechnical data and their distribution in each geological Formation. The level of accuracy and availability of each of these data are different in this project. In general, the construction methods, the workmanship, the type of support system, efficiency of grouting of rock and soil, discrepancies between design and what is realized on the construction sites, and delay between each phase of construction can have a significant influence on the probability of risk occurrence.

When the risk assessment is done on behalf of the owner, it is important to include risk-reducing mitigation measures that can be planned at all stages of the project. This way, the owner is fully prepared for adverse conditions and has an idea of the additional costs and scheduling implications or other contingencies. The assessment has to start early on in the project so that there is time to limit the area of uncertainty by adding targeted borehole investigation or additional testing before the start of the project or the tendering process.

The ITIG proposition for the owner's (the insurer's client) to ask tenderers for their own risk assessment on ground conditions and mitigation measures (given the fact that the GDR and GBR are included in the tender documents) is a brilliant concept. It gives the owner a sense that the tenderer has a team with the competency, or not, to analyze the data, consider the risks and include certain mitigation costs in their bidding price. It is an aspect that has not been suggested in AFTES method.

7. CONCLUSION

Risk assessment is intended to provide a cost effective approach to decision-making based on analysis of data. In the present paper, the consequences of a ground failure were evaluated for safety, security, damages to third party, costs and delay to the project.

In this paper, three basic risk management concepts or methods are presented. Despite being different from each other, they all provide useful tips on what to consider when carrying out a risk assessment analysis of a project. In each case, the risk level is a function of the likelihood of an event and its consequence. There exist many methods, each with their own particularities, which can cater to the client's criteria of risk tolerance. In the case study presented, the risk assessment is exclusively based on

ground conditions and is only a part, although a critical one, of a greater risk management scheme. In this study, the geotechnical team assessed the risk from geological, hydrogeological and geotechnical point of views, which are somewhat all related to each other. The timing was appropriate since it allowed for the team to propose some additional investigation along the process.

A risk register is also created or inspired by more than one method as long as it provides the client with the information necessary to make the right decisions. The presented risk register for identifying the common geotechnical risks, as used in a case study, helps to optimize resources and to plan and prioritize future repairs in the eventuality of ground failure.

An integral part of risk management for this project is for the owner to have competent geotechnical professionals with a vast experience in underground projects who can assess the ground conditions from data obtained during several phases of geotechnical investigations. The timing of the assessment process is important and must continue throughout all phases of the project, from the planning and design stages to the construction stages.

One must keep in mind however that a risk-free project is practically impossible. Despite the best risk assessment analysis, UNFORESEEN EVENTS cannot be predicted, no matter how thorough the investigations were carried out. The excavation of the tunnel used in the case study has not yet begun. Only time will tell at what extent the assessment method used was appropriate or satisfactory.

8. REFERENCES

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