4. ULUSLARARASI YERALTI KAZILARI SEMPOZYUMU BİLDİRİLER KİTABI

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13-14 Eylül / September 2018, İSTANBUL

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TMMOB
MADEN MÜHENDİSLERİ ODASI
İSTANBUL ŞUBESİ
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Istanbul Branch

TÜNELCİLİK DERNEĞİ
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TMMOB Maden Mühendisleri Odası - Tünelcilik Derneği

On the Concept of Innovative Risk Analysis-Driven Design Approach in Mining Engineering

R.R. Osgoui, G. Russo, P. Grasso
GEODATA Engineering SPA. Turin, ITALY

ABSTRACT This paper is intended to describe comprehensively an innovative approach of tunnelling design so-called "Risk Analysis-Driven Design", to be integrated as a robust design tool into the mining practice in such a way as to fulfil the mining project in term of both technical and economical benefits. The approach is fully integrated with the ordinary design method, usually used in tunnelling and mining. This innovative approach, originally invented and evolved by GODATA Engineering (GDE), has been successfully used in any type of tunnelling fields since 1990s and ever since approximately more than 2000km of road, energy, sewage, railway, metro, water, hydro tunnels and underground caverns have applied the risk analysis-driven design approach. The main reason of demanding such an approach is to cope with the uncertainty arising from the inability of the designer to form a complete structure of the rock mass before construction as well as the inability to fully comprehend and model interaction between the rock mass and excavation domains. This requirement has successively been ordered with increasing the tunnelling and mining activities in great depth and a certain level of uncertainty. Two cases in South America, El-Teniente Mine İn Chile and Hydro project in other country, in which the risk analysis-driven design has recently been applied, are addressed. In particular, the tunnelling-induced seismicity "rock burst" events resulting from the recent tendency of tunnelling in great depth in hard rock are analyzed.

1 INTRODUCTION

Even though mining and tunnelling are the oldest engineering activities performed by man underground and current engineering technology and design approaches in these fields have many great achievement to their credits, there is still a general lack of interacting between conventional mining and innovative tunnelling method. It is believed that much can be learned by interaction between mining and tunnelling and by an exchange of ideas, innovations, and the experiences which already made the tunnelling projects successful.

Mining Engineering continues to provide strong motivation for the advancement of tunnelling with increasing of depths and stress induced failure mechanism in complex rock mass condition from very poor to very good.

For these reasons, both the knowledge of the strength parameters of rock mass, and the prediction of rock mass behaviour upon excavation, improve as observations are made of in-situ rock behaviour, and as analytical, numerical techniques evolve and are verified by practical application.

The design and construction of long and deep tunnels, recently being common in mining engineering, are often associated with the risks arising from the inadequacy of geotechnical and geomechanical information, a wrong choice of construction methodology, and a potential accident during construction. The risk analysis-driven design approach aims to identify and to quantify the risk or potential problem, select and implement the measures mitigating or controlling the risk, and indicate if there is a residual risk which would need to be shared among the parties involved in the project and for further decision making.

The risk analysis-driven design is based on rational process combined with probabilistic approach that makes it possible to take into account all uncertainties and variability in various design phases as possibly foreseen scenarios in such a way as to reduce the major risk levels to acceptable range.

2 NEED FOR RISK ANALYSIS-DRIVEN DESIGN

The design of tunnelling has traditionally followed a deterministic approach based on indirect management of the potential risks through a series of predetermined project decisions.

A major problem in tunnelling is that most of design process and above all the decisions must be made under conditions of uncertainty. In reality, both the design and construction phases are always characterized with a certain degree of uncertainty. These conditions involve nature of characteristics and their spatial variation, geological and geomechanical parameters, behaviour of rock mass, limitations of existing methods of analysis, human-equipment material effects on the tunnelling process, and political and economic influences. Application of engineering judgment and experience, usually qualitative, is required to draw practical conclusions which always involve a certain degree of risk.

Although design and decision under uncertainty are routinely addressed in other fields of engineering and science, they are only occasionally dealt with in tunnelling due to the complexity of the problems and a lack of suitable and effective tools. The risk analysis-driven design approach including its auxiliary tools has been developed to respond to this challenge.

Risk analysis driven design is based on probabilistic analysis and thus allows the user to quantify design reliability or risk by mathematically modelling the variability and uncertainty of the key parameters involved, and assessing the time and cost impact of the parameter-value variation.

Risk analysis driven design can be applied, in all project phases, both for project control by the owner and as a decision-support tool by the designer and the contractor.

2.1 State-of-the-Art of Risk Analysis Driven Design

In the filed of tunnelling engineering, the following trends have progressively been developed in the course of last decades:

– The 1980’s were characterized by the absence of an approach towards defining and managing risk, above all during the pre-construction phase. The management of uncertainty, specifically geologic, was made through the deterministic use of the classification systems. The geologic profile was prepared during construction. Often, the differences between the foreseen and encountered conditions were not adequately identified and the consequences were exacerbated due to the inadequacy of the support or the construction technique. A combination of these circumstances is often transformed into litigation.
– In the 1990’s, the concepts of uncertainty, probability, and evaluation of risk were introduced. The observational method, proposed by Peck in the 1960’s, became an alternative process of design, based on the control of construction through monitoring the key parameters, the use of pre-defined counter measures, and the eventual modification of the design. The observational method was, however, integrated only in some limited types of contact. In the late 1990’s and in the early 2000’s, with the advent of the computer based software, the application of a robust and rigours risk analysis was introduced by GEODATA through a series of risk-analysis-based powerful tools, namely DAT (Decision Aids in Tunnelling), GDMS (GEODATA Management System), PAT (Plan for Advance Tunnel)

as described elsewhere (Einstein et al. 1998, Grasso et al. 2002, Chiriotti et al. 2003).

– In the new millennium, the flexible design and the risk management are two aspects that are integrated in the process of development of design and construction. The evolution described above shows a gradual increase in the awareness that an underground construction project cannot be accomplished without risks: the risks can be managed, minimized, shared, transferred, or simply accepted, but cannot be ignored.

3 KEY ELEMENTS

Figure 1 presents the key-elements of Risk-Analysis Driven Design. Recently, some key concepts of this approach have been also shared in the AFTES Recommendations (AFTES, 2012) and are compatible with ITA guideline (ITA, 2004).

A risk analysis driven design consists of four essential elements: risk identification, risk qualification, risk response development, and risk response monitoring.

In the primary steps of the risk identifications and qualification, the suitable mitigation measures are defined and assigned to the project based on reliability design approach while during risk responses the effective countermeasures are, if necessary, defined.

While the main references of principle of risk analysis, methodology, and applications have been specified elsewhere (ITA 2004, Guglielmetti et al. 2007), in what follows the sequential and logical steps of the risk analysis-driven design is dealt with.

Evidently, the systematic implementation of the probabilistic approach is a key element in each step of this approach.

The important feature of this approach let the design be optimized to meet both cost and time requirements.

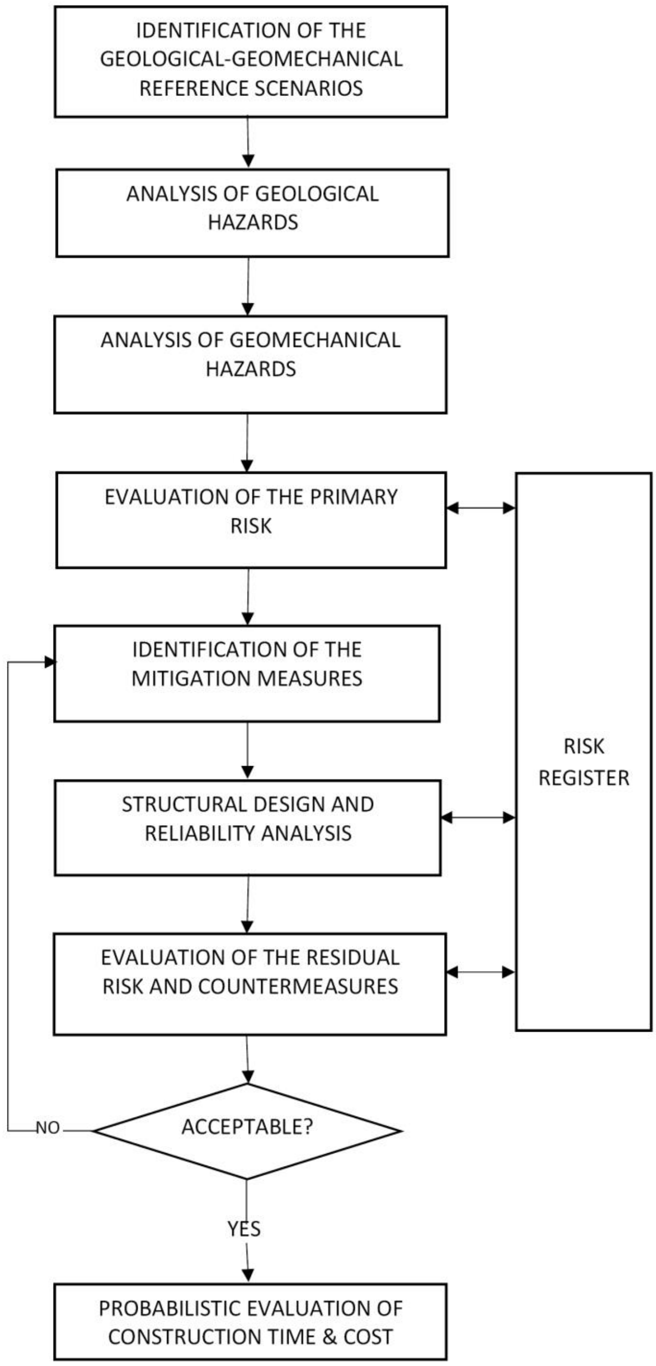
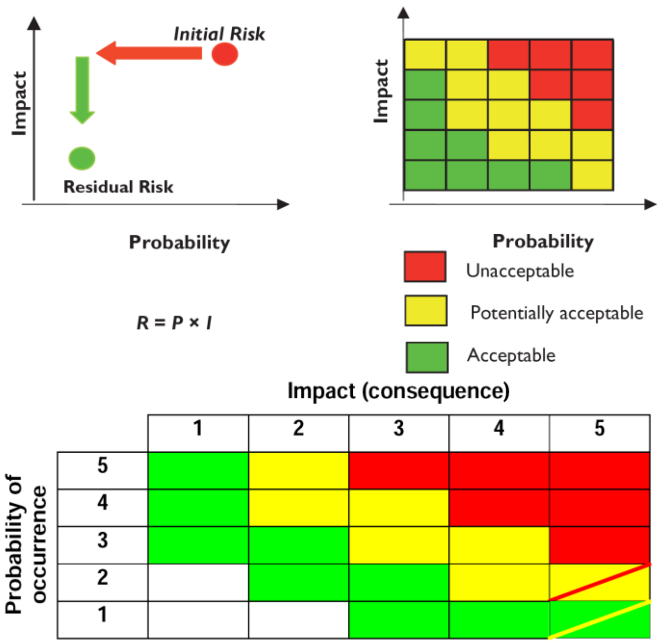


Figure 1. Principle of GDE Risk Analysis-Driven Design

The evaluation of the initial (primary) risk for tunnelling involves the estimate of the potential impact (consequence) deriving from the damages related to the identified hazards. The impact is characterized in term of intensity of relevant hazard consequence. According to ITA (2004), the impact could be characterized in terms of delay in tunnelling activity (Fig. 2).



	Risk Definition	Actions
	Unacceptable	The risk shall be reduced at least to Unwanted, regardless of the costs of risk mitigation.
	Unwanted	Risk mitigation measures shall be identified. The measures shall be implemented as long as the costs of the measures are not disproportionate with the risk reduction obtained.
	Acceptable	The hazard shall be managed throughout the project. Consideration of risk mitigation is not required.
	Negligible	No further consideration of the hazard is needed.

Figure 2. Definition of the Risk (ITA 2004, Guglielmetti et al. 2007)

4 EL TENEINTE MINE

El Teniente Mine, located in the Libertador General Bernardo O'Higgins Region 80 km southeast of Chile's capital Santiago, is the largest underground copper mine in the world, with more than 2400 km of mine drifts and tunnels producing more than 400000 tons per year of fine copper recovered from the ore, either as refined ingots or as copper cathodes. As a result of ore processing, nearly 5000 tons of molybdenum are recovered as a by-product.

The owner of the mine, Codelco (Corporación Nacional del Cobre de Chile, División El Teniente), is currently developing the New Mine Level Project to ensure the continuity of the exploitation and the increase of ore production.

The New Mine Level (NML) project (Fig. 3 and 4), located at 1000m depth, is being planned to extend the life of the mine by 60 years, entering production phase in shortcoming future. New reserves of 2020 million tons at present with 0.86% average copper grade and 220 ppm of molybdenum, will maintain the mine's production at its 137000 tons/day.

A significant component of the NML project is the construction of 24 km of access tunnels, which began in March 2012, consisting of two adits (Ltot=6km), proposed by the Contractor (CTM – Constructora de Túneles Mineros, joint venture between Vinci and Soletanche Bachy), and two main tunnels (Ltot=9+9km): a tunnel for vehicular access of personnel and a twin conveyor tunnel for the transport of the ore. Conventional method by means of D&B is being used for all excavation processes.

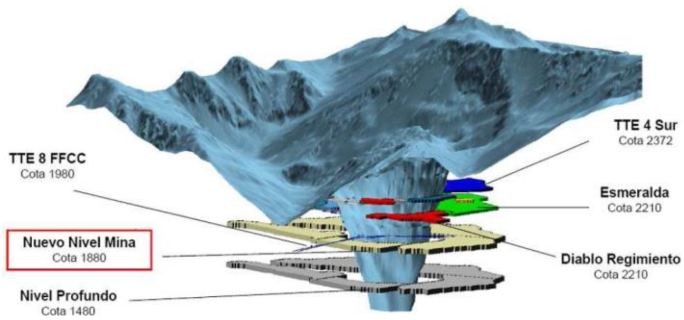


Figure 3. New Mine Level (NML)

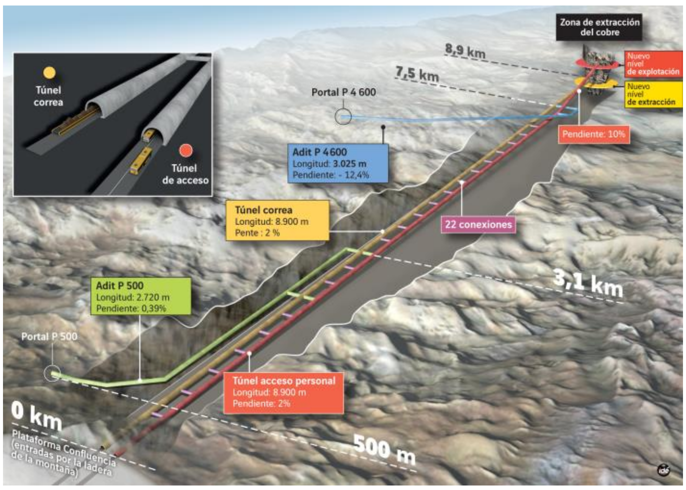


Figure 4. NML access and tunnels presently under construction

4.1 Reference Geological Scenario

Generally speaking, the tunnels design and construction involve a high level of risk mainly due to geological-geomechanical uncertainties.

Uncertainty mainly concerns the inherent variability of the input geo-parameters and the real state of each parameter along the tunnel, conditioning the excavation behaviour.

The two types of uncertainties described can be reasonably related to the Type A and B reported in Figure 5 (Hoffman et al., 1994, Russo et al. 1999).

To manage the different types of uncertainties basically the following procedure are applied:

– Type A: on the basis of the statistical best-fitting of the available data, adequate probabilistic distributions are associated to each geomechanical parameters (Figs. 6 and 7);
– Type B: three geological-geomechanical scenarios are considered to simulate the reference context: 1) Favourable, 2) Most likely and 3) Unfavourable scenario. Evidently, this approach permits to consider different faults extensions, contacts positions, parameter values, classification assessments, etc. In some case, as for the example reported in the present paper, the Most likely scenario is considered coincident with the Basic Design developed by the Owner (here called "H_lik") and the effective position with respect the other scenarios is consequently checked.

Figure 6 shows the reference geological profile called as the "H-lik" scenario including all rock mass units. While Figure 7 depicts the frequency of uniaxial compressive strength and relative density function obtained by statistical best-fit analysis, Figure 8, on the other side, presents the calculation of GSI of all rock mass units expected during excavation of access tunnels by means of statistical distribution of rock mass parameters, the rock mass block volume and the rock mass joint conditions. In this way, the variation of geomechanical parameters was suitably taken into consideration. Furthermore, with reference to Figure 8, the presence of various faults and tectonic/volcanic contacts between the igneous rock masses have been recognized.

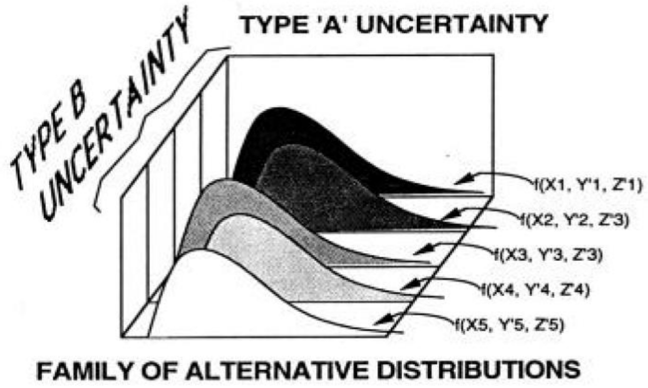


Figure 5. Different type of uncertainties (Hoffman and al. 1994)

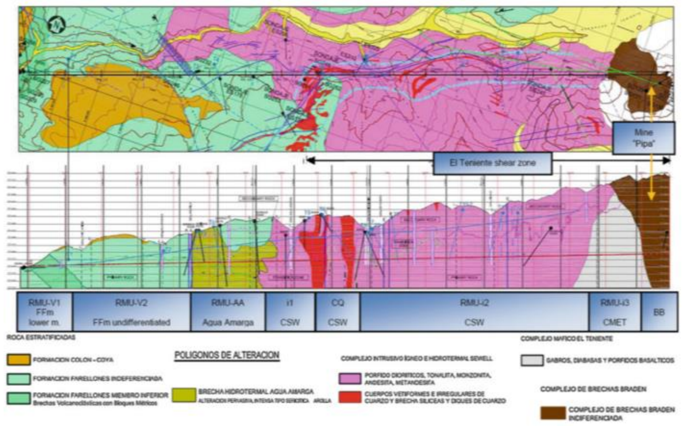
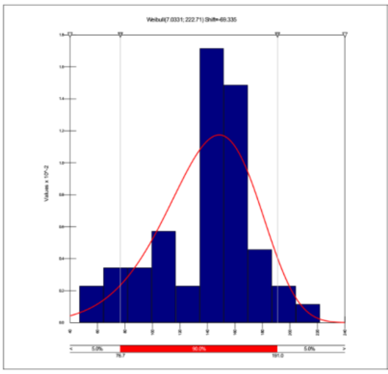


Figure 6. The reference "H-lik" scenario for main tunnels connection to NML



Results obtained from statistical best-fit analysis	
Type of distribution	Weibull
Number of samples	50
Minimum	47.0 MPa
Mean	139.0 MPa
Maximum	222.0 MPa
Standard dev.	35.5 MPa
Goodness of fitting (test value based on Anderson-Darling)	0.6655

Figure 7. Histogram of frequency of uniaxial compressive strength and relative density function obtained by statistical best-fit analysis

4.2 Geological and Geomechanical Hazard Identification and Quantification

Defined the geological setting, the reference context for the designer is completed by the consequent identification of the main hazard for tunnelling and their evaluation in terms of probability of occurrence and the specific intensity.

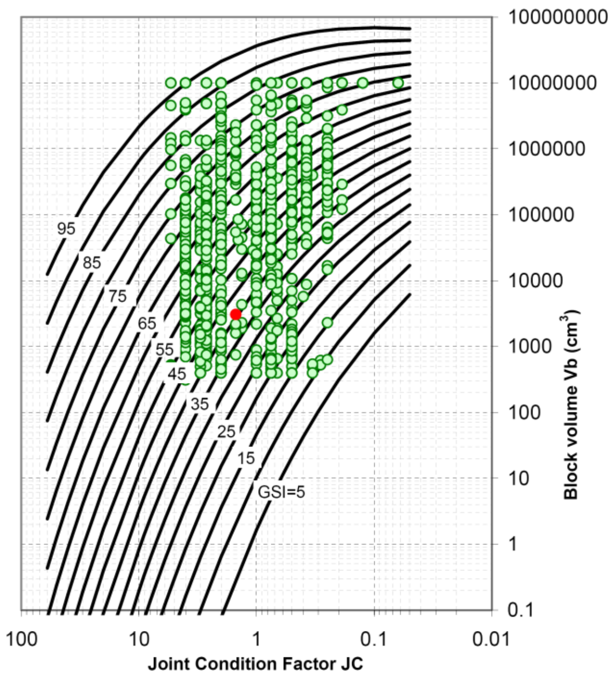


Figure 8. Estimation of GSI variation based on probabilistic approach considering variation of rock mass fabric parameters

Two main categories of hazard events are identified in connection to geological and geomechanical issues (Table 1), namely:

– Hazard phenomena associated with unfavourable geological conditions.
– Geomechanical hazard related to rock mass behaviour upon excavation.

Geomechanical hazards are mainly related to ground behaviour upon excavation, thus taking into account the intrinsic properties of rock masses and the associated stress conditions. The forecast analysis for evaluating the response upon excavation and then the most probable hazard is performed for each rock mass unit by necessarily taking into account both stress and geostructural analyses.

The reference classification of the excavation behaviour is consequently based on both stress and geo-structural type analysis (Fig. 9) as developed by Russo et al. (1998).

The matrix that results from such a double classification approach allows an optimal focalization of the specific design problem.

Furthermore, a rational choice of the type of stabilization measures may be derived as a function of the most probable potential deformation phenomenon that is associated to the different stress and geo-structural combination.

For the quantification of the probability of occurrence of the hazards, the probabilistic analytical method is applied, by implementing the GRC (Ground Reaction Curve) and LDP (Longitudinal Deformation Profile) for each rock mass unit and geo-scenario as exemplary presented in Figure 10.

Table 1. Definition of geological and geomechanical hazards

A) Hazards related to unfavourable environmental and geological conditions

n.	Hazards	Associated factors and boundary conditions	Adopted method to assess the Probability of occurrence and Severity
Tectonics, morphology			
A1	Active fault	Tectonically active areas	Geological study
A2	Asymmetric stress	Complex natural stress field (neotectonic effects; morphologic conditions; rock anisotropy; structural conditions; tectonic erosion)	Geological study
Fluids, temperature			
A3	Noxious/Dangerous gases	Presence of coal seams in mudstones ; release of hydrothermally generated gases ; alteration of minerals ; radioactive decay from uranium bearing materials	Geological study
A4	Aggressive waters	Hydrothermal water circulation; sulphide minerals	Geological study
A5	High temperatures	Thermal waters deep circulation.	Geological study
Ground conditions			
A6	Faults and/or disturbed zones	-	Geological study
A7	Hard rocks	-	Geological study
A8	Abrasive	Quartz content and mineral texture	Geological study
A9	Radioactive rocks	-	-
A10	Sticky ground	-	-
A11	Swelling ground	Clayey rocks, fault affected rocks	Geological study
A12	Heterogeneous ground	-	-
A13	Natural voids	-	-

n.	Hazards	Associated factors and boundary conditions	Adopted method to assess the probability of occurrence and severity
Gravity driven instabilities			
B1	Rock block fall, wedge instability	Fractured rock mass, where the intersection among discontinuities can give rise to potentially unstable blocs	Analytic probabilistic and empirical (Geomechanical Classification) assessment
B2	Caving (Unstable behaviour at the face and/or at tunnel walls)	Fractured/weathered rock masses, with or without water, exhibiting a limited self-supporting time (e.g., fault zones and/or zones of high tectonic disturbance)	Analytic probabilistic and empirical (Geomechanical Classification) assessment
Stress induced instabilities			
B3	Rockburst	Stress conditions on tunnel walls not compatible with stiff rock masses available strength	Analytic probabilistic and empirical (Canadian Rockburst manual) assessment
B4	Squeezing (radial convergences, face extrusion)	Unfavourable relationship between rock mass strength and the surrounding stress field, with possible occurrence of time-dependent deformations	Analytic probabilistic and empirical (GD and Hoek & Marinos classification) assessment
Mainly water influenced			
B5	Flowing behaviour	Incoherent grounds and/or cataclastic rock masses subject to high hydrodynamic forces (e.g., interception of pressurized water bearing cataclastic rocks bounded by relatively impervious fault gauges)	Expert assessment based on geotechnical and hydrogeological conditions
B6	Water inrush	Permeable fractured water bearing rock masses possibly totally or partially confined	Expert assessment based on anticipated hydrogeological conditions
B7	Piping	Collapse of tunnel face and/or cavity caused by water pressure	Expert assessment based on anticipated hydrogeological conditions

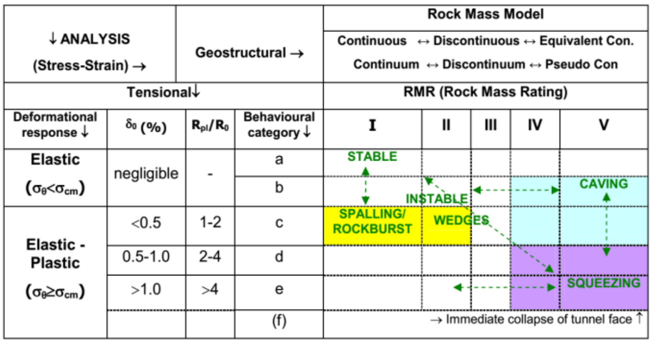


Figure 9. GDE Risk analysis-driven design, classification of the excavation behaviour including type of rock mass response, development of plastic zone, maximum radial deformation, behaviour category and associated geomechanical risk

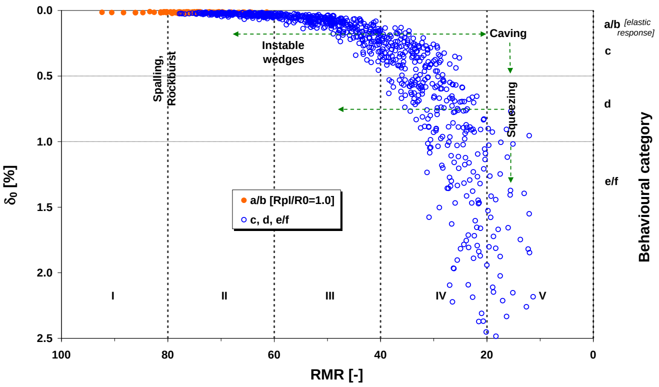


Figure 10. Example of the probabilistic results of the analyses of excavation behaviour and risk, with specific reference to the classification of Figure 9

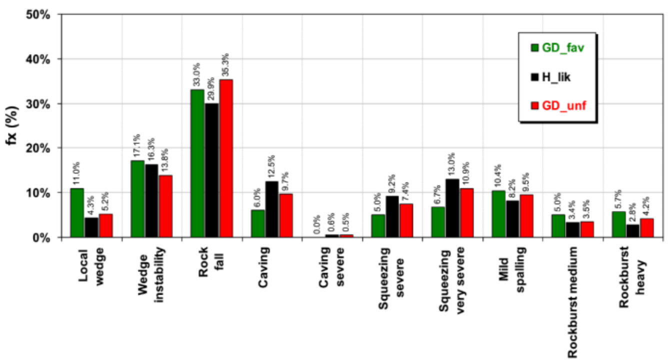


Figure 11. Probability of occurrence of the different geomechanical hazards (H_lik scenario has been derived by interpreting the Basic Design of reference)

4.3 Evaluation of the Initial Risk

The calculation of the probability of occurrence of the hazards and the estimate of the potential impact on tunnelling (D&B and TBM) allow for the initial risk register compilation (Fig.12).

The longitudinal geological profile is combined with representation of the initial risks, geological and geomechanical, along the tunnel, providing the fundamental basis for the design (Fig.13).

4.4 Mitigation Measures and Residual Risk

On the basis of the Hazard and Risk Register, the appropriate mitigation measures (i.e. design solutions) are selected, both for D&B and hard rock TBM excavation. The indicative examples of typical mitigation measures for conventional D&B excavation related to each type of hazards are addressed in Table 2.

Consequently, according to the design logic and criteria given in Table 3, the most suitable and effective mitigation measures are defined to make the desired support system. Depending on hazard type, adequate calculation methods are consequently adopted for the structural design and verification.

As remarked in the flowchart of Fig. 1, an iterative process is implemented to dimensioning the support section type and estimating the residual risk. The latter estimation is based on the evaluated potential damages (Table 4) and allows for updating the risk register (Fig. 14), up to mitigate any unacceptable risk. Moreover, for the residual unwanted risk, adequate counter-measures should be defined.

5 DESIGN OF SUPPORT SYSTEM BASED ON RISK ANALYSIS- DRIVEN DESIGN

Common practice in tunnel design considers a deterministic approach for dimensioning primary support and final lining. Usually, support design is based on some statistical parameters (for example the mean) and a fixed factor of safety is required to take into account different sources of uncertainty. However, this index is not sufficient to quantify the reliability of a support structure, and can be easily shown that to the same factor of safety could be related to the different values of probability of failure.

The single input values are generally representing the "best-estimates" of the parameters and cannot account for either the inherent variability or the uncertainty in the parameters, and the factor of safety, commonly defined as the ratio between the available capacity of the designed support and the demand for support of the excavation, is often found to be inadequate for quantifying the reliability of the system. For the latter case, it can be easily demonstrated that two different tunnel sections having the same factor of safety may have quite different probability of failure as presented in Fig. 15.

The current, unsatisfactory situation can be improved through application of probabilistic approaches to design as it practised in the field of structural design, incorporating explicitly the various sources of uncertainty and variability in design analysis.

Hazard identification: CATEGORY / Sub-category / TYPE / Sub-type	HAZARD	Hazard Probab. [P]	Primary risk D&B Impact [I]	Primary risk D&B Risk [R=PxI]	Primary risk TBM Impact [I]	Primary risk TBM Risk [R=PxI]	Mitigation measures D&B	Mitigation measures TBM
GEOMECHANICAL HAZARDS (EXCAVATION BEHAVIOUR AND LOADING CONDITION RELATED)								
Gravity driven instability								
B1	ROCK BLOCK FALL (® OVERBREAKS)	5	2	10	1	5	M01,M02,M23, M24	M01,M22,M23, M24
B2	CAVING (®FACE / CAVITY COLLAPSE)	4	3	12	2	8	M01,M02,M03, M24	M01,M22,M24
Stress induced instability								
B3	ROCKBURST	5	4	20	1	5	M1,M2,M23	M1,M22,M23
B4	SQUEEZING, FACE EXTRUSION	2	3	6	4	8	M01,M02,M07, M21,M24	M1,M22,M25,M 27
Mainly water influenced								
B5	FLOWING GROUND	5	5	25	5	25	M01,M02,M06, M07,M08,M24	M01,M08,M22, M25,M27
B6	WATER INRUSH	5	5	25	5	25	M01,M02,M06, M07,M08,M24	M01,M08,M22, M25,M27
B7	PIPING	5	5	25	5	25	M01,M02,M06	
Load conditions, etc.								
B8	VISCOUS LOADS	4	4	16	4	16	M27	
B9	SWELLING LOADS	3	3	9	3	9	M24,M27	
B10	ASYMMETRIC LOADS	5	3	15	3	15	M24,M27	
B11	DEFECTIVE BEARING CAPACITY	3	3	9	4	12	M08	
.....	....							

Figure 12. Example of the initial risk estimation as resulting from the probabilistic calculations and the severity of the impact on excavation. For the classification, basic reference is done to ITA (2004, see also Fig.13), according to which: R=P*I, where R=Risk; P=Probability of occurrence; I=Impact. Risk may result: Unacceptable (Red), Unwanted (Yellow) and Negligible/Acceptable (Green). The analysis is performed for both D&B and TBM excavation.

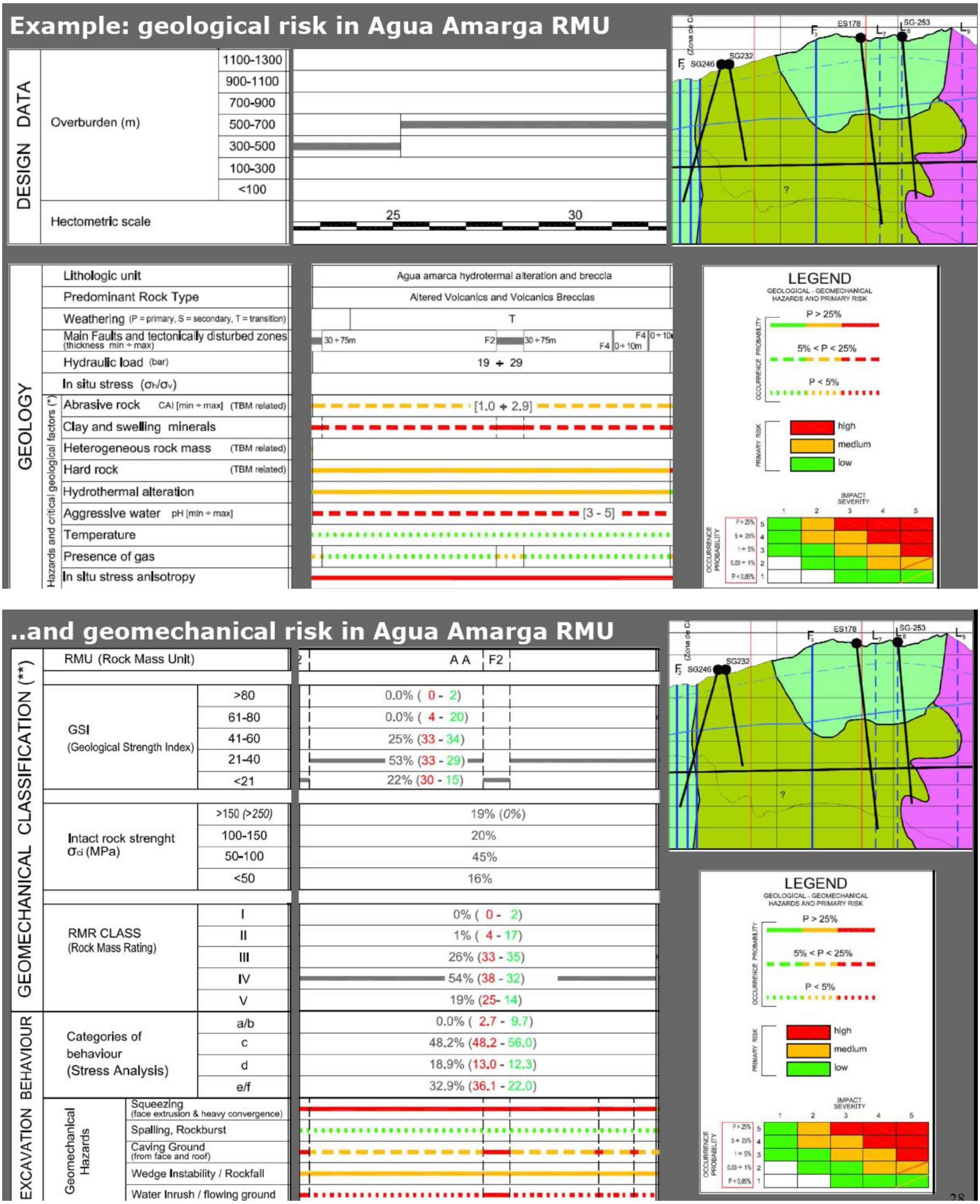


Figure 13. Risk Analysis-Driven Design: tunnel profile resulting from the risk analysis-driven design

Table 2. Mitigation measures defined for both D&B and TBM excavation methods

Code	Risk mitigation measures [M]	
	Conventional Method (D&B)	**Mechanized Method (TBM)**
	A. In advancement to the excavation	
M01	Probing in advancement to excavation	
M02	Controlled drainage ahead the tunnel face	
M03	Pre-confinement of instable wedges (inclined bolts, spilling, forepoling,..)	-
M04	Pre-confinement of excavation contour (sub-horizontal jet-grouting canopy,..)	-
M05	Pre-reinforcement of rock mass contour (by fully connected elements)	-
M06	Pre-support of excavation contour (forepoling, umbrella arch,..)	-
M07	Tunnel face/contour pre-reinforcement (injected fiberglass elements, jet-grouting,..)	
M08	Grouting for water-tightness	
M09	De-stressing hole-blasting	
...	...	
	B. During excavation	
M21	Over-excavation to allow excavation convergences	
M22	-	Shielded (protection) , McNally System
M23	Radial confinement of instable wedges, mild spalling (bolts and/or shotcrete,..) D&B and Open Gripper TBM	
M24	Support system differently composed by steel ribs,fibre-reinforced shotcrete,bolts,..)	-
M25	Controlled de-confinement to allow high convergences (sliding steel-ribs, shotcrete with joints and/or deformable elements,..)	Special TBM features to allow convergence, as copy cutter, conical shield, and short shield design, shield lubirication , special Torque-RPM design for gearbox, etc.
M26	High energy absorbing system composed by steel mesh+ yielding bolts+fiber-reinforced shotcrete	Special and improved steel typed used for shield for protection of rockburst, Mc Nally system
M27	Final lining by reinforced shotcrete	Final lining by pre-cast concrete segmental lining
M28	Use of special material (in presence of aggressive waters)	
M29	-	Tail void filling/grouting
M30	Radial drainages	
M31	Impermeabilization (partial or full round)	Impermeabilization by means of EPDM Gasket (even anchored types)
M32	Cooling system	
M33	Catching and treatment of water inflows, auxiliary emergency pump ‘at the face’	
M34	Forced ventilation	
M35	Non-deflagrating equipment	
M36	Adequate jumbo power	Adequate TBM power and torque
M37	Adequate drill bit	Adequate cutting tools
M38	-	Cleaning/washing of cutting tools

Table 3. Risk Analysis-Driven Design logic for determination of the most effective support section type /class in relation with the related geomechanical hazard, excavation behaviour, behaviour category, RMR, and type of mitigation measure

Hazard	Excavation Behaviour	Risk Analysis-Driven Design		Mitigation Measures		Support Type /Class	
		B.C	RMR	D&B	TBM	D&B	TBM
Wedge instability / Rockfall	* Stable rock mass, with only possibility of local rock wedge fall controlled by jointing systems * Rock mass of good to very good quality demonstrating elastic response upon excavation	a/ b	I	M01,M02,M22,M23		A	A_{TBM}
		b	II	M01,M02,M22,M23		B	B_{TBM}
	* Tendency to rock fall in rock mass of fair quality, with possible occurence of slight to moderate development of plastic zone around tunnel	c	III	M01, M02, M24	M01,M02, M22,M23	C1	E_{TBM}
Spalling/ Rockburst (bulking)	* Good quality hard rock overstressed * Minor spalling / rock burst due to mild brittle failure even associated with the rock minor ejection	c	I-II	M01,M02,M24, M30	M01, M02, M22, M23,M30		
	* Good quality hard rock moderately overstressed * Moderate spalling / rock burst due to sudden brittle failure even associated with moderate rock enjection	c	I-II	M01, M02, M24	M01, M02, M22, M23	C3	E_{TBM}
	* Good quality hard rock highly overstressed * Severe spalling / heavy Rock burst due to sudden and violent brittle failure associated with moderate rock block enjection with considerable velocity and strain energy	c	I-II	M01,M02,M09,M26	M01,M02, M22,M27, M29,M26	C4	E_{TBM}
Squeezing/ Time dependent plastic deformation	*Development of plastic/viscous deformations as a results of overstresses fair to poor rock mass, resulting in a significant face extrusion and radial deformation (convergence) *Severe squeezing	d	III-IV-V	M01, M02, M05, M07, M21, M24, M25,M30	M01,M02, M21,M22, M25, M26,M29, M30	D	E_{TBM}
	* Intense development of plastic/viscous deformations due to overstressed fair to poor rock mass, resulting in a large extrusion of face and radial deformation (convergence) *Very severe squeezing	e	III-IV-V	M01,M02, M05,M07, M21 M24,M25,M27,M30	M01,M02, M26,M21, M22,M25, M26, M29	E	E_{TBM}
Caving/ flowing, ravelling ground	Gravity-driven instability due to significant reduction of self-supporting capacity (very low stand-up-time) in poor rock mass condition like influence shear/fault zones or intrusive dykes, associated with moderate development of plastic zone	c	IV	M01,M02, M03, M24, M30 M01,M02, M06, M07,M24, M27, M30	M01,M02, M22,M27, M30 M01,M02, M06, M07, M22,M27, M30	C2	E_{TBM}
	Severe gravity-driven instability due to lack of self-supporting capacity or immediate collapse of tunnel face /excavation countor manifesting flowing and ravelling ground in very poor rock mass condition generally under conditions of high hydrostatic pressure /water inflow like shear/fault zones	f	V	M01, M02, M06, M07, M08, M24,M27, M30	M01,M02, M06, M07, M08, M22, M27,M30	F	F_{TBM}

Table 4. Definition of residual risks and relating potential damage

Code	Potential damages--> Residual risks [R]
	R0) Excavation related damages
R01	Tunnel face/cavity collapse
R02	Rockfall & Overbreaks
R03	Excessive convergence/defective section
R04	High water inflows/flooding of working area
R05	High temperature
R06	Tossicity/explosion (gas related)
R07	Violent ejection of rock block
....	....
	R1) Tunnel structure damages
R10	Tunnel support damages
R11	Tunnel lining damages
R12	Structural weakening
R13	Excessive settlements
....	....
	R2) Construction equipment damages
R20	Damage of D&B equipment
R21	Damage of TBM and back-up
R22	Trapping of TBM
R23	TBM blocking due to face/cavity collapse (chimney, voids, etc.)
R24	Blocking of TBM shield for rockfall
R25	Excessive wear of cutting tools
....	....
	R3) Other advancement related problems
R30	Low advancement rate
R31	TBM driving difficulty
R32	Adverse working condition
....	....
	R4) General construction problems (not analyzed)
R40	Power supply failure/interruption
R41	Tunnel access interruption
R42	Obstruction or ineffectiveness of the preventive drainage system
R43	Water treatment system failure
R44	Ineffectiveness of preventive consolidation treatments
R45	...

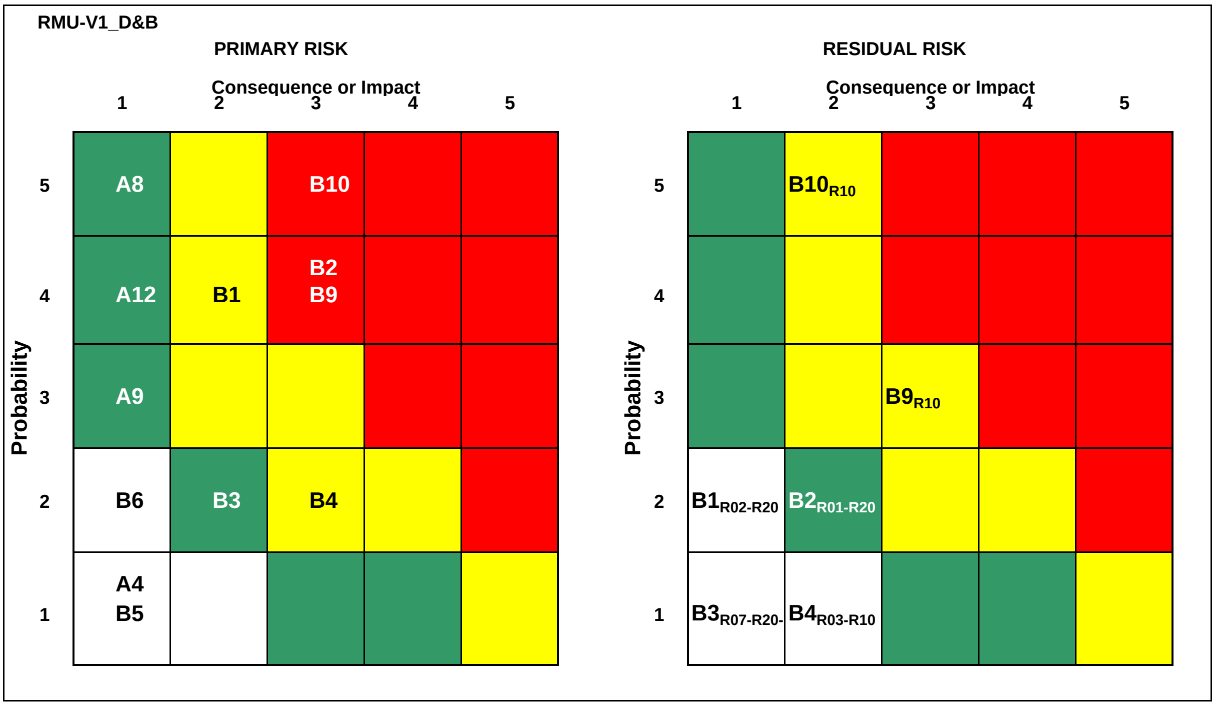


Figure 14. Updating residual risk register

5.1 Reliability Based Design

A probabilistic study allows uncertainty related to a parameter (or a random variable) to be integrated in the analysis through the use of probability density functions (pdf). Various sources of uncertainty can be compared, analyzed and combined using a probabilistic procedure. For a given level of uncertainty in the problem, the implied level of reliability can also be quantified, thus allowing for comparison of the safety (reliability) of alternative designs (Tang, 1993).

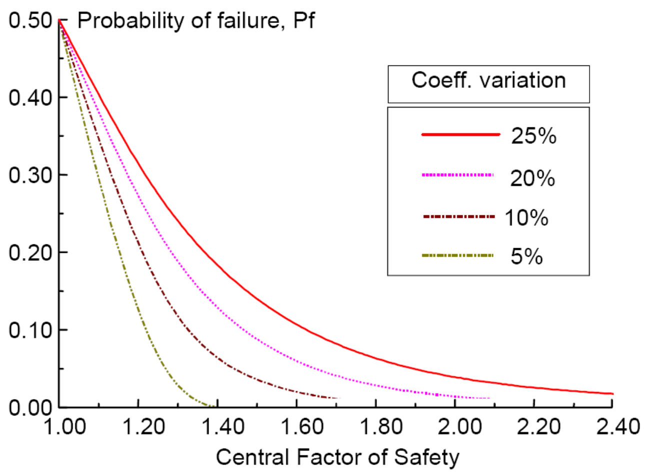


Figure 15. Variation of probability of failure with respect to the central factor of safety, defined as expected capacity over expected demand, for different coefficients of variation (Bieniawski et al., 1994)

A practical way to assess the reliability of a design solution is to consider the safety margin (S), which is defined by the difference between capacity (C) and demand (D). Inadequacy of a design is considered within the negative portion of the safety margin distribution:

$$Pf = P[(C-D) \le 0] = P[S \le 0] \quad (1)$$

Another measure of a design adequacy is the reliability index, β, defined as the inverse of the coefficient of variation of S (mean μ(S) over the standard deviation σ(S)):

$$\beta = {}^{\mu(S)}\!/_{\sigma(S)} \quad (2)$$

In general, any reliability-based analyses shall consist of the following steps:

1. Definition of the empirical, analytical or numerical model that is suitable for the rock mass conditions - structure interface.
2. Definition of the character of the input variables, deterministic or probabilistic (stochastic).
3. Fitting the appropriate pdf to the collected data and/or assignment of an adequate pdf to the stochastic variables.
4. Incorporation of the different sources of uncertainty in the design analysis methods. There are mainly three approaches for doing so:
   - Monte Carlo simulation (Metropolis and Ulam, 1949) where repeated samples are taken from actual or estimated pdf of the variables which enter in a function f (e.g. support capacity) until the distribution of this function is defined with acceptable precision.
   - Taylor series (First Order Second Moment, FOSM method), where Taylor's formula is used for expanding a function *f* about the average value x up to the quadratic term.
   - The Point Estimate Method, PEM (Rosenblueth, 1975), where only two values for each input variable are used to calculate the basic moments of a function *f*.
5. Reliability analysis of the design solution and investigation of its sensitivity to the input varieties.
6. Optimization of the construction practice to maximize the reliability of the design solution selected.

5.2 Determining Reliability of Support System

The reliability based design can properly incorporated in one of the most common tunnel design methods, namely, empirical, analytical, and numerical.

5.2.1 *Description of the applied method*

Empirical methods are generally limited to the case of response to excavation in elastic-domain or very limited extension of plastic/damaged zone, where rock block falling is the typical instability. In Figure 16, an example of application of the RMi system is presented.

In empirical methods, a reliable support design is mostly assigned with variability range in the thickness of shotcrete and spacing of the bolting or steel ribs.

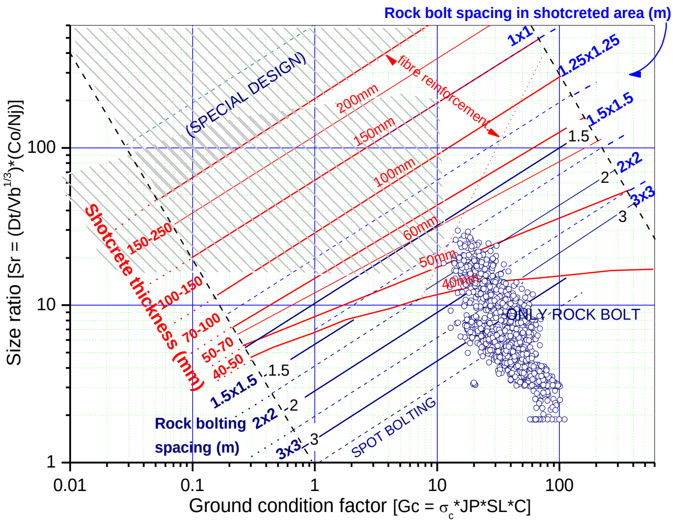


Figure 16. Example of probabilistic application of the RMi system of Palmstrom (2000) to define the support system based on the input variability of geomechanical parameters

On the other hand, as regards analytical methods mostly based on convergence-confinement method (CCM), it is suitable for analysis of the rock mass manifesting elasto-perfectly plastic and elasto-strain softening or hardening with a considerable extension of the plastic zone. Hence, the analytical methods can be used to evaluate most geomechanical risks like slightly, medium, and severe time-independent deformation (only large deformation) or time-dependent squeezing ground condition, fault and shear zone influence zones, incorporation of pore water pressure on support and so on.

Figure 17 shows the distinct logical steps to be followed for the reliability design of support system by means of CCM.

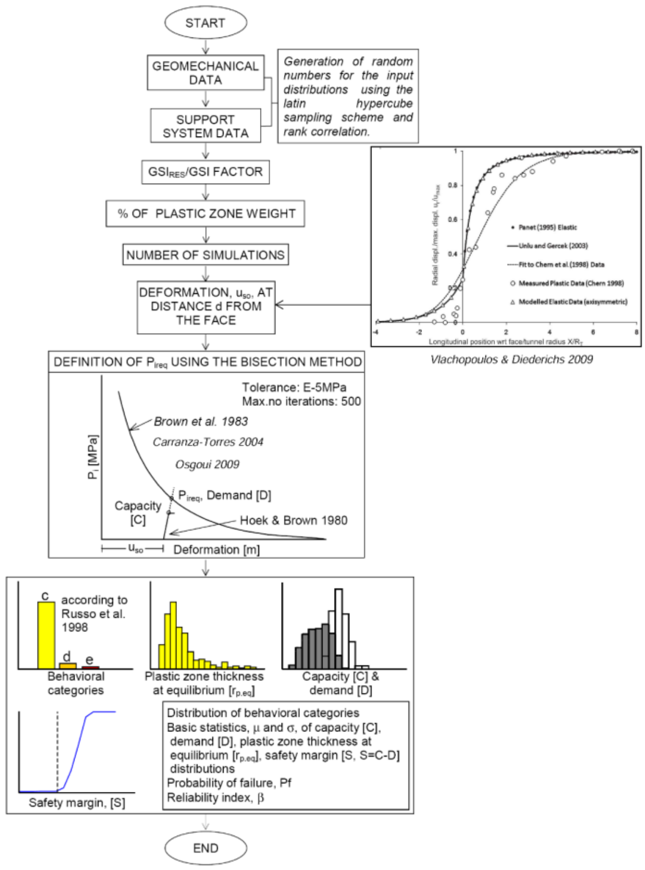


Figure 17. Logical steps of reliability design of support system using the integration of Monte-Carlo simulation and CCM

As observed, the final goal is to work out the reliability of the assigned support in terms of probability of failure "*Pf*" and reliability index "*β*", resulting adequately in optimizing chosen support system.

In terms of decision making and with respect to cost of the support system, one can evaluate different design alternative taking into account the responsibility of the residual risk of support failure. Figure 18 demonstrates the ranges of safety margin "S" of two support solutions envisaged for a tunnel in South America.

Figure 19 are the examples of reliable design method used for verification of support sections in elasto-plastic domain of rock mass behaviour defined properly for time-independent deformation and time-dependent squeezing ground condition in El-Teniente Mine.

Recently the reliable based design approach has been implemented in numerical methods both explicitly and implicitly (Fig.20). The implicit way is to integrate the

Point Estimate Method (PEM) to allow for the uncertainties in design. The example presented in Figure 20, shows the application of reliability based design in limit state verification of a concrete (shotcrete) lining.

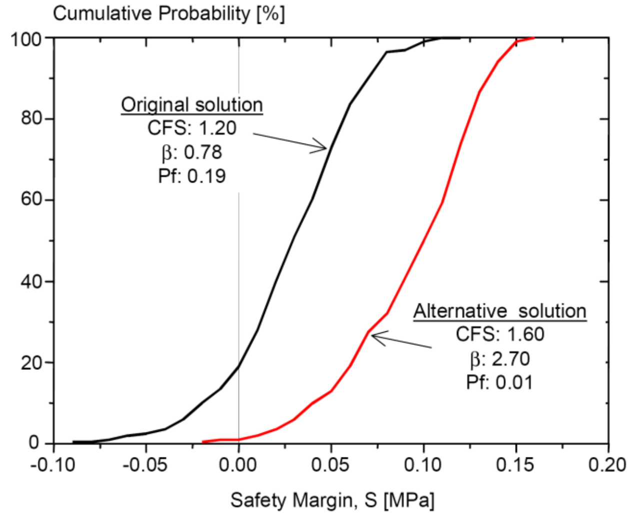


Figure 18. Cumulative distributions of safety margin for original(shotcrete and rockbolts) and alternative (shotcrete and steelsets) primary support solutions for a railway tunnel in South America

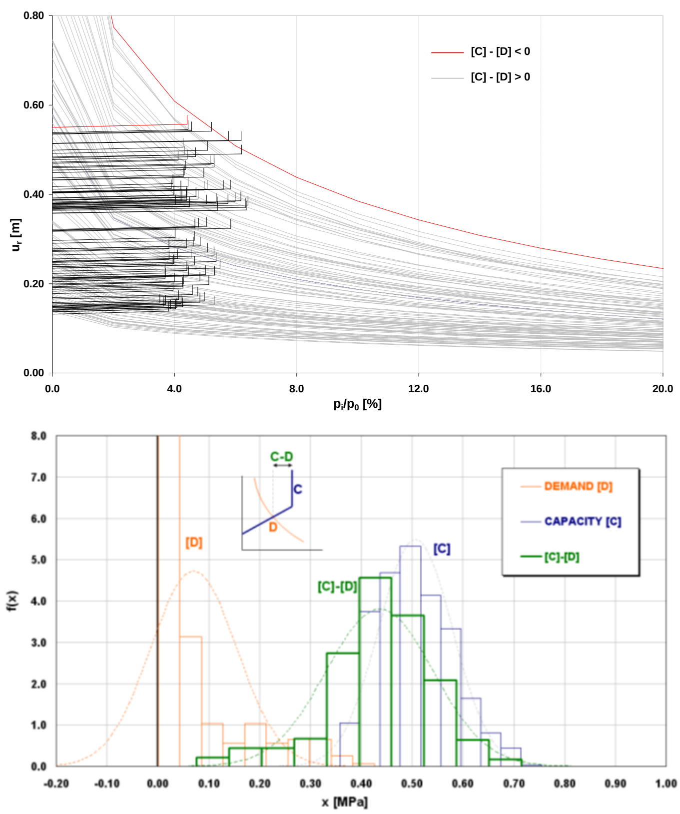


Figure 19. Probabilistic implementation of the Convergence-Confinement method (Top: rock-support interaction with red marked case that not reached to equilibrium), used for the estimation of the Safety Margin by the "Capacity-Demand" analysis (Down).

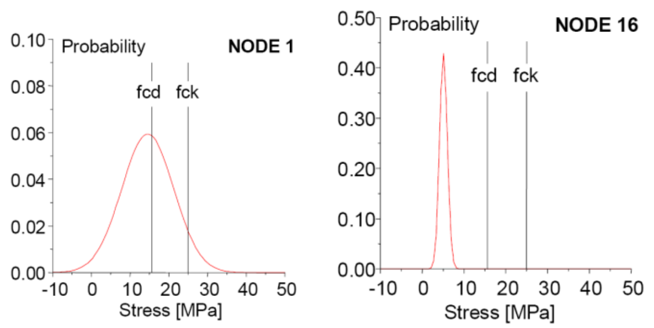


Figure 20. Distribution of numerically obtained stresses in invert and sidewall of a tunnel by means of PEM (Russo et al., 1999). fck and fcd signify the characteristics and design value of compressive strength of concrete in 28 days, respectively

The nodes 1 and 16 stand for measured point of stress in the crown and side wall, respectively, of a tunnel analyzed by numerical method. The distribution of probability was drawn by PEM. As seen, while the invert lining (Node 1) of tunnel is over-stressed (tensile stress (-)) and an unacceptable probability of failure results, the resulting stresses in sidewall of the tunnel are lower than design compressive strength of concrete.

At node 1, more than 50% of probability falls down the capacity of the concrete strength, implying need for either adequate steel reinforcement (steel wire-meshes) or steel fibres at invert to increase the resistance capacity of the lining.

6 NEW CHALLENGE IN HARD ROCK TUNNELLING ASSOCIATED WITH MINING-INDUCED SEISMICITY

Mining-induced seismicity and the related phenomenon of rockbursts (violent type of brittle spalling failure mode) have become more prevalent in hard rock mining. Similarly tunnelling engineering both conventional and mechanized have been suffering from such serious events at long and deep tunnels whole around the world. Recently, many case records have experienced severe rockburts damages. Even though a dozen of research studies on the rockburst have been published more recently and being applied in the field of tunnelling (Kaiser and Cai 2012, Cai 2013, Diederichs et al. 2010, Diederichs et al. 2013, Perras and Diederichs 2016, Hoek and Marinos 2009), hardly any have detailed the practical solution in terms of effectiveness of the support type for such a risk.

In the event of a rockburst, the support system will be subjected to large, rapid deformations. It must be able to absorb energy rapidly in decelerating and limiting the displacements of blocks of fractured rock.

More recently, South American tunnelling in both mining and civil engineering has faced up with the rockburst events, even with fatal losses.

In Figure 21, the derived approximate relationship between the Damage Index and the estimated energy released by the rockburst events is presented. As can be observed, the main rockburst events occurred indicatively in the range DI=0.8 & 0.9, i.e in the domain of the "serious overbreak" presented in Figure 23 (Diederichs et al. 2010).

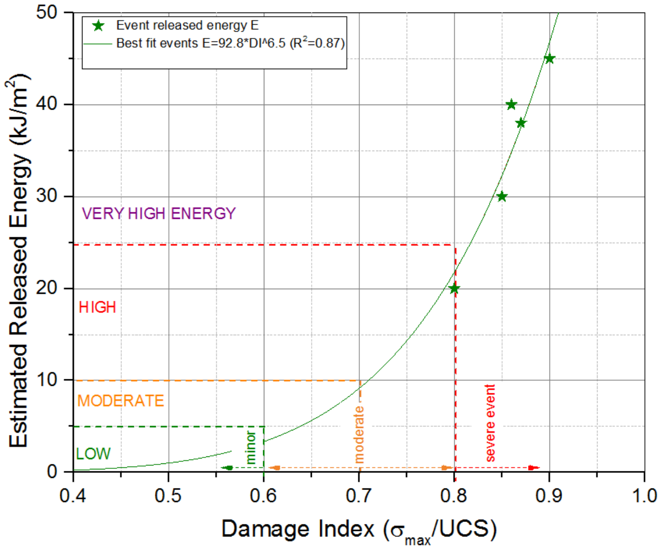


Figure 21. Example of approximate relationship between the calculated Damage Indices and the estimated energy released by the most significant. The data are referred as well to the Energy and Spalling classifications proposed by the CRRH (Canadian Rockburst Research Handbook" CAMIRO", 1996 and Diederichs et al. (2010).

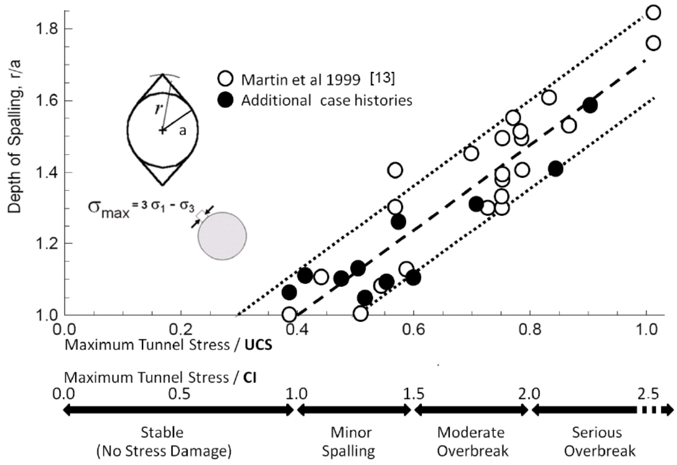


Figure 22. Empirical prediction of spall related overbreak depth (Diederichs et al., 2010)

As can be seen, a rather satisfactory fitting with the estimated released energy was derived. However, the effective occurrence and severity of rockburst events mainly depends also on local conditions affecting the excavation system stiffness. This would be main reason for uncertainty and randomness associated with rockburst event that should properly manage through a pertinent risk analysis approach.

In Figure 22 the empirical prediction of the Depth of brittle failure (Martin et al., 1999) based on the Damage Index DI=σmax/UCS is presented together with the Spalling classification proposed by Diederichs et al., 2010, which introduced the reference to the Crack Initiation Threshold (CI).

The simplified approach used to model the rockburst event might be the so-called DISL (Damage Initiation and Spalling Limit) approach (Diederichs, 2005) to be implemented by RS2 code of Rocscience.

In Figure 24, the simplified calculation of the difference (ΔSED) between the strain energy density before and after brittle failure is as well provided, remarking the relative zero iso-line, which is the limit of the zone in which strain energy density reduced (i.e. it was released) in the change from peak to post-failure condition.

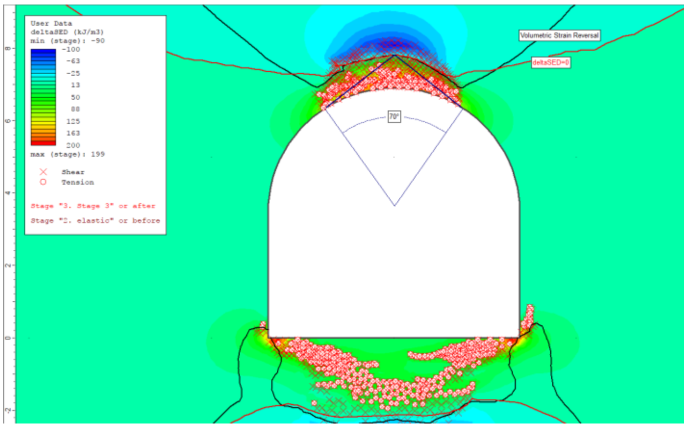


Figure 24. Example of results of ΔSED calculation showing the relative zero iso-line, the Volumetric Strain Reversal and the assumed brittle failure notch according Martin et al.(1999)

According to the approach proposed by Villaescusa et al. (2016), the rockburst ejection velocity is related to the rock strength as indicated in the in graph of Figure 25 and the Energy demand by the support can be consequently calculated on the basis of the involved unstable mass. If the volume of the notch in Figure 18 is taken for reference, the resulting pressure is about 1t/m2 and then Ek=32kJ/m^2.

It should be noted that both induced seismicity and fault/shear band interferences in a complex rock mass may further accentuate the severity of rockburst and relative randomness.

In such a severe environment the importance of seismic monitoring is fundamental and additional effort should be focused in understanding the complex mechanisms of interaction and propagation of the events in relationship to rockburst occurrence.

Figure 26 depicts an effective support system for severe rockburst event that should absorb the released energy of 32kJ/m^2, adopted for the access tunnel of Alto Maipo Project.

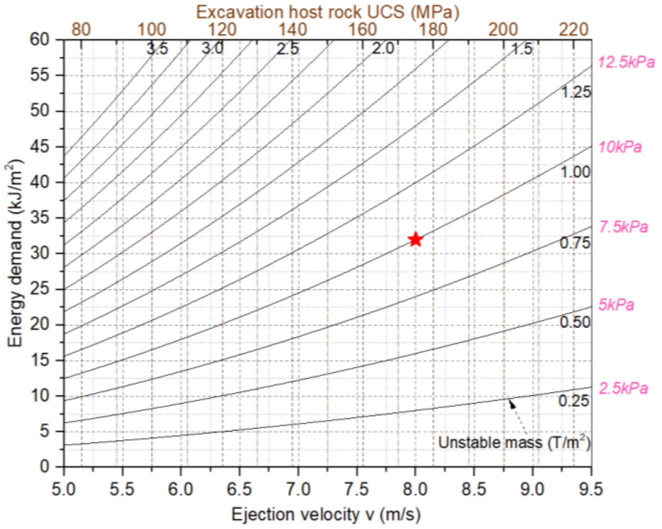


Figure 24. Example of range of energy demand by support system for stress-driven failures in hard rock (derived from Villaescusa et al. 2016)

7 PROBABILISTIC ESTIMATION OF TIME AND COST

On the basis of the expected distribution of Section Types along the tunnels, the probabilistic estimation of the construction time and cost is finally developed, incorporating also the estimated probability and impact of the residual risk.

In particular, the calculation involves the probabilistic assessment of:

- The unitary cost of the Section Types;
- The relative advance rate;
- The time & cost estimation of the residual risk (“accidents” in Fig. 25)
- As observed, mainly on the basis of the geomechanical classification assessments, either the Favourable or Unfavourable scenarios result in the case some better than the basic reference scenario. In particular, by referring to the obtained Expected Values (EV), it is obtained:

•EVFAV ≈ 0.85 EVHLIK
•EVUNFAV ≈ 0.95 EVHLIK

In other words, the reference scenario results about correspondent with the simulated unfavourable scenario and therefore it appears reasonable to expect some more favourable conditions.

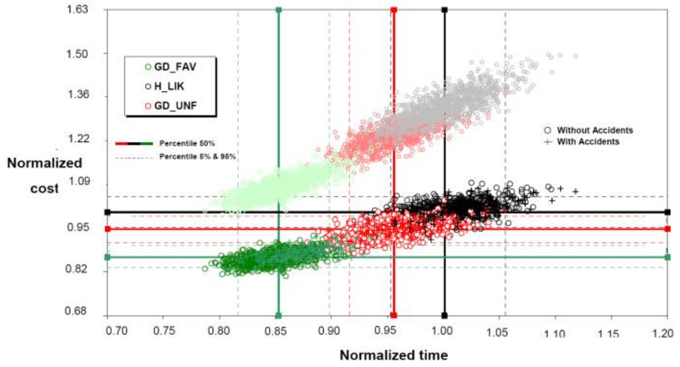


Figure 25. Example of time and cost probabilistic estimation normalized with respect the resulting mean value of the H-lik scenario. Note that the upper shaded clouds incorporate a 5% for year increasing of costs for inflation, etc.

8 CONSTRUCTION STAGE AND THE DETEMINATION OF SUPPORT TYPE

The tunnels and adits of El-Teniente and the other projects are being constructed and GDE provides clients with an experienced team on site collaboration and technical support to Codelco.

Also in this challenging phase, the same basic concepts described in the previous sections are implemented.

For example, the main hazards for the excavation are systematically checked during the advancements of the tunnels, by very detailed face mapping and the concurrent application of the “GDE Multiple graph” (Russo, 2014).

The GDE multiple graph is composed by 4 sectors (Fig. 26), each of them finalized to a user-friendly quantification of the following engineering equations (proceeding clockwise from the bottom-right quadrant to the top-right):

1. Rock block volume (Vb) + Joint Conditions (jC)= Rock mass fabric (GSI);
2. Rock mass fabric (GSI) + Strength of intact rock (σc) = Rock mass strength (□cm)
3. Rock mass strength (σcm) + In situ stress = Competency (IC)
4. Competency (IC) + Self-supporting capacity (RMR) = Excavation behaviour (→Potential hazards)

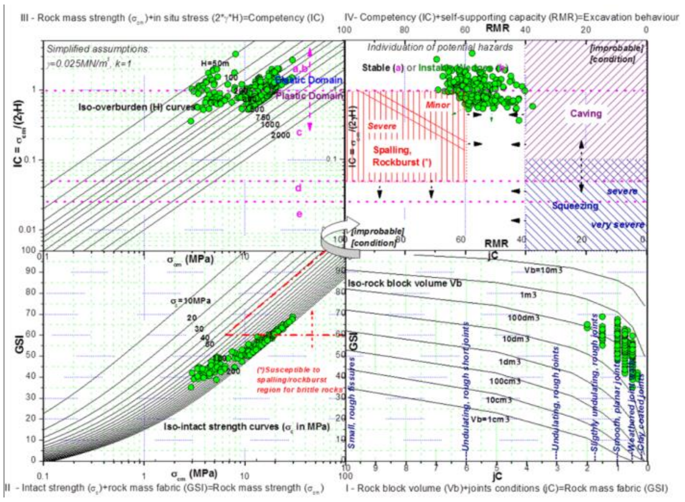


Figure 26. Application of the GDE Multiple graph for one of the main access tunnels

9 CONCLUSIONS

A major problem in tunnelling and mining is that most of design process and above all the decisions must be made under conditions of uncertainty. In reality, both the design and construction phases are always characterized with a certain degree of uncertainty. If not properly recognized and acknowledged, the undesired safety, cost, and time impact would fail the project, causing severe claims among involving parties of the project.

More recently, due to significant rise in tunnelling projects in complex and difficult ground conditions under certain degree of uncertainty and variability, particularly in great depth, the claim issues have become a serious problem.

Many international consulting engineer and insurance companies are in charge of judging and engineering observation to settle the claim and to reach common compromise. However, most of engineering judgment and arbitration, usually qualitative, may result in misleading decision.

The risk analysis-driven design approach presented in this paper aims to identify and to quantify the risk or potential problem, select and implement the measures mitigating or controlling the risk, and indicate if there is a residual risk which would need to be shared among the parties involved in the project and for further decision making. This ability of the approach makes it possible for all parties and joint ventures engaged in the project to recognize and to understand the possibly associated risks and to share the residual risks. Therefore, in case of happening a serious problem in tunnelling activity, a efficient action may, in common, be agreed and activated.

A risk management plan would help the client to depict the perspective of the project from the bidding phase to construction in terms of possibly inherent risks. The case of El-Teniente mine described in this paper is a successful case in which the client and all engineering firms have already been informed with the potential geological and geomechanical hazards such that almost all construction operation have not been interrupted by reason of unwanted geo-problems.

ACKNOWLEDGMENT

The authors wish to acknowledge the contributions and assistance of all their colleagues of GEODATA Engineering since late 1990s, those who have had an important role in originating and developing of risk-analysis-driven design as a part of overall risk management plan. But for them, this invited lecture has not been prepared and presented.

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