The Risk Analysis Applied to Deep Tunnels Design—El Teniente New Mine Level Access Tunnels, Chile

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Abstract

El Teniente Mine, with 2,400 km of tunnels excavated since the beginning of the last Century is the largest underground copper mine in the world. El Teniente Mine production plan has a thin overlap between the exhaustion of the current production level and the activation of the New Mine Level, located at almost 1,000 m depth, planned for 2017. The infrastructure system involves the construction of 24 km of access tunnels, consisting of two adits, a tunnel for vehicular access of personnel and a twin conveyor tunnel for the transport of the ore. The definition of geological and geomechanical scenarios, as predicted on the basis of the reference models, and the related hazards identification and mitigation (following a risk analysis based design), are cornerstones along the production chain. Tunnel alignment intersects a complex geological environment characterized by rock variability: from igneous (effusive and intrusive) to sedimentary volcanoclastic rocks, with sectors of intense hydrothermal alteration. Due to high overburden and variability of rock mass properties, geomechanical hazards such as squeezing and rockburst are expected, together with caving and flowing-ground conditions crossing fault sectors associated with high hydraulic pressures. This paper synthesizes the design methodology, focused on risk management (Risk Analysis-driven Design, Geodata 2009). The construction of the tunnel is actually in process and then also a preliminary comparison “predicted versus observed” is anticipated.

Keywords

Risk management plan • Risk analysis-driven design • Probabilistic reference scenarios • Hazards mitigation measures

186.1 Introduction

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 2,400 km of deep tunnels producing more than 400,000 tons per year of fine copper.

El Teniente Mine production plan has a thin overlap between the exhaustion of the current production level and the activation of the New Mine Level (NML), located at almost 1,000 m depth, planned for 2017. The underground infrastructures are under construction; the NML will extend life of the mine by 50 years; a deeper level has been investigated at 1,400 m depth (Fig. 186.1).

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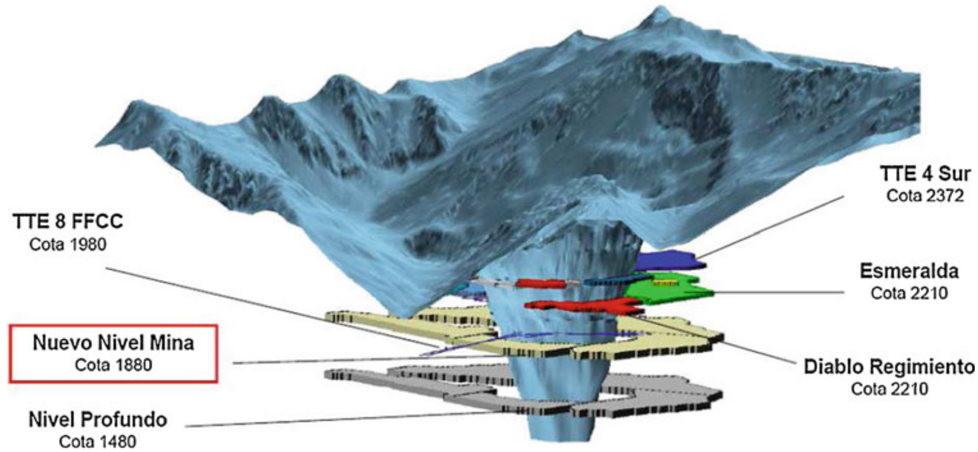


Fig. 186.1 Mine levels (by Codelco)

The NML project foreseen the construction of 24 km of access tunnels, consisting of two adits (Ltot = 6 km) and two main tunnels (Ltot = 9 + 9 km): a tunnel for vehicular access of personnel and a twin conveyor tunnel for the transport of the ore. Geodata Engineering (GDE), as a consultant of Codelco and tunnels Contractor's counterpart on geotechnical issues, has been present on site since April 2012.

Prior to the construction phase, Geodata Engineering (GDE in association with Ingeroc) developed for Codelco a design for the two main tunnels, based on the risk analysis (Risk Analysis-driven Design, RAdD) as reference for the owner about engineering solutions and construction costs and time assessment. Conventional and mechanized excavation methodologies were analyzed.

Constructora de Túneles Mineros–joint venture between Soletanche Bachy and Vinci (CTMSA) won proposing the conventional method (D&B), with two additional adits to increase the number of parallel advances along the main access tunnels (Fig. 186.2). Actually the constructions of both the main access tunnels and the adits are in process.

186.2 Risk Analysis-Driven Design (RAdD)

The design and construction of long tunnels particularly those at great depth, is generally associated with a high level of risks due to a whole series of uncertainties involved. The risk management approach consists in identifying and listing

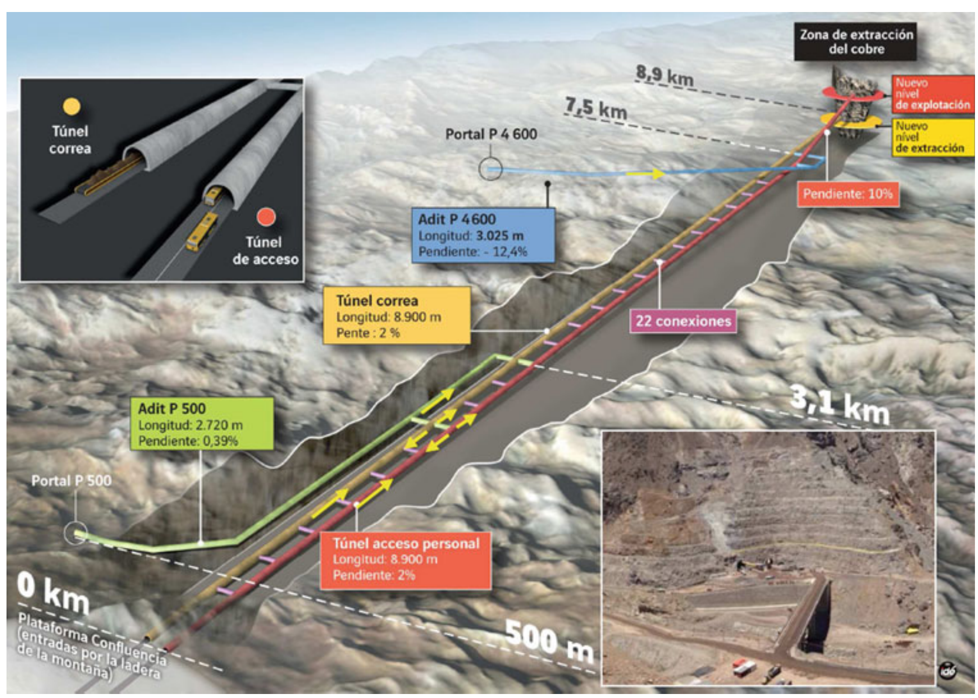
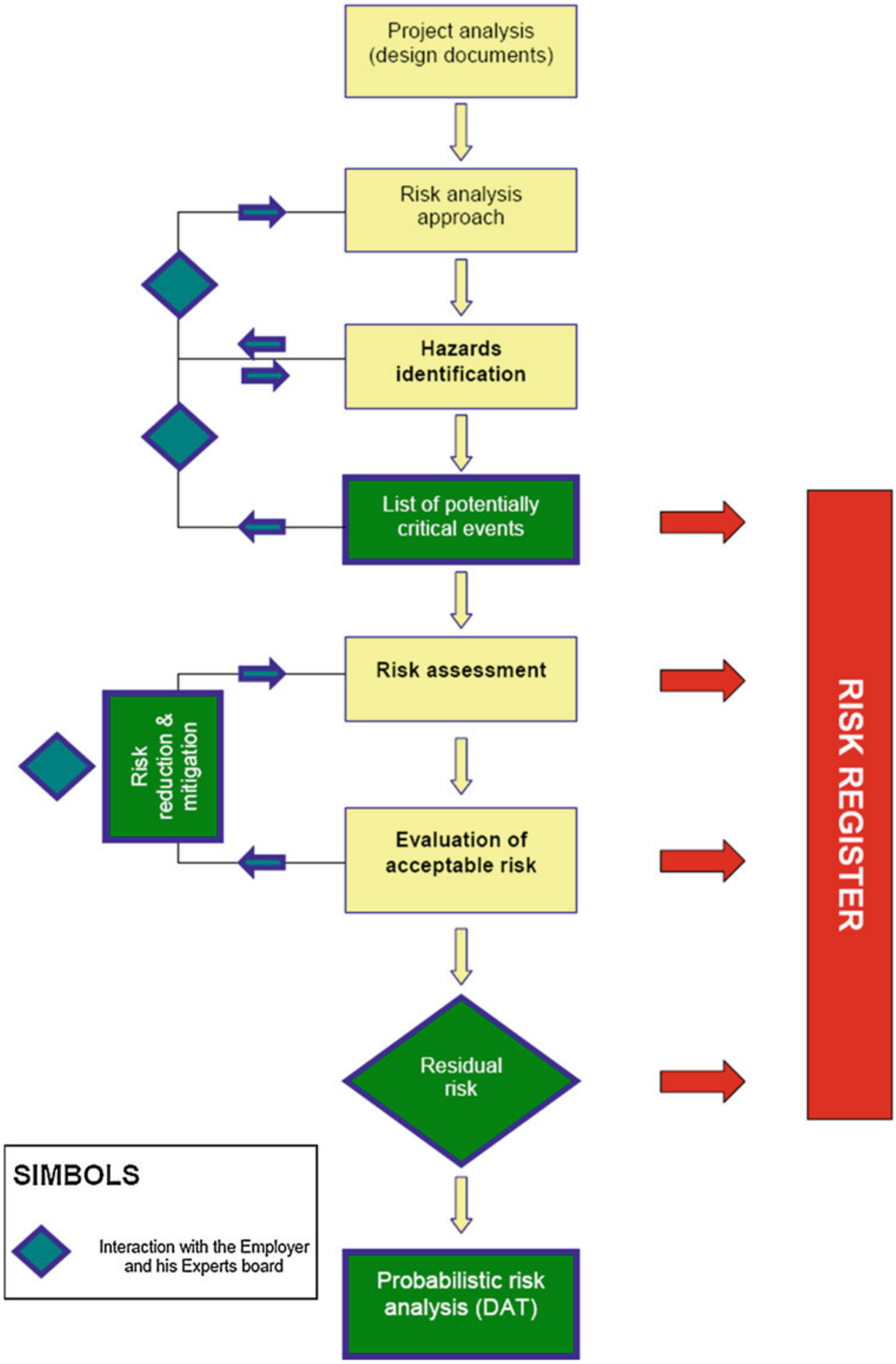


Fig. 186.2 NML tunnel access system (by CTMSA)

Fig. 186.3 RAdD flow chart



the potential hazards associated with the tunneling activities, assigning a probability of occurrence to each hazard, and allocating an index of severity to the consequence (impact). Two main categories of hazard events are identified in connection to geological and geomechanical issues, namely: (Fig. 186.3)

- Hazard phenomena associated with unfavorable *geological conditions* (fault, water acidity, etc.)

- Geomechanical hazard related to *rock mass behaviour* upon excavation (squeezing, rockburst, etc.).

The risk (R) is defined as the product of the probability of occurrence of the hazard (P) and the related impact (I): R = P*I. In cases where the initial risk (i.e. the risk to which the project is exposed in absence of any mitigation measure) level is not acceptable, the relevant mitigating measures should be identified and designed.

After application of the mitigation measures, an analysis should be performed to reassess the remaining risk level, obtaining an updated risk level, which is called the "residual risk level". It should be examined for acceptance as the maximum risk level that is to be confronted with its "global cost", necessary for reducing or completely eliminating the risk itself.

All the relevant information about the hazards, the associated risks and counter measures are filled and regularly reviewed in a risk register.

186.3 Geological Setting and Related Risks

The regional geology of El Teniente area is characterized by volcanic rocks and sedimentary volcanoclastic deposits, with felsic to intermediate intrusive. As shown in the Geological Reference Model, proceeding from West (portal) to East (mine), the following lithological formations and Rock Mass Unit (RMU) would be crossed:

- Farellones Formation lower and undifferentiated members (FFm, RMU.V1-V2)
- Agua Amarga Hydrotermal Alteration and Breccia (RMU.AA)
- Sewell intrusive Complex (CSW, RMU.i1-CQ-i2)
- El Teniente Mafic Complex (CMET, RMU.i3)
- Braden Breccia (RMU.BB).

The tunnel axis crosses three major faults (F1, F2) and a large number of minor faults (F4). Moreover the El Teniente shear zone (F3) is foreseen along CSW and CMET formations. On the basis of the Geological Reference Report (GRR Codelco-Hatch 2009), some potential geological hazards were identified. Among them, the main ones in terms of impact are: geological structures, hydraulic load and water pH, natural stress field and anisotropy, rock weathering and hydrothermal alteration (Fig. 186.4).

Moreover some additional hazards were analyzed for the mechanized method (TBM): rock hardness-abrasiveness and heterogeneity. The main geological hazards are probabilistically quantified and the risk register is compiled, both for D&B and TBM, considering the required mitigation measures for each potential risk. Since March 2012, the following geomechanical units have been excavated: RMU.V1 and RMU.V2 in FFm (main tunnels and Adit 1); the structural contact RMU. V2/AA (Adit 1) and RMU.I2 in CSW (Adit 2).

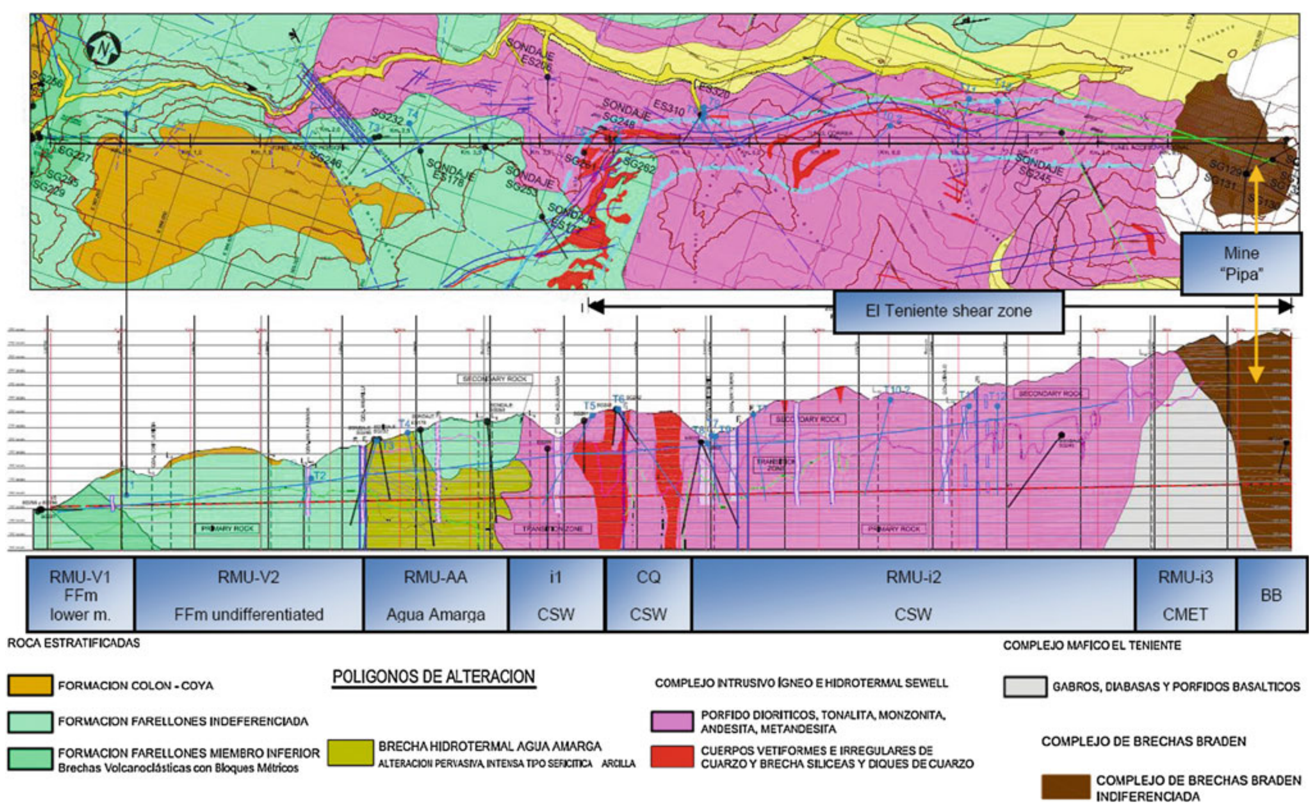


Fig. 186.4 Geological setting

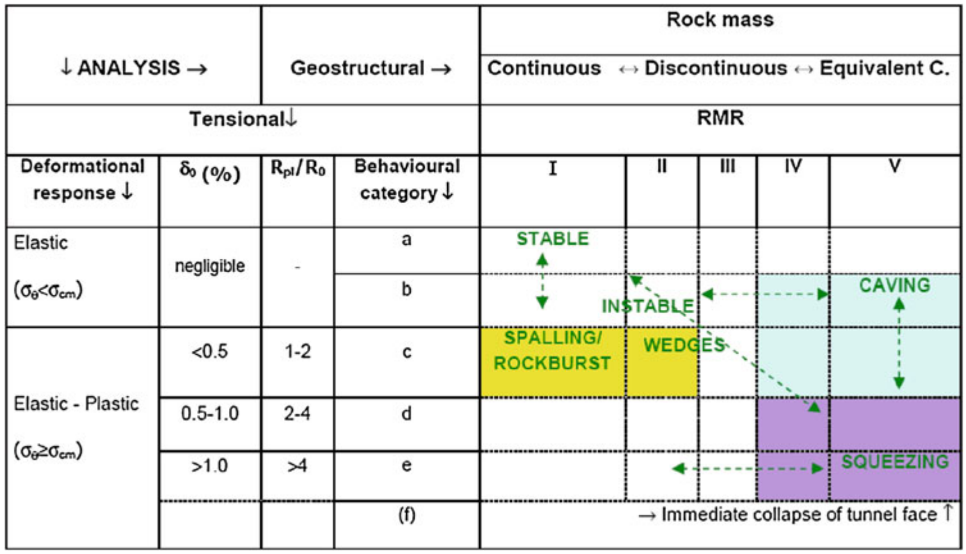


Fig. 186.5 GD Classification (*Notes* Russo and Grasso (2007); δ_0 = radial deformation at the face; R_{pl}/R_0 = palstic radius/ radius of the cavity; σ_θ = max tangential stress; σ_{cm} = rock mass strength. The limits of shadow zones are just indiactive) of the excavation behaviour

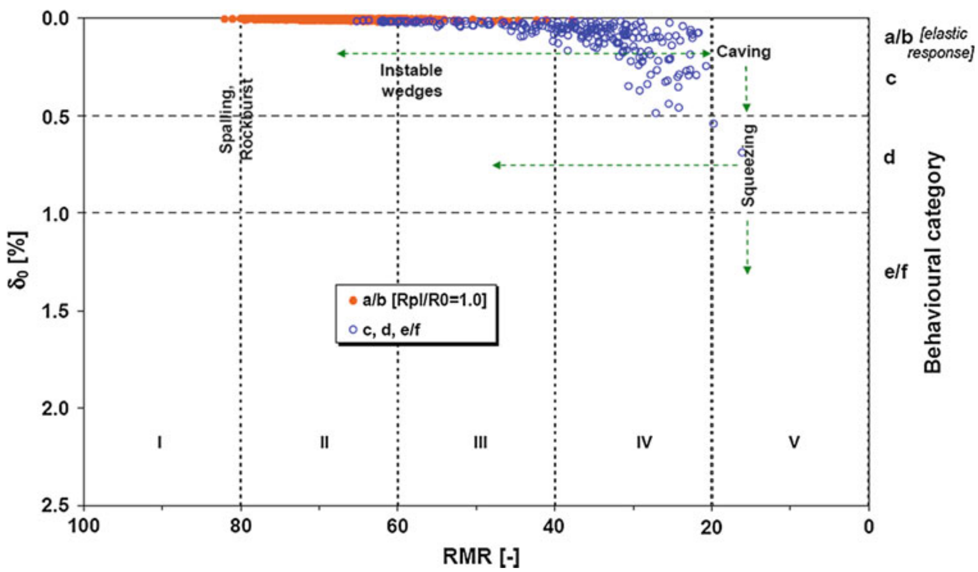


Fig. 186.6 Design scatter diagrams (RMU.V1)

Fig. 186.7 Hazard probability/ intensity (RMU.V1-V2)

RMU Rock Mass Unit (Overburden)	Scenario ↓ / Intensity →	Hazard [%] Wedge instability / Rockfall s1	Wedge instability / Rockfall s2	Wedge instability / Rockfall s3	Caving s2	Caving s3	Squeezing s2	Squeezing s3	Spalling/Rockurst s1	Spalling/Rockurst s2	Spalling/Rockurst s3
V1 (40<H<290m)	H_LIK	0.3%	67.1%	16.1%	15.0%	0.0%	0.20%	0.0%	1.3%	0.0%	0.0%
	GD_FAV	28.0%	35.1%	29.4%	7.4%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
	GD_UNF	0.6%	38.6%	45.3%	15.0%	0.3%	0.0%	0.0%	0.2%	0.0%	0.0%
V2 (250<H<420m)	H_LIK	12.3%	33.1%	38.8%	8.1%	0.7%	1.5%	0.5%	4.7%	0.3%	0.0%
	GD_FAV	15.2%	39.0%	32.6%	5.5%	0.0%	1.5%	0.2%	5.2%	0.8%	0.0%
	GD_UNF	8.2%	25.6%	40.1%	11.3%	2.2%	3.7%	2.0%	6.2%	0.7%	0.0%

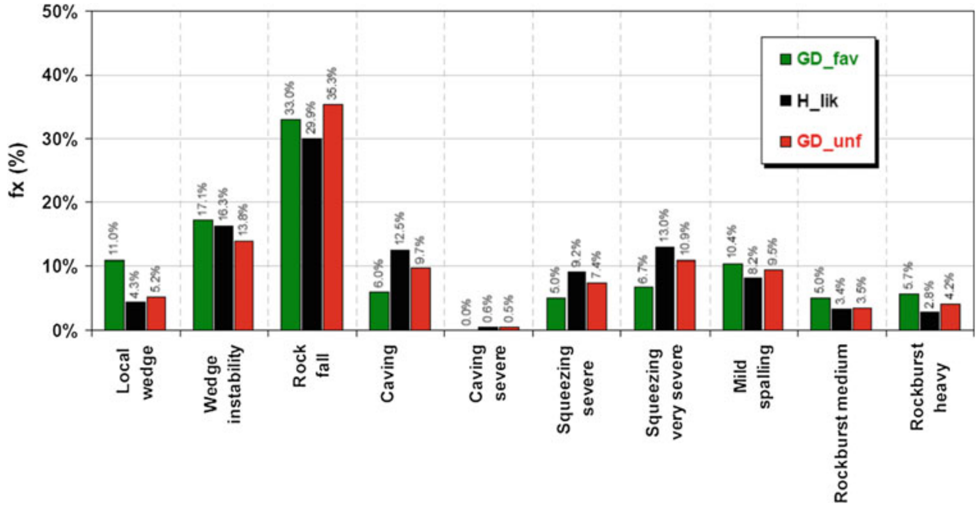


Fig. 186.8 Hazards frequency: probabilistic results for the n.3 scenarios of reference (9 km in personnel tunnel)

Fig. 186.9 Risk register (RMU. V2)

Hazard identification (CATEGORY / Sub-category / TYPE / Sub-type / HAZARD)		Primary risk: Hazard Probab. [P]	D&B Impact [I]	D&B Risk [R=PxI]	TBM Impact [I]	TBM Risk [R=PxI]	Mitigation measures* (*or cross-reference to geomechanical hazard [→]) D&B	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,M06,M07,M08,M24	M01,M08,M22,M24,M25,M27
Stress induced instability								
B3	ROCKBURST	2	3	6	2	4	M1,M2,M21,M23,M26,M27	M01,M22,M23,M26
B4	SQUEEZING, FACE EXTRUSION	2	3	6	4	8	M01,M02,M05,M07,M21,M24,M25,M27	M01,M22,M25,M27
Mainly water influenced (fault zone)								
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	

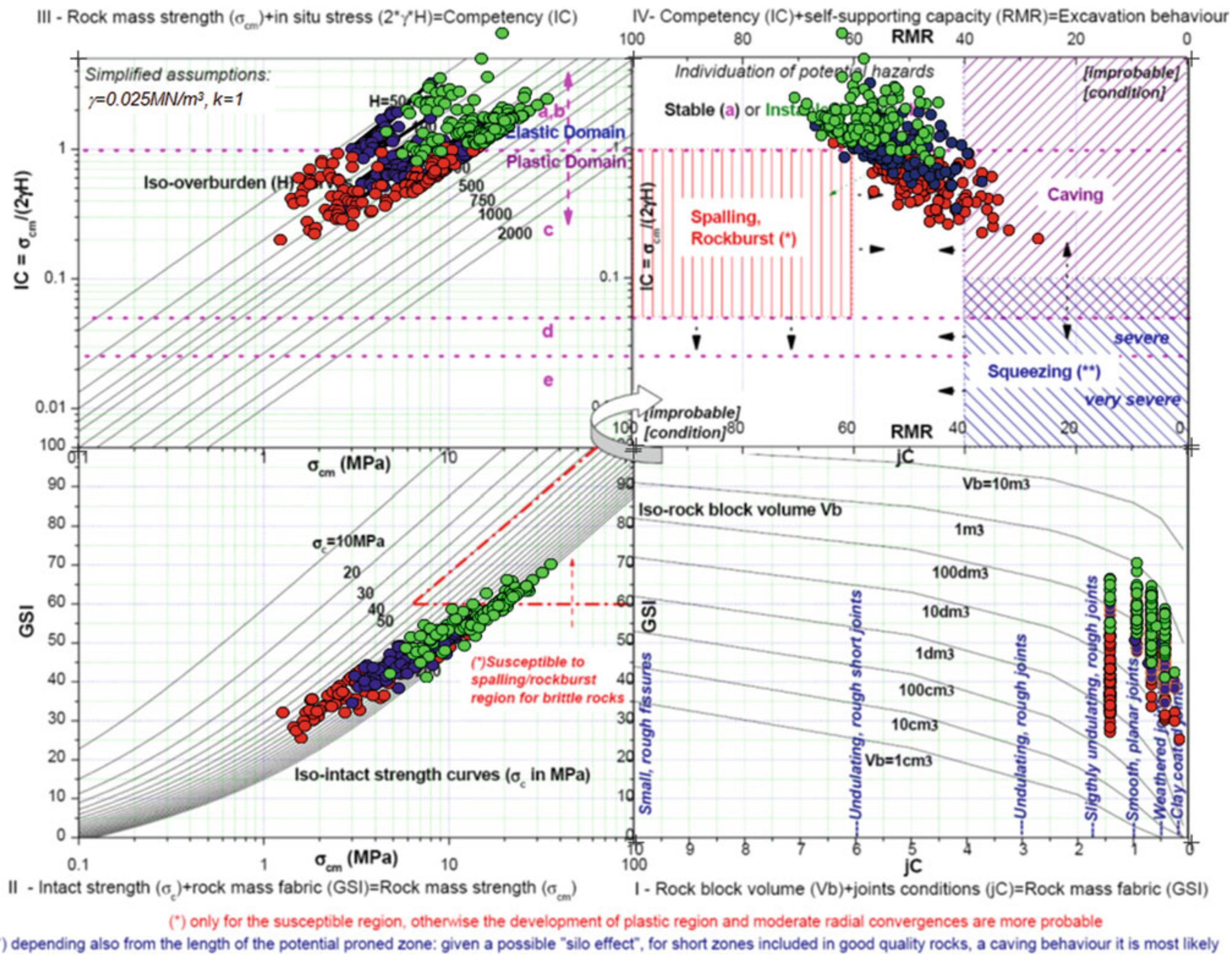


Fig. 186.10 RMU-V1, results of the geomechanical classification at tunnel face by the method of GDE multiple graph (Russo 2009)

186.4 Geomechanical and Residual Risks

The first step for RAdD is the geotechnical characterization of the different RMU. Related to the available information, the statistical analysis has adopted different approaches in order to define, in a probabilistic way, the three reference scenarios as geomechanical inputs for design: the most-likely scenario (from previous studies: H_lik), the favorable and the unfavorable ones (by data processing: GDE_fav/unf). 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 reference classification of the excavation behaviour is based on both stress and geo-structural type analysis (matrix in Fig. 186.5), in the theoretical hypothesis of absence of any design interventions (→primary risk).

An example of the resulting design scatter diagrams is presented for one of the rock mass unit excavated in the personnel tunnel (RMU-V1, Fig. 186.6). The assessment of the geomechanical risks is obtained with reference to the occurrence probability and intensity of the related hazards. Along RMU V1 and V2, mainly geomechanical hazards due to gravity, as wedge instability, are expected (Figs. 186.7 and 186.8). The risk analysis proceeds with the initial risk assessment. Its evaluation involves the estimate of the potential impact (consequence) deriving from the damages related to the identified hazards. The Risk Register (Fig. 186.9) is consequently compiled for each RMU, both for the D&B and the TBM methods. The type and the dimensioning of the stabilization measures will be directly related to the hazards and their potential impact on tunneling (→primary risk). The adequate mitigation measures (design solutions) are consequently individuated, concurring to the composition of the different Section Types, dimensioned and probabilistically distributed along the tunnels. The last step for risk analysis process is the assessment of the new risk level obtained after the application of the design (→residual risk). The risk has been managed and reduced from its initial (primary) level to a lower (residual) value. If all the initial risks have been mitigated and the tunnels construction is not more exposed to unacceptable risks but the residual risk level remains classified as unwanted, some counter-measures are consequently defined.

186.5 Construction

The construction of the NMN tunnel access system started on March 2012, with the Adit 1. Currently, 18 months after the beginning, almost the 35 % of the 24 km totals has been excavated. The experience along the Adit 1 and the two main tunnels (RMU V1-V2 and contact zone RMU.V2/AA), permits to have a comparison with RAdD-design expected conditions. Outside from gully influence areas, along ordinary rock mass sections in RMU.V1-V2, the instabilities mainly related to gravity (wedge instability, rock fall with a lower probability of caving) were expected by GDE risk analysis. By the comparison among data collected during the advancement in RMU.V1, summarized by the method of the "GDE Multiple Graph" (Russo 2009; Fig. 186.10), and the probability of occurrence of the hazards expected by the design (Figs. 186.6 and 186.7, referred to RMU.V1), the reliability and effectiveness of the adopted risk analysis approach is confirmed.

186.6 Conclusions

Eighteen months of advancements in the NMN access tunnel, allow to obtain a first positive feedback on RAdD results. The Risk Analysis is a process that should support and follow a project, from the conceptual up to the construction stage.

The risk should be managed through the implementation of a specific Risk Management Plan (RPM, Grasso et al. 2002), fully integrated in each part of the design study, in accordance to a real development of a "Risk Analysis-driven Design".

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