How to Quantify the Reliability of a Geological and Geotechnical Reference Model in Underground Projects

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ABSTRACT

Today the Geotechnical Baseline Report (GBR) and the Geotechnical Database Report, (GDR), are becoming standard contractual documents in any underground project to describe the expected geological and geotechnical conditions. The GBR contains a synthesis of all the acquired geotechnical data listed in the more comprehensive and purely factual GDR, and ultimately provides a geotechnical reference model for the project. Despite this, usually few or no information about the reliability of the model are provided. The article intends to present the R-Index innovative methodology, a quantitative method to evaluate the reliability of the Geological Reference Model through a multiparametric approach and to improve the geological risk assessment. Applied examples from an alpine base tunnels (TELT) will be presented.

INTRODUCTION

Tunneling industry is daily faced worldwide with major contractual issues related to unexpected subsurface conditions and their impacts in terms of cost increases and schedule delays. The tunneling community, represented by the International Tunneling Association (ITA), has not still reached a common and homogeneous approach on this matter, also due to the laws, rules and regulations which are very often defined by each Country in which the underground project is realized. However, ITA Working Groups, made multiple suggestions in several contributions published in 2011 (WG3), 2013 (WG19), 2014 (WG4) 2016 (WG14/19) and 2017 (WG17), referring to the GBR as a common and useful practice to define the expected geotechnical conditions.

Today the literature about this subject is quite wide and articulated, vary from legal contributions to technical papers regarding specific case histories. Almost everyone agrees in the need to define the appropriate tools to clearly allocate risks and liabilities in subsurface projects between Owners and Contractors.

The tunneling community is also quite aligned in claiming the need to have a geotechnical baseline to develop the project and allocate the risks, by the Contractor to price the works during the tender phase and by both the Owner and the Contractor to determine and manage the differing site conditions (DSC).

In spite of this, only few contributions and suggested methodologies have been dedicated to the qualification and quantification of the uncertainties related to the geotechnical baselines, or, in other words, to the quantification of the reliability of the geological models that are the basis of any geotechnical baseline.

This article presents an overview of the state of the art regarding this matter in relation with the GBR, which seems to become more and more a common practice not only for the North American tunneling industry but for many other underground markets worldwide.

The ultimate goal of this contribution is to set up a certain number of concepts related to the determination of the reliability of geological modelling for underground projects, which will certainly require a more in-depth treatment in the future, with the involvement of specific Organizations to acquire the consensus and ultimately to let the quantification of the reliability (or uncertainty) becoming a common practice to decrease or efficiently manage risks in tunneling.

THE GBR APPROACH

The Suggested Guidelines to prepare Geotechnical Baseline Reports (GBR) for Construction (Essex 2007, Essex et al., 2001) states in its executive summary that "The primary purpose of the GBR is to establish a single source document where contractual statements describe the geotechnical conditions anticipated (or to be assumed) to be encountered during underground and subsurface construction. The contractual statement(s) are referred to as baselines."

While some contract models require the contractor to validate and/or interpret unwarranted geological information provided by the owner (and thereby assume some level of risk, notwithstanding the application of unit price and change order mechanisms) or to execute their own investigations, the following discussion is confined to contract scenarios in which the geological and geotechnical methods are to be fully specified by the owner at the bid stage.

"Risks associated with conditions consistent with or less adverse than the baselines are allocated to the Contractor, and those materially more adverse than the baselines are accepted by the Owner. (…) The baselines should be meaningful, reasonable and realistic, and to the maximum extent possible should be consistent with available factual information contained in the GDR."

"The greatest risks are associated with the materials encountered and their behavior during excavation and installation of support. The main purpose of the GBR is to clearly define and allocate these risks between the contracting parties."

Translating these major concepts in a graphic, we could represent them as shown in Figure 1. The line represents the state of the expected geotechnical condition during the project execution. In case of no changes, the line would remain horizontal. Any more adverse geological/geotechnical conditions would shift the line in the upper side of the graphic guiding the Owner to calculate and add some contingencies.

The GBR Guidelines recommend to clearly define a unique geotechnical profile to avoid later misunderstanding and to provide a clear set of geotechnical data to be used for the design and the correct choice of the construction methods. All the data sets acquired through the investigations, site and laboratory tests to generate the mentioned data have to be presented in the Geotechnical Database Reports.

This approach certainly allows GBR users to estimate with good detail, ideally supported by statistical parameters, the reliability of the geotechnical parametrization but does not give any information regarding the geological model that has been chosen to describe the baseline and from which the likely geotechnical parameters are based. In other words, the possible changes of the geological baseline today are not quantified

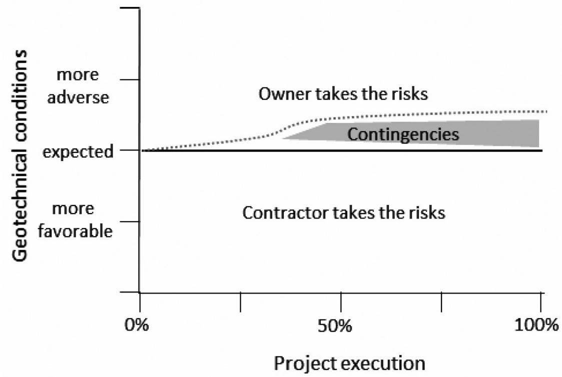


Figure 1. Graphical representation of the geotechnical baseline and the theoretical "contingency" areas

by the GBR; moreover, their qualification is not included in the report and remain an internal discussion between the Owner and the GBR authors.

The aim of this contribution is to share some consideration about possible methodologies which could be useful applied to help the GBR user to qualify and quantify the reliability of the geological model and ultimately to better quantify the contingencies which should be considered while pricing the project.

Uncertainty in Geological Modelling

Geological complexity can vary dramatically from project to project, depending from multiple factors: geological context (sedimentary, plutonic, metamorphic), tectonics (no deformation, folding, faulting, shearing), geodynamics (compression, extension, uplifting), morpho-dynamic (belts, marine, slope, plane, glacial, etc.) and several others.

Geological models are the result of the combination of many of these factors, resulting in 3D structures of different materials with different characteristics, modified during their geological evolution (4D), enabling the delineation of zones in which geotechnical parameter ranges can be specified or specific locations of discrete geotechnical concern.

Using a numeric progressive scale from 1 to 12, the simplest geological models are those constituted by unfolded and un-faulted sediments, deposited in low energy environments and located in the shallow portion of the crust (from 1 to 3). Progressively, models become more complex if affected by brittle and ductile tectonics (from 4 to 7). The combination of sedimentary and plutonic protoliths, folded and faulted generate a further increasing if the geological complexity (from 7 to 10). Finally, the chemical and physical modification of these rocks under variable conditions of temperature and pressure (metamorphism) generate a further increasing of the complexity (from 10 to 12) (Table 1). This table is certainly subjective and does not pretend to define an absolute and unique evaluation scale, also considering how geology can be complex and variable. Nevertheless, this matrix provides a useful tool to quickly evaluate the level of the complexity of the geological model considered as starting point of the geotechnical parametrization.

Complexities from 1 to 6, mainly related to sedimentary and quaternary geology, characterizes most of the urban projects worldwide, meanwhile higher complexities from 6 to 12 usually refer more to infrastructure and water projects located in the major

Table 1. Simplified numerical representation of the geological complexity

Geological complexity (simplified from 1 to 12)						
	Sedimentary		Magmatic		Metamorphic	
	Simple	Difficult	Simple	Difficult	Simple	Difficult
Unfolded	1,2	3	2	3		
Folded	3	4	4	5,6	5	7
Folded + Faulted	4	5	6,7	7,8	8,9	10,11
Folded + Faulted + Sheared		6,7		9	9	12

Table 2. Uncertainty of the different models after a standard site investigation expenditure

Uncertainty (after standard site investigation expenditure)						
	Sedimentary		Magmatic		Metamorphic	
	Simple	Difficult	Simple	Difficult	Simple	Difficult
Unfolded	VL	LM	L	LM		
Folded	LM	LM	LM	M	M	H
Folded + Faulted	LM	M	MH	H	H	VH
Folded + Faulted + Shared		MH		HVH	HVH	EH

VL = very low; L = low; LM = low-medium; M = medium; MH = medium high; H = high; HVH = high- very high; VH = very high; EH = extremely high

mountain belts, like Rockies, Andes, Alpes, Himalaya and several other minor but not less complex orogenic structures worldwide.

As shown in Table 2, the less complex conditions are thus characterized by lower uncertainty (VL to LM) due to the fewer number of elements that interact in the generation of the model, meanwhile the most complex models are characterized by extremely high uncertainty. The uncertainty level represented in Table 2 has been estimated considering a standard site investigation expenditure, represented by (a) bibliographic analysis, (b) comparisons with closer and similar projects (c) geological profiles extrapolated from existing large scale geological interpretative maps and (e) few boreholes and scatter geophysics.

Uncertainty and Baselines

By the definition of a Geotechnical Baseline, geological complexity and its consequent uncertainty do not have a direct impact on the baseline itself, which must be discretely specified for any geological assessment, depending from the experience and sensibility of the engineering team. Complexity and the associated geological uncertainty, rather, largely impacts on potential changes from the initial baseline conditions and, as consequence, on the contingencies and the final project execution schedule.

If, the same graphic shown in Figure 1, we consider different complexity scenarios, we obtain different drifting curves of the baseline, as represented in Figure 2. Although all data are at present qualitative and based on case histories, experience and common sense, the results are quite meaningful. These curves diverge from the baseline following a progressive increase if the geological complexity.

The drifting from the Baseline very rarely happens during the mobilization phase. Some preliminary signs of deviating conditions can appear during the ramp up phase but most of the past experiences show that the appearance of more adverse conditions (compared to the Baseline) is very often encountered between 20 and 50% of the project completion.

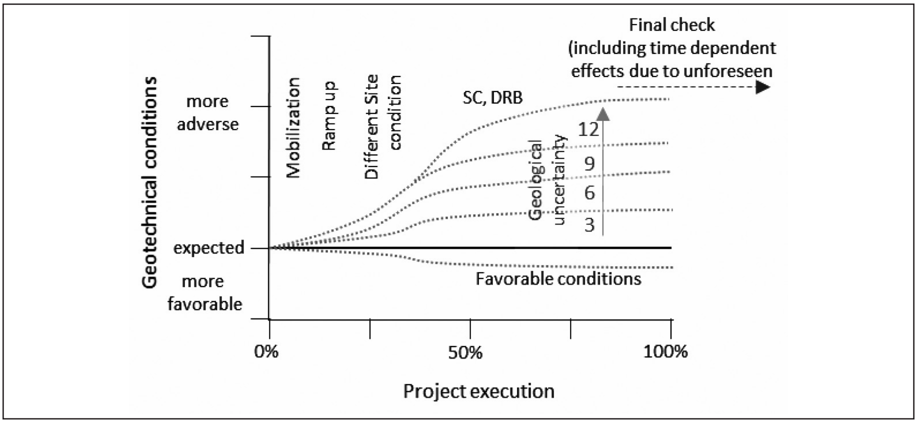


Figure 2. Graphical representation of the geotechnical baseline and the theoretical "contingency" areas: SC = Steering Committee; DR = Dispute Resolution Board; numbers 3 to 12 refer to Table 1.

For the lower complexity models, some adjustment of the Baseline can be made quite easily with minimal impact on costs and timing. In case of high complexity, the Baseline can drift from its original position almost indefinitely with dramatic impacts on the project delivery both in term of budget and schedule. Summarizing these concepts:

- the order of magnitude of potential diverge of the Baseline depends from the complexity of the geological model,
- the uncertainty in the geological forecast (or conversely, the reliability of the geological model) is directly related to the complexity of the model,
- the difference between the Baseline and its potential deviation should be defined to determine the contingencies to mitigate the geological risks,
- contingencies cannot be adequately evaluated without quantifying the uncertainty or reliability of the model.

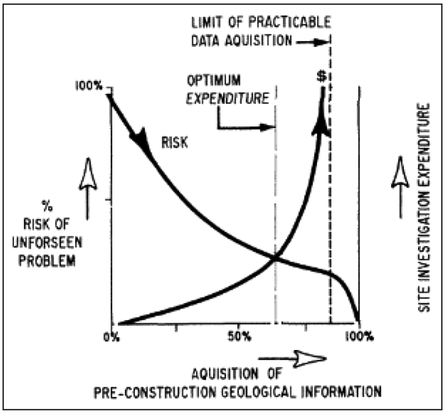
INVESTIGATIONS AND UNCERTAINTY

This first part of this dissertation clearly states that quantify the uncertainty should be considered a major task in any project and certainly in those with complexity ranging from six to twelve.

Uncertainty in geological model leads to uncertainty in failure mode prediction and behavioral uncertainty (Vaan der Pouw Kraan et al 2014) and thereby to performance uncertainty (e.g., Langford et al. 2013, 2015). Recently, the technical and scientific community has engaged in discussions about uncertainty in geological models (Sandersen, 2008; Wellmann et al., 2011, 2014; Schweizer et al., 2017), especially with regard to *Oil & Gas* projects. In spite of that, only few contributions analyze the impact of geological model uncertainty in infrastructure projects. Carter (1992) has shown how the percentage of risk relates to unforeseen geological conditions.

Carter (1992) introduced in two major concepts: (a) the limit of practicable data acquisition, where the site acquisition expenditure curve becomes a vertical asymptote and (b) the optimum expenditure, which is defined as the intersection between the decreasing risk curve and the increasing expenditure curve. Today, in spite of hundreds of projects that have been designed and executed, an extended review of these concepts is still missing, and only general suggestions have been advanced by the ITA-AITES (1996, 2011, 2013, 2014, 2016, 2017) or by other authors (Brierley and Soule, 2009; Parnass et al., 2011; Freeman et al., 2014) at this regard.

The approach proposed by Carter (1992), which had the undeniable value to highlight the importance of correlating geological risks with investigation expenditure, has been revised hereafter, introducing the geological model complexity as one of variables that impact on the shape of these curves. Case A to D in Figure 4 show propose different curves and their consequent results by decreasing the level of complexity.



Source: Carter 1992.

Figure 3. Inverse relationship between the geological risk and site investigation expenditure

Graphics in Figure 4 show four risks curves (sloping downwards from left to right) set at complexity levels 3, 6, 9 and 12 and four site investigation expenditure curves (rising from left to right) set at the same complexity levels. Risks curves all start from 100%, in the theoretical case of fully unknown geological conditions. Their slope and the consequent risk decreasing, varies depending on the complexity. In fact, in case of simple geological models, a few general studies and investigations can considerably decrease the risk to encounter unforeseen conditions. Meanwhile for more complicated models, sophisticated and very often expensive investigations are required and can have limited success in reducing risk levels.

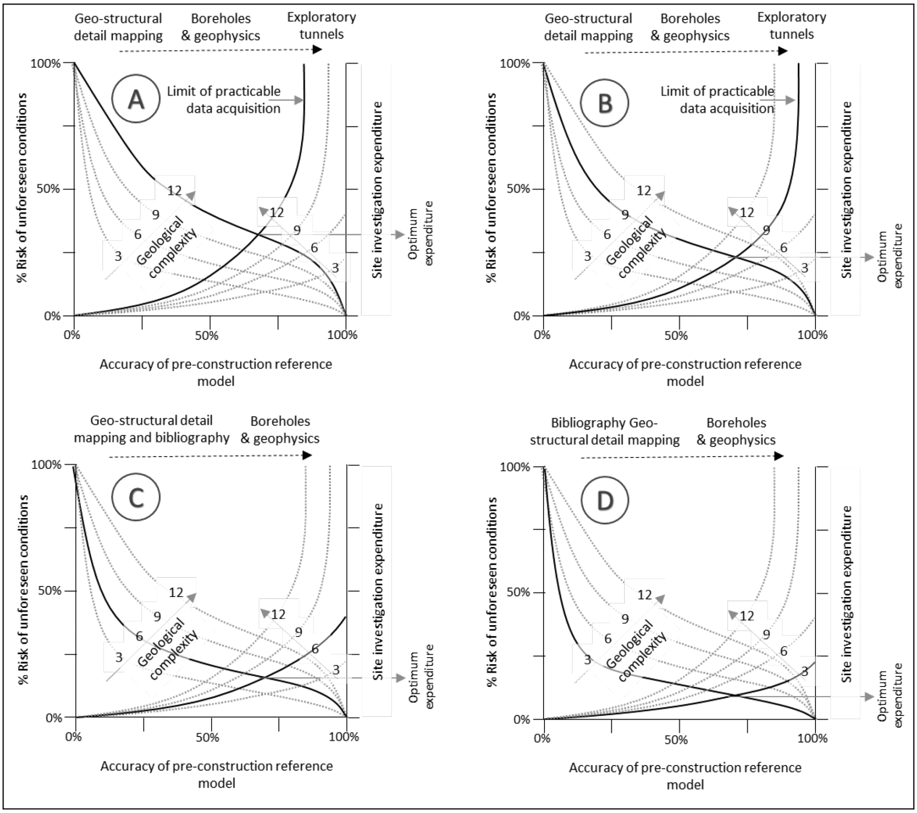
At the same time, the site investigation expenditure curves have been revised, also considering the complexity of the models to be analyzed. For instance, if we are facing with a shallow sedimentary and quaternary model, we can reach 100% of accuracy of the pre-construction reference model by carefully investing in borehole campaign and targeted geophysics. Such campaign will also generate an expenditure curve extremely lower that an investigation plan requested to determine high complexity models, like, for example, those that apply to long and deep transalpine tunnels.

This approach results in a revision of the uncertainty of the different models as presented in Table 3. In fact, following an optimum site investigation expenditure, all low complexity models (from 1 to 6 of Table 1) will be characterized by a very low to low uncertainty, meanwhile the most complex models, also after a detailed and expensive investigation campaign with be characterized by medium to high levels of uncertainty, which could still be also very high in some specific and localized conditions.

As a first preliminary conclusion we can suggest that necessity to qualify and quantify the uncertainty of a specific geological model, in order to understand how the Baseline could deviate from its original position, is quite negligible in case of low complexity geological environments. Such an exercise, however, becomes in our opinion mandatory for projects located within high complexity geological contexts.

RELIABILITY OF GEOLOGICAL MODELS

Reliability is defined as "how accurate or able to be trusted something is considered to be" (Cambridge Dictionary, 2018), meanwhile uncertainty is the opposite of the reliability and is define as "something that is not known or certain."



Source: modified after Carter 1992.

Figure 4. Revised inverse relationships between the geological risk and site investigation expenditure, depending from the complexity of the geological model. (A) complexity from very high to extremely high; (B) complexity from high to very high; (C) complexity from medium to high; (D) complexity from low to medium.

Table 3. Uncertainty of the different models after an optimum site investigation expenditure

Uncertainty (after optimum site investigation expenditure)						
	Sedimentary		Magmatic		Metamorphic	
	Simple	Difficult	Simple	Difficult	Simple	Difficult
Unfolded	VL	VL	VL	L		
Folded	L	L	L	LM	LM	MH
Folded + Faulted	LM	M	M	MH	MH	H
Folded + Faulted + Shared		M		H	H	VH

VL = very low; L = low; LM = low-medium; M = medium; MH = medium high; H = high; VH = very high

Currently, the tunneling community seems to prefer to use the "uncertainty" instead of the "reliability" of defined geological forecast. In this paper we prefer to implement the concept of reliability, with the final goal to introduce it as a component of the GBR in its future review.

In the previous chapters we have introduced the notion of increasing complexity of geological models, depending from their geological families and deformation history.

Then we have seen how the complexity can impact in the potential divergence of the Baseline from its original state and we've discussed about how the complexity of the model impact on the geological risk percentage related to the site investigation expenditure curve.

Finally, we have stated that quantification of the reliability of geological models is a paramount process to understand and eventually quantify the possible deviation of the Baseline from its original position.

Starting from the nineties, several long and deep tunnel project through the Alps where developed to connect allow northern and southern Europe to be connected by new high-capacity and high-speed railway links (Trans European Network Transports, TEN-T). Some of these projects, like the Lotschberg, Gottard, Perthus, Frejus, Bologna-Florence tunnels have been already completed meanwhile several others like the Brenner, Lyon-Turin, Milan-Genoa, Ceneri, Trento by-pass, Koralm and Semering tunnels are all under construction at different development stages.

These projects vary from 15 to 57 kms in length and they include stretches with over 2000 meters of overburden. Initial project values range from $1B to $8B and project and construction life time varies from 15 to more than 30 years. All these projects are located within polygenetic and polymetamorphic complexes, composed by sedimentary and plutonic rocks which were lately affected by high pressure and high temperature metamorphism. The original units were subducted up to 100 kms deep and then uplifted. As consequence, most of them were affected by a wide range of ductile and brittle deformations including mylonitic and shear zones, faults, up to three generation of folding, fractures, etc.

This impressive underground development program generated the opportunity for engineering geologists, geotechnical engineers and risk engineers to face with new challenges, especially with respect to the progressive development of the geological and geotechnical baseline for each of these projects.

Extensive and systematic geological surveys were performed followed by intense campaigns of deep vertical and inclined geotechnical boreholes and in some cases deep directional boreholes, similar to those drilled for oil and gas purposes. Investigation investments in some cases largely exceed $100M. Finally, several projects were investigated by exploratory tunnels, most of them realized also with the aim to later become access galleries to the base tunnels (anticipated investments).

It can be said that, while the presence of uncertainty is understood by the cast of tunneling actors on a project, there is reluctance to adopt terminology that allows a common consideration of this uncertainty. Statistical treatment of geotechnical parameters based on measured uncertainties is more commonplace but a consideration of the model uncertainty (position of faulting, intensity of alteration, frequency of folding, etc.) leading to uncertainties in the interpolation or extrapolation of measured data is not typically expressed.

The converse terminology of reliability suffers, even within the limited exercise of geotechnical condition definition, from inaccessible language and the use of abstract multi-dimensional expressions of parameter and response space (Langford et al 2013, 2015). Very few practical developments exist to allow expression of geological model reliability.

To support the Owners to plan and develop their investigation campaign Venturini et al. (2001) lately followed by Perello et al. (2003, 2005), Bianchi et al. (2009), and Perello (2011, 2015) introduced a methodology do determine the reliability of the forecasted geological, called R-Index.

The R-Index was lately retaken by Perello (2011), which introduced the Geologic Model Rating or GMR. The index is computed on the base of two main groups of parameters which may be recognized as influencing the reliability of geological forecasts:

a. Investigation parameters, i.e., parameters which define the quality of the investigation methods used in order to explore the rock volume to be excavated. The investigation parameters comprehend:
   - Quality of mapping process, including mapping scale, extension of the mapped area, mapping technique, outcrop percentage and depth of the tunnel from the surface along the examined area
   - Quality of the direct investigations, including number of boreholes, type of boreholes (destructive, core recovering, BHTV, sonic, etc.), distance from the tunnel, depth reached by the investigation,
   - Quality of the geophysical investigations, including number of available geophysical profiles, quality of the survey (HR vs. LR), average distance from the tunnel alignment, depth reached by the investigations
b. System Parameters, i.e., parameters which define the geological complexity of the rock volume and therefore the system to be investigated, as stated in previous sections of this work.

Each one of elements that characterize these parameters is waited and calculated through the method of the "Interaction Matrices" or Fully Coupled Model developed by Jiao and Hudson (1995) and Hudson and Jiao (1996).

The advantage of this methodology is that the area of improvement that impact on the reliability of the model are easily highlighted and can thus be improved by additional investigations, if need. The R-Index is usually calculated for homogeneous sections along the tunnel, allowing to define which part of the project are more reliable which others need more investigation or some other particular and carefully approaches.

Figure 6 shows an extract from the geological profile of the Lyon-Turin Base Tunnel (France–Italy) presently under construction, where the R-Index was systematically applied and calculated every 500 meters. In the considered section R-Index ranges between 3.5 (low reliability) and 7.3 (medium–high reliability) in a scale from 1 to 10, depending from complexity of the geology, the number and quality of boreholes, other existing tunnels or exploratory galleries, etc.

CONCLUSIONS

GBR represents a useful contractual tool to define the boundary (baseline) of the liability between Owner and Contractor with respect to the geotechnical model. At present the suggested Guidelines to prepare Geotechnical Baseline Reports (GBR) for Construction (Essex et al., ASCE, 2007), do not indicate a methodology to define the uncertainty of the baseline and the consequent contingencies that have to be considered for the project.

At the same time the potential deviation of the baseline from its original position depends from the complexity of the geological model. In a scale from one to twelve, models with low level of complexity, usually ranging from one to six, are also

Factors contributing to DPQ (drillholes potential quality)

Factor	Value	Rating	Factor	Value	Rating	Factor	Value	Rating	Factor	Value	Rating
Drillholes quantity in an interval of 2 km	1	3	m% of cored drillhole	0%	1	Average distance from tunnel axis (m)	2000	1	Average drillholes depth vs. tunnel depth	0,25	1
	3	5		30%	3		500	4		0,75	5
	5	8		60%	5		250	8		1,00	9
	>7	10		100%	9		0	10		1,20	10
Add the rating (10-rating) 0.5 if some of the drillholes are extrapolable with certainty to the considered stretch; rating 10 with 1 drillhole intersecting the stretch			Add the rating (10-rating) 0.5 if BHTV is available; rating=10 for 100% cored drillhole + BHTV			Add the rating (10-rating) 0.5 if some of the drillholes are extrapolable with certainty to the considered stretch;rating 10 with 1 drillhole intersecting the stretch			Rating 10 with 1 drillhole intersecting the stretch		

Factors contributing to MPQ (mapping potential quality) derivation

Factor	Value	Rating	Factor	Value	Rating	Factor	Value	Rating	Factor	Value	Rating
Mapping scale	1:50000	1	Mapped area (km²) vs. tunnel depth (km)	2	1	Outcrop percentage	<10%	1	Field data collection method	A	2
	1:25000	3		4	4		30%	4		B	5
	1:10000	7		10	8		60%	8		C	10
	1:5000	8		>20	10		>90%	10			
			This parameter is not referred to a specific section, but to the whole tunnel layout			This parameter must be evaluated over a distance of some km (0.5–3) around the considered layout, depending on tunnel depth (see also note 2 below)			See note (1) below		

Factors contributing to GPQ (geophysic potential quality) derivation

Factor	Value	Rating	Factor	Value	Rating	Factor	Value	Rating	Factor	Value	Rating
km of sampling lines in an interval of 2 km	<0,1	1	Method resolution	A	2	Average distance from tunnel axis (m)	2000	1	Average investigated depth vs. tunnel depth	0,25	1
	0,5	4		B	4		500	4		0,75	5
	1	7		C	7		250	7		1	9
	2	9		D	10		0	10		1,2	10
Add the rating (10-Rating) 0.5 if some line is extrapolable with certainty to the considered stretch; rating 10 with 1 line intersecting the stretch			A=low reslution w ithout validation drillholes; B=high resolution without validation drillholes; C=low resolution with validation drillholes; D=high resolution with validation drilholes			Add the rating (10-Rating) 0.5 if some line is extrapolable with certainty to the considered stretch; rating 10 with 1 line intersecting the stretch			Rating 10 with 1 line intersecting the stretch		

Source: Perello, 2011.

Figure 5. Investigation parameters considered to determine the reliability of the geological models. The variance of each factor is rated depending on the available data. The combination of these factors defines the R-Index, which represents the quantitative evaluation of the reliability of the geological model at the time of the evaluation.

characterized by low levels of uncertainties. The uncertainty and its geological associated risks also depend from the level of expenditure of the site investigation campaign.

In order to quantify the uncertainty of the model or, in other words, the reliability of the geological forecasts presented in the project geological profile, a numerical evaluation, called R-Index has been developed and applied in most of the major long and deep tunnel projects through the Alps.

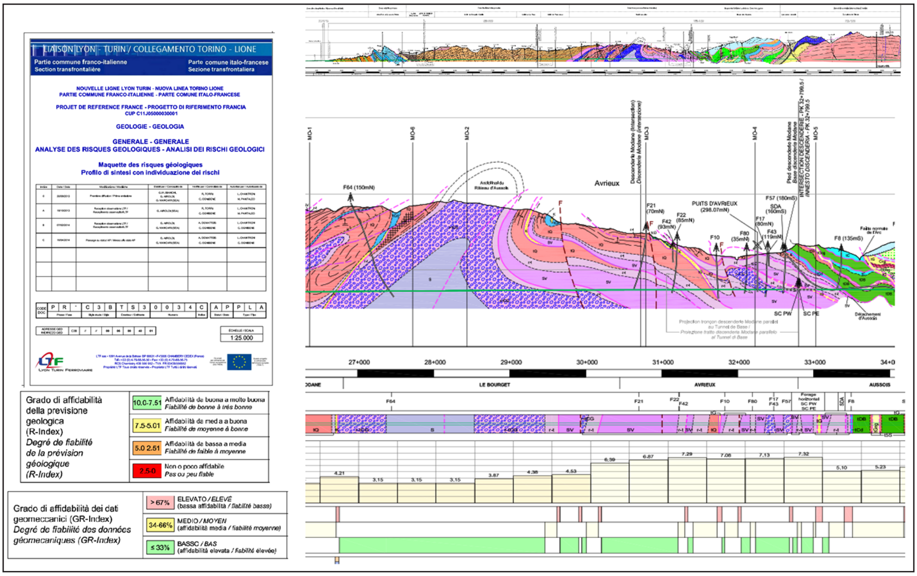


Figure 6. Geological profile of the Lyon-Turin base tunnel, 2014 (scale 1:25,000) with associated geological risks and quantification of the reliability of the geological and geomechanics forecast every 500 meters. This document represents the geological baseline for the entire project. The evaluation of the reliability level (grado di affidabilita' in Italian and degre' de fiabilite' in French) shown in the profile allows contractors to finalize the most appropriate methods to mitigate the risks. On the same time the Owners and its consultants are aware of the potential variability of the geology due to the variable complexity of the model.

The quantification of the reliability of the geological model since early stages of underground projects and its integration in the GBR as basic tool for identifying the uncertainties of the baseline model may lead to a significant improvement in the aim of cost control for underground projects.

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