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Estimate of the Reliability in Geological Forecasts for Tunnels: Toward a Structured Approach

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Abstract In tunnelling, a reliable geological model often allows providing an effective design and facing the construction phase without unpleasant surprises. A geological model can be considered reliable when it is a valid support to correctly foresee the rock mass behaviour, therefore preventing unexpected events during the excavation. The higher the model reliability, the lower the probability of unforeseen rock mass behaviour. Unfortunately, owing to different reasons, geological models are affected by uncertainties and a fully reliable knowledge of the rock mass is, in most cases, impossible. Therefore, estimating to which degree a geological model is reliable, becomes a primary requirement in order to save time and money and to adopt the appropriate construction strategy. The definition of the geological model reliability is often achieved by engineering geologists through an unstructured analytical process and variable criteria. This paper focusses on geological models for projects of linear underground structures and represents an effort to analyse and include in a conceptual framework the factors influencing such models. An empirical parametric procedure is then developed with the aim of obtaining an index called "geological model rating (GMR)", which can be used to provide a more standardised definition of a geological model reliability.

Keywords Geological uncertainty · Tunnelling · Risk · Reference geological model · Rock mass characterisation

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1 Introduction

The construction of a reference geological model (RGM) is the starting point of every tunnelling design process. Many of the subsequent steps of this process rest on the RGM, e.g. hydrogeological and geomechanical characterisation, structural design etc. For this reason, wrong geological forecasts may compromise a tunnelling project, even if any other design element is provided with the adequate accuracy. Obvious consequences of an inaccurate RGM are wrong evaluations of construction costs and times, as well as unexpected environmental impacts.

Whatever the investigations accuracy and the efforts dedicated to the definition of a geological model, a certain degree of uncertainty will always be present, irrespective of the ability and experience of the involved geologist(s). The RGM reliability estimate has a great relevance and is an aspect that cannot be omitted if a complete risk analysis is needed.

In common practice, most geological reports for tunnelling purposes give general insights on the reliability of geological predictions; such insights usually consist of indications derived from the geologist's personal feeling about the degree of accuracy of the model (low, medium, high reliability) often obtained through a process hard to be retraced.

This paper provides a method aiming at a structured approach to the estimate of the RGM reliability in tunnelling, obtained by a parameterisation of the most important factors that contribute to the creation of the RGM itself.

2 Key Concepts

The concept of "reliability" of a geological model is related to the concept of "uncertainty". The greater the uncertainty, the greater the possibility that the model is unreliable. According to the ISO 31000:2009 standard and its supplement guide ISO/IEC 73, "uncertainty (or lack of certainty) is a state of being that involves a deficiency of information and leads to inadequate or incomplete knowledge or understanding". This means that uncertainty can be either considered as a lack of knowledge or as a lack of interpretation. In the first case it is the consequence of a data and/or investigations scarcity; in the second case it is mainly related to the lack of available base models allowing the interpretation of a highly complex and variable natural context, or to mistakes of the interpreter.

A relevant aspect concerns the reason, or "nature of the uncertainty". Generally speaking, two categories of uncertainty nature exist (Walker et al. 2003):

- epistemic—uncertainty due to an imperfect knowledge;
- stochastic—uncertainty due to inherent variability (randomness).

The epistemic uncertainty can be reduced, for instance in tunnelling this can be achieved by improving investigations (drillholes, surface mapping, etc.). The stochastic uncertainty cannot be reduced below a certain limit; as an example, joints spacing is a parameter typically varying within a range of values, for which only a statistical distribution law can be deduced, whereas it is impossible to establish the exact spacing or position of each couple of joints of the population.

When one takes into account the concept of "uncertainty" applied to a model aiming to represent a specific natural context, like a reference geological model for a tunnel is, different "states of uncertainty" can be outlined (Brown 2004):

1. certainty, or the state where both the model and the outcome of the model are known;
2. bounded uncertainty, or a state where there is an uncertainty between different possible models but all possible models are known;
3. unbounded uncertainty, or a state where some or all of the possible models are deemed unknown.

Type 2 (bounded uncertainty) implies a consciousness of the unreliability, while in type 3 (unbounded uncertainty) there is an ignorance or a lack of awareness that knowledge is wrong or imperfect (see also Refsgaard et al. 2007).

As an example, in geological models for tunnelling, a type 2 uncertainty exists when there is a doubt about the presence or absence of a fault in a certain section of the tunnel alignment; this implies that two possible reference models exist, one with the fault and another without it, but one of these two model is certainly reliable. A type 3 uncertainty exists when one has no data about faults, implying that some possible model is certainly unknown.

In more detail, type 2 and 3 uncertainties can be further subdivided. For type 2, three more subdivisions are possible: (i) all probabilities of the different models are known, (ii) some probabilities are known, (iii) no probabilities are known. Similarly, for type 3: (i) some models and their probabilities are known, (ii) some model but not their probabilities are known, (iii) no models are known.

Many of the most severe construction problems in tunnelling can be related to type 3 (unbounded) uncertainties, because they generate situations where totally unexpected and non-quantified events are met during the excavation.

More specifically, in tunnelling, some authors started conceptualising the nature of uncertainty since the early 1970s (Baecher, 1972; Einstein and Baecher 1982, 1983; Einstein 2003). Four sources of uncertainty can be identified: (1) spatial variability; (2) measurement errors; (3) model uncertainty; (4) omissions. The first two mostly fall in the category of stochastic uncertainties, while the others are mostly epistemic uncertainties.

Classical problems of "spatial variability" related to tunnelling in rock masses are for instance the definition of joints distribution and properties, but other similar ones exist, e.g. the variation of the rocks mechanical properties. These problems are usually partially solved by improving knowledge by means of geo-statistical methods (La Pointe 1980) and/or by modelling spatial distributions by means of dedicated software (Dershowitz et al. 1993; Ivanova 1998). "Measurement errors" are related to the data collection process. Typical examples are the sample disturbance during collection, or errors in measuring the joints attitude with a compass in the field. To this category also belong subjectivity-related errors or errors related to the use of wrong criteria in data collection, i.e. the bias error. Such errors can only be reduced, not eliminated, by adopting particular sampling procedures and applying statistical corrections (Baecher and Lanney 1978; Priest and Hudson 1976).

Model uncertainties and omissions, due to their epistemic nature, are the most critical aspects for a correct evaluation of the tunnelling forecasts reliability, because they cannot be constrained; in this case, one can only try to infer the probability that such types of uncertainties affect the predictions, which is the main object of this paper.

"Model uncertainties", in the specific case of an RGM creation, are related to the fact that data must be interpreted in the frame of some general conceptual model known from the literature or, more generally, from previous researches worldwide. Two types of problems are associated with this process: one is related to the fact that, due to our imperfect knowledge, not all the possible conceptual models are known today; the other is that all possible conceptual models are simplifications of the natural context and can be subject to more or less relevant variants to the geological predictions. In all cases, the model uncertainty can be reduced or eliminated by improving investigations. Despite this, as already pointed out by some authors (Einstein et al. 1979; Einstein 2003), it remains questionable up to which degree an effective benefit can be obtained by the collection of a greater amount of base data, since these data too contain errors and the amount of information gained often does not improve proportionally with the amount and quality of data.

"Omissions" are obviously due to lacks in the investigations and they can therefore be reduced or eliminated by improving the data collection programme.

Possible uncertainty-related knowledge gaps may lead to wrong design choices and constructive problems, which can be of different types (Bieth et al. 2009):

1. Imprecision—events having a minor impact on the work flow such as errors in the exact position of a lithological boundary. They can be usually ascribed to the category of the bounded stochastic uncertainties.
2. Unexpected events—events that can cause sizable modification of the project, whose occurrence was considered possible but poorly probable and was therefore not included in the design. Such events can be therefore foreseen by an expert and fall in the category of bounded stochastic uncertainties.
3. Unforeseen events—events related to natural conditions that cannot be anticipated even by a competent expert, whose impact on the work completion can be considerable. Events of this type are related to unbounded epistemic uncertainty and can be avoided only by improving the investigations.

Point 2 in particular, introduces a factor often neglected by the thematic literature, i.e. the influence of the expert judgement on the reliability of a RGM. The choice of considering a particular natural condition more or less probable mainly rests, on one hand, upon available data, but on the other hand it is certainly related to the experience and competence of the engineering geologist who is responsible for the RGM. Furthermore, also the time available to an expert, or expert team, for data analysis and RGM production is a key factor, due to the fact that human processes involved in the construction of a logical frame are often trial-and-error paths requiring numerous reiterations.

3 Geological Model Rating

It is evident from the previous discussion that uncertainties in constructing a RGM have different origin (data collection, interpretation, complexity of the natural context, etc.) and can be of different types; furthermore, some of them are not numerically constrainable, both because of the amount of work that this would require, and because this is simply not feasible.

In this work, a solution is proposed for deriving a quantity called "geological model rating" or GMR, by making a quality assessment of the key parameters affecting the construction of the reference geological model. Of course, a delicate step consists in the conversion of a quality assessment into a quantitative parameterisation. Since the assessment process is subjective, the method aims at making it retraceable, by reducing subjectivity whenever possible, or by constraining it and making it explicit. This is obtained through a guided evaluation path and by rating the key parameters according to a standardised description of their characteristics, similar to what is often done in geomechanical classifications (e.g. Bieniawski 1989; Barton et al. 1980; Hoek et al. 1995). The key parameters ratings are then combined by means of simple mathematical functions, in order to obtain the expected output. The method presented in this paper relies on the basic principles outlined by Perello et al. (2005) in a previous work, where an index precursor of GMR (the *R-Index*) was derived. Since then, the application to practical case histories leaded to a progressive improvement, both in the computation process and in the definition of the relationships between parameters. The GMR calculation is easily attained by means of a pre-structured electronic spreadsheet written with a software of common use, freely available on the author's website (http://www.gdpconsultants.eu).

In the following, the key parameters considered by the method will be described first (Sect. 3.1) and the computation procedure second (Sect. 3.2).

3.1 Key Parameters

The GMR aims at analysing and defining the elements that generate uncertainty in a RGM and the accuracy of the measures that have been set for reducing it (investigations, studies etc.). Despite some minor simplification, three fundamental types of parameters can be identified for the RGM reliability assessment:

1. Investigation parameters—they define the quality and accuracy of the investigation methods adopted to explore the rock volume to be excavated.
2. Interpretation parameters—they allow to evaluate the adequacy of the interpretation applied in order to fit the data to a model.
3. System parameters—they define the geological complexity of the rock volume, and therefore the natural system to be investigated.

3.1.1 Investigation Parameters

In a RGM for tunnelling, data are usually provided by three main types of investigation methods: (i) borehole drillings, (ii) geological mapping, (iii) geophysical investigations. The quality of data that contribute to the RGM construction is therefore directly related to the quality of these three investigation methods. A quality designation can be established for each of these three methods if the factors that contributes to the generation of this quality are individuated. The flow diagram of Fig. 1 summarises the factors individuated for each investigation method. Their contribution to the investigation method quality can be easily understood. For instance, the higher the number of boreholes around a tunnel section, the greater the amount of knowledge gained; the greater the outcrop percentage, the greater the information gained by geological mapping. The three groups of factors shown in Fig. 1 allow therefore to find three aggregated factors, called "investigation parameters" from here on, defining the quality of the investigation methods, i.e. the Drillholes Potential Quality DPQ, the Mapping Potential Quality MPQ and the Geophysics Potential Quality GPQ.

These parameters bear the term "potential" in order to emphasise the fact that data collected by investigations give the interpreter the possibility of defining a reliable geological model but, to do this, the "potential" information contained in the data set has to be transformed into "effective" information by interpretation. This means that DPQ, MPQ and GPQ are quantities aiming at defining the investigations quality independently from any subsequent interpretation; therefore, they are uniquely related to the accuracy of the investigation campaigns.

3.1.2 Interpretation Parameters

Defining the quality of an interpretation is one of the most difficult and problematic issues in the evaluation of a RGM reliability, because it indirectly implies an evaluation of the interpreter's capacities ("interpreter skill" in Perello et al. 2005). Variables influencing the interpretation process are so many that it would be useless and impossible to analyse all of them. Despite this, some aspects leading to the RGM definition can be selected; these are: (i) extrapolation criteria, (ii) conceptual models, (iii) interpreter's experience. A judgement of the weight that these aspects quality have in any given RGM can lead to a parameterisation useful for the derivation of the GMR.

"Extrapolation criteria" are essential in the RGM creation process, because the model is in fact a picture of how different geological discontinuities and/or boundaries intersect, crosscut and interfere with each other. This picture is deduced by spot observations (outcrops, drillholes, etc.) that have to be extrapolated according to some logical rule. The understanding of the relationships between the different geological elements is an inescapable need.

A main boundary in the quality of extrapolation criteria lies somewhere between a simple geometrical extrapolation and what is called a "genetic" extrapolation. The former is the simple extension, or regular replication, of the

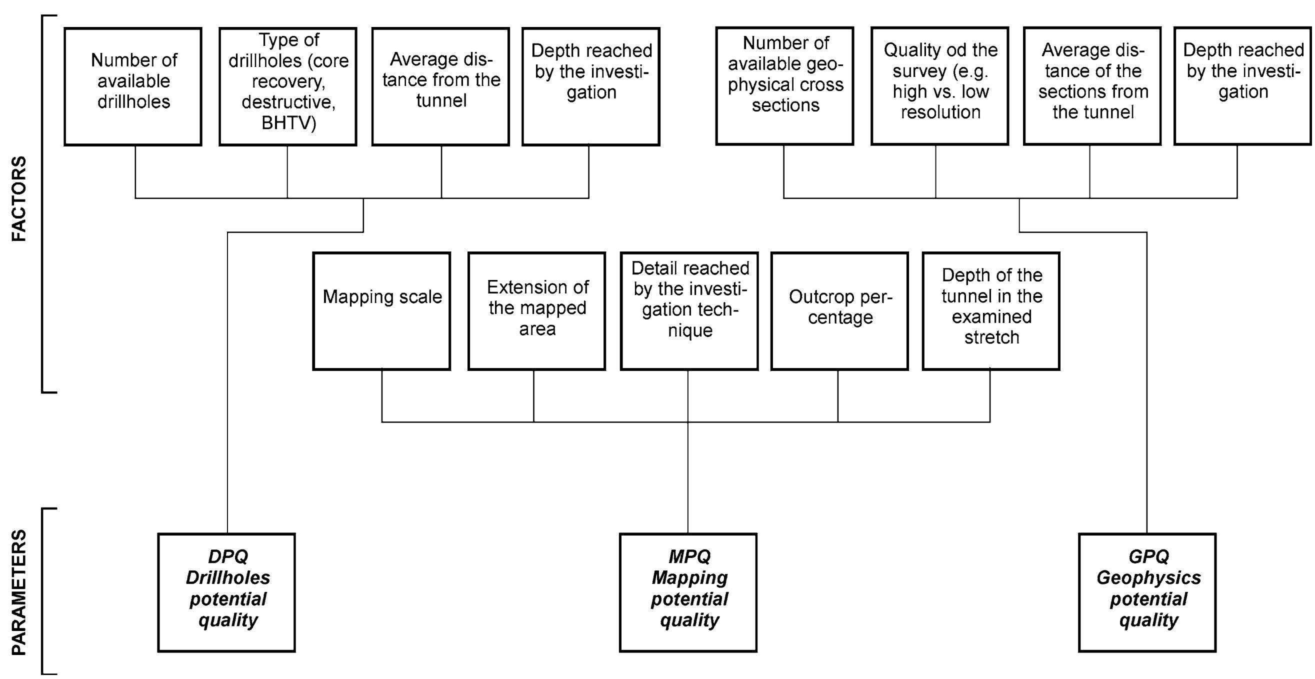

Fig. 1 Factors contributing to the quality designation of the three main investigation methods used for the RGM construction in tunnelling

identified geological discontinuities, starting from the point where they have been observed (outcrop, drillhole, geophysics imagery). The latter involves a more complex logical path, where some fundamental stratigraphy and/or structural geology rules must be taken into account when extrapolating as, for instance: the rheological conditions leading to the development a given discontinuity set, the geological processes that led to the development of the discontinuities, the mutual relationships among the different structures, the relative temporal succession in which the structures developed and therefore the intersection relationships.

In dealing with interpretation, a second aspect to consider is the reliability of the "conceptual models" used as a reference in the extrapolations. Data are usually interpreted in the frame of one or more conceptual models from literature thus establishing mutual relationships among data by means of a logical framework. The choice of the conceptual model(s) to be used as a reference is a delicate path and should fulfil concepts of modernity, pertinence with the regional geological framework, diffusion and acceptance by the scientific community.

A third and last aspect of relevance is, inevitably, the "interpreter's experience". This concept does not require further comments, since it is evident that, in applied earth sciences, the ability of the experts in problem-solving increases with time, according to the number of case histories they had the opportunity to face before.

3.1.3 System Parameters

The rock mass in which a tunnel excavation occurs is a system of physical elements influencing the construction (rock type, faults, etc.). This system is characterised by a complexity, which, most of the times, is influenced by three main aspects: (i) complexity of the lithostratigraphic setting, (ii) complexity of the structures related to ductile deformations, (iii) complexity of the structures related to brittle deformations. These aspects can be rated through a judgement process and parameterised for use in deriving the GMR.

The complexity of lithostratigraphic setting (LC) can vary significantly from one site to another. As an example, Fig. 2 shows two natural systems with different lithostratigraphic complexity. In the system of Fig. 2a the extrapolation of punctual data is obviously more reliable than for the system of Fig. 2b. This implies that the same starting conditions for the investigation parameters (in this case the same number of available boreholes) may lead to geological predictions with a different degree of reliability.

Similar considerations can be done about the complexity of structures related to ductile deformation (DC). Increasing structural complexity may lead to less reliable

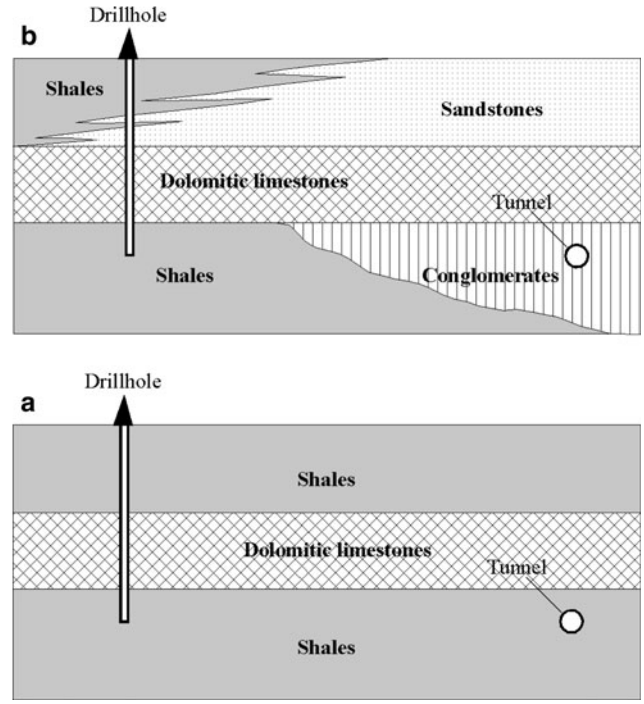

Fig. 2 Example of two geological contexts with different degree of lithostratigraphic complexity (LC): **a** low complexity, **b** high complexity

interpretations, as shown in Fig. 3: in the case of Fig. 3b, where two or more superposed folding events are shown, much more input data (i.e. investigations) will be necessary to obtain the same reliability as in the case of Fig. 3a, where a natural context characterised by a single and simple folding event is shown.

Concerning the complexity of the brittle deformation-related structures (BC), Fig. 4 provides an example of how this aspect can influence forecasts reliability: highly segmented fault systems are more difficult to extrapolate, compared to mature systems, and generate therefore more uncertainty in our model.

3.2 GMR Derivation Procedure

The GMR for a specific tunnel section is obtained by a weighted sum of the investigation parameters ratings (DPQ, MPQ, GPQ) along that section. Weights are defined according to mutual influences between the investigation parameters. The system and investigation parameters ratings enter in the computing procedure as further coefficients. A flow diagram of the entire computing procedure is represented in Fig. 5. The considerations which led to the adoption of this procedure are as follows:

(a) the three investigations parameters (DPQ, MPQ, GPQ) described in Sect. 3.1.1, influence somehow the geological model reliability; therefore, deriving an

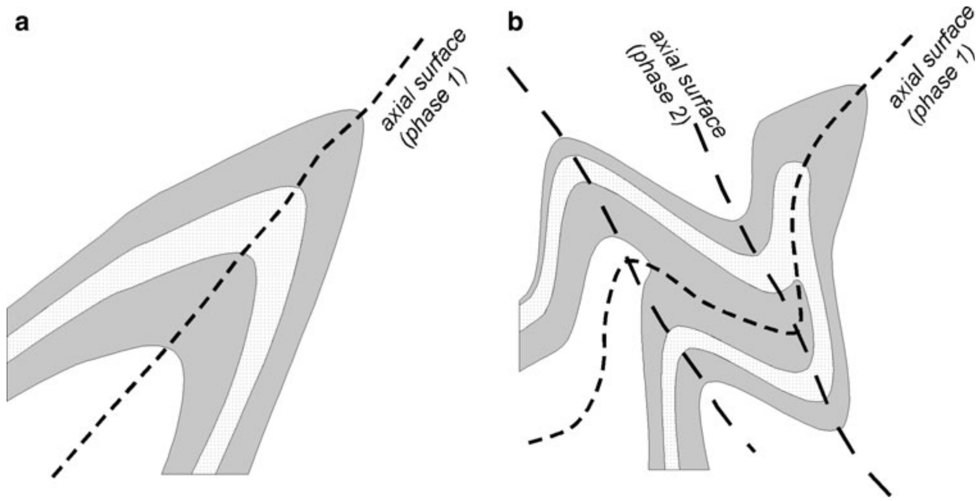

Fig. 3 Example of two geological contexts with different degree of ductile deformation complexity (DC): **a** low complexity with one folding phase; **b** high complexity with two superposed folding phases

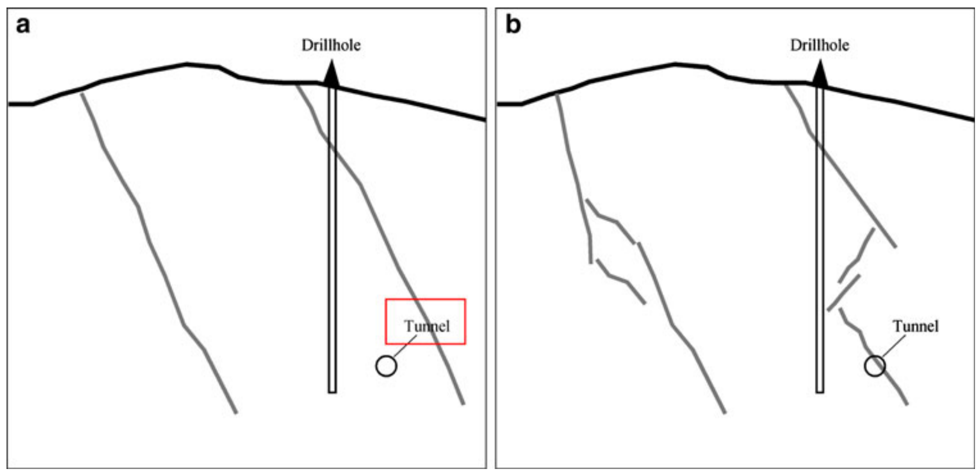

Fig. 4 Example of two geological contexts with different degree of brittle deformation complexity (BC): **a** low complexity with individual non-segmented faults; **b** high complexity with individual segmented faults

index implies their numerical quantification by means of a rating procedure, aiming at reducing the subjectivity and/or making it more explicit.

(b) Investigations (see Sect. 3.1.1) are the fundamental "bricks" of every geological model; each of the three investigation types brings key data for the realisation of a reliable model, i.e. each type of investigation add a peculiar information to the model. Therefore, a reliability index can be essentially expressed as the sum of the DPQ, MPQ and GPQ ratings. Yet this sum cannot be a simple one, but rather a weighted one, because the contribution of each parameter is not the same, e.g. from site to site DPQ could be more relevant than GPQ, or MPQ, and vice versa. Defining the weights is a complex task, owing to the reasons exposed in the following points.

(c) There are mutual influences between DPQ, MPQ and GPQ, because data derived from an investigation type can benefit of data derived from the other; the benefit derived from an investigation type can be greatly implemented by the quality increase of data derived from another investigation type or vice versa. This influences the weights.

(d) The individual contributions to the forecasts reliability of the three different investigation parameters (their weight) can vary depending on the natural setting investigated (system parameters).

(e) The overall contribution of the three parameters to the forecasts reliability can also vary depending on the investigated natural setting, i.e. the greater the natural system complexity, the lower the possibility to get reliable forecasts by means of the three investigation types.

(f) Contributions (weights) to the model of DPQ, MPQ and GPQ may change depending on the interpretation quality (interpretation parameters).

In the proposed procedure, a quantification (rating) of the investigation, system and interpretation parameters is obtained first (point "a"). Second, in order to take into account the mutual influences between DPQ, MPQ and GPQ (point "c"), the method of the "Interaction Matrices"

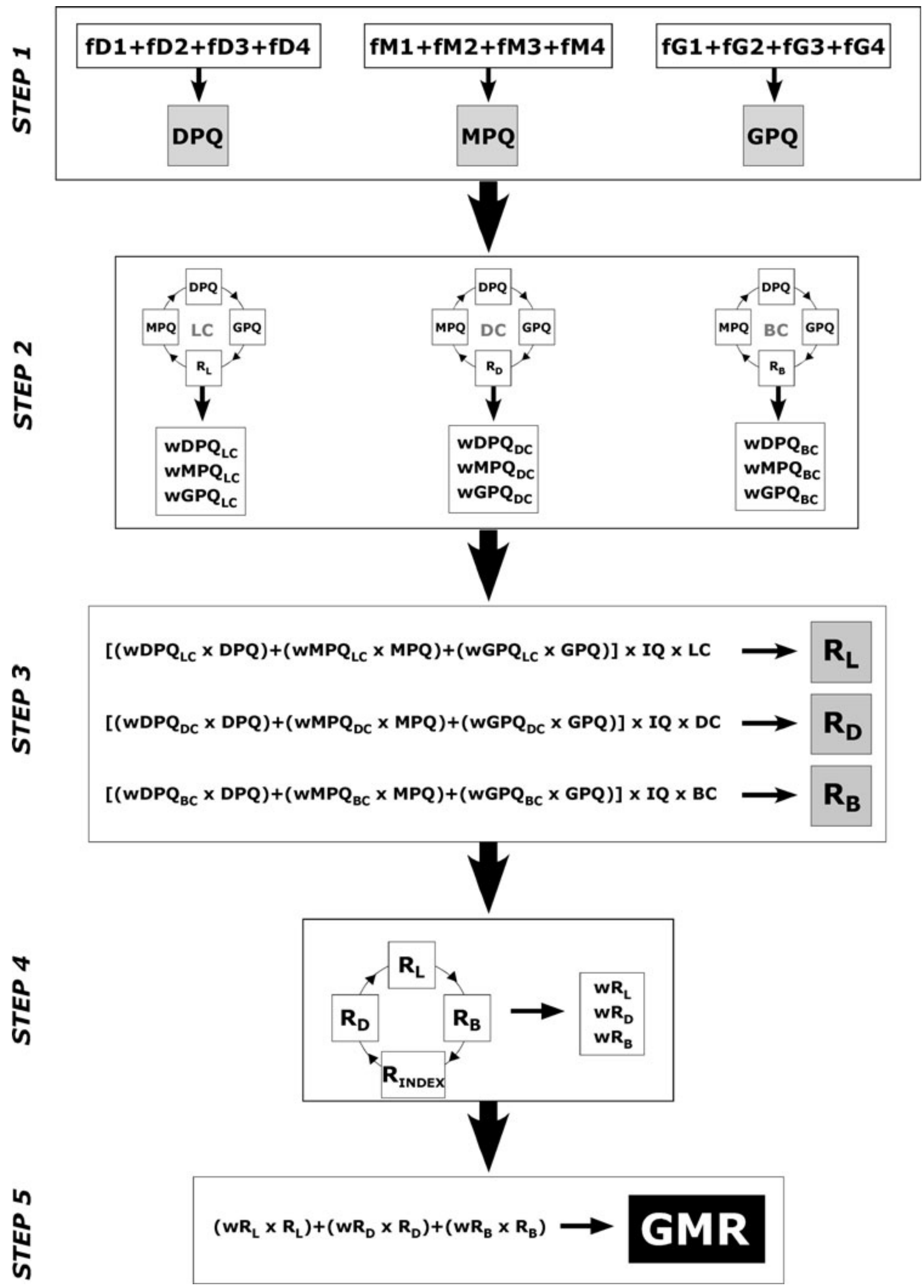

Fig. 5 Flow diagram showing the process that leads to the GMR estimate; fD, fM and fG indicate the factors influencing the drillholes, mapping and geophysics quality estimate respectively; see text for other abbreviations

or Fully-Coupled Model (Jiao and Hudson 1995; Hudson and Jiao 1996) has been applied. Briefly, the method is based on the construction of a matrix where the relevant parameters (variables) are listed along the leading diagonal. Initially the binary interactions between the variables are established, compiling therefore the other boxes of the matrix and obtaining an "uncoupled" matrix that, in this first step, still does not take into account multiple interactions. Successively, by means of the graph theory, the contributions of all mechanisms in all possible interactions paths is established and a "fully-coupled" interaction matrix is obtained. This matrix returns the weights for deriving the investigation parameters weighted sum (point "b"; Sect. 3.2.3).

The aspect cited at point "d" (weights variation with varying natural setting) has been taken into account by changing the interaction rules in the above described matrix according to the natural system complexity (Sect. 3.2.2). The aspects cited at point "e" and "f" have been taken into account by applying to the weighted sum two coefficients, depending on the natural system complexity and the interpretation quality (Sects. 3.2.2, 3.2.3).

The GMR is therefore the result of judgements or estimates of aspects such as e.g. quality or complexity evaluations, expressed as numerical ratings and then combined in order to obtain a final value. The significance of this value in terms of forecasts reliability has been deduced empirically by examining different case histories. It has been arbitrarily decided to constrain the index within a range from 0 to 10 (Chapter 4).

In order to proceed with the index calculation, a longitudinal geological section of the tunnel retained for the excavation must be available. As a standard procedure, the tunnel alignment is subdivided in 100 m-long sections, that will be the subject of individual GMR evaluations. A standard 100 m length has been used since usually geological structures of interest for tunnels maintain a certain homogeneity at this scale; this value is not strictly fixed anyway, and can be reduced in complex environments or increased for simple situations.

3.2.1 *Quantification of the Investigation Parameters DPQ, MPQ and GPQ*

The first step in the GMR derivation process is the evaluation of the three parameters that allow to define the quality of the investigations, i.e. DPQ, MPQ and GPQ (Fig. 1, Sect. 3.1.1; step 1 in Fig. 5). Their quantification is attained by attributing a rating to the factors influencing the investigations quality (Fig. 1; Table 1). Since the GMR has been assigned a priori a range between 0 and 10 (Sect. 3.2), the same range has been applied to the factors and parameters used for deriving it.

The rating of each searched parameter (DPQ, MPQ and GPQ) has been obtained by summing the weighted ratings given to each factor that contributes to its definition and normalising by the sum of the weights. The normalisation leads to a final value ranging between 0 and 10, as for the factors and for the final value of the searched GMR. The factors combination is a sum because it has been supposed that each factor contributes linearly and independently from the others to determinate the value of the rating (i.e. the quality of the investigation).

The weight (importance) of each factor on the rating of each parameter (DPQ, MPQ and GPQ) is not independent from the other factors. As an example, for the drillholes (Fig. 1), the weight of the factor "number of available drillholes" is greater if the average distance from the examined tunnel section is lower. As a matter of fact, if we consider two different situations where the number of available drillholes is the same (identical rating), the weight of this factor (drillholes quantity) is greater if the drillholes are closer to the tunnel section. Similar examples could be made for any other variable.

This means that the weight of each factor is a function of the other factors. Functions between weights and factors have been defined according to the expected influence among factors themselves and are of the following type:

$$W_{V1} = \frac{\log\{[(R_{V2}/10) + 1] + [(R_{V2}/10) \times (10^{A} - 2)]\}}{A} \tag{1}$$

where V1 and V2 are two factors, W_{V1} is the weight of V1 and R_{V2} is the rating for V2, A is a constant in the range −3/+3 defining the shape of the function. Equation 1 allows to obtain weight values always comprised between 0 and 1. Four examples of functions for the definition of weights are reported in Fig. 6.

When the weights depend on more than two parameters, the functions are multiplied since the weight is influenced by more than one parameter:

$$W_{V1} = \frac{\log\{[(R_{V2}/10) + 1] + [(R_{V2}/10) \times (10^{A} - 2)]\}}{A} \times \frac{\log\{[(R_{V3}/10) + 1] + [(R_{V3}/10) \times (10^{A} - 2)]\}}{A} \times \ldots \tag{2}$$

Therefore the value of the three searched parameters (DPQ, MPQ and GPQ) will be, more exactly than previously defined, the weighted sum of the factors ratings.

The basis for the factors rating and weights is empirical, deriving from the author's direct experience in tunnelling and comparison with others engineering geologists' experience. The definition of the rules governing factors ratings and weights consists of two steps:

1. rough derivation of ratings and weights rules according to empirical information;
2. refinement of the rules by a trial-and-error process.

In the first step, rating rules have been set according to case histories where, in the same geological context, investigations with different accuracy have been carried out. For instance, in some of the used case histories, different portions of the same brittle shear zone were investigated by drillholes with different characteristics (e.g. drilling method, depth etc.); by judging the contribution of each investigation to the understanding of the shear zone, an estimate of the rating and weight is achieved.

In the second step, rules have been refined and adjusted once the global GMR spreadsheet is fixed, in order to fit the outcome of the anticipatory geological model to real tunnelling case histories. This second step is, of course, a general refinement phase of the whole rules and functions used in the GMR method, not only of those of the investigation parameters.

Table 1 Factors to be rated for the investigations parameters derivation

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	See note (1) below		
			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)					

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 without 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		

Note (1) *A* no genetic interpretation available concerning structures and stratigraphic successions, poor collection of structural and stratigraphic data (e.g. joint sets, schistosity and/or bedding surfaces orientation); *B* no genetic interpretation available but relevant collection of structural and stratigraphic data; *C* genetic interpretation available with relevant collection of structural and stratigraphic data

Note (2) If most outcrops are not accessible due to rough topography or other reasons, introduce a rating reduction of 50%

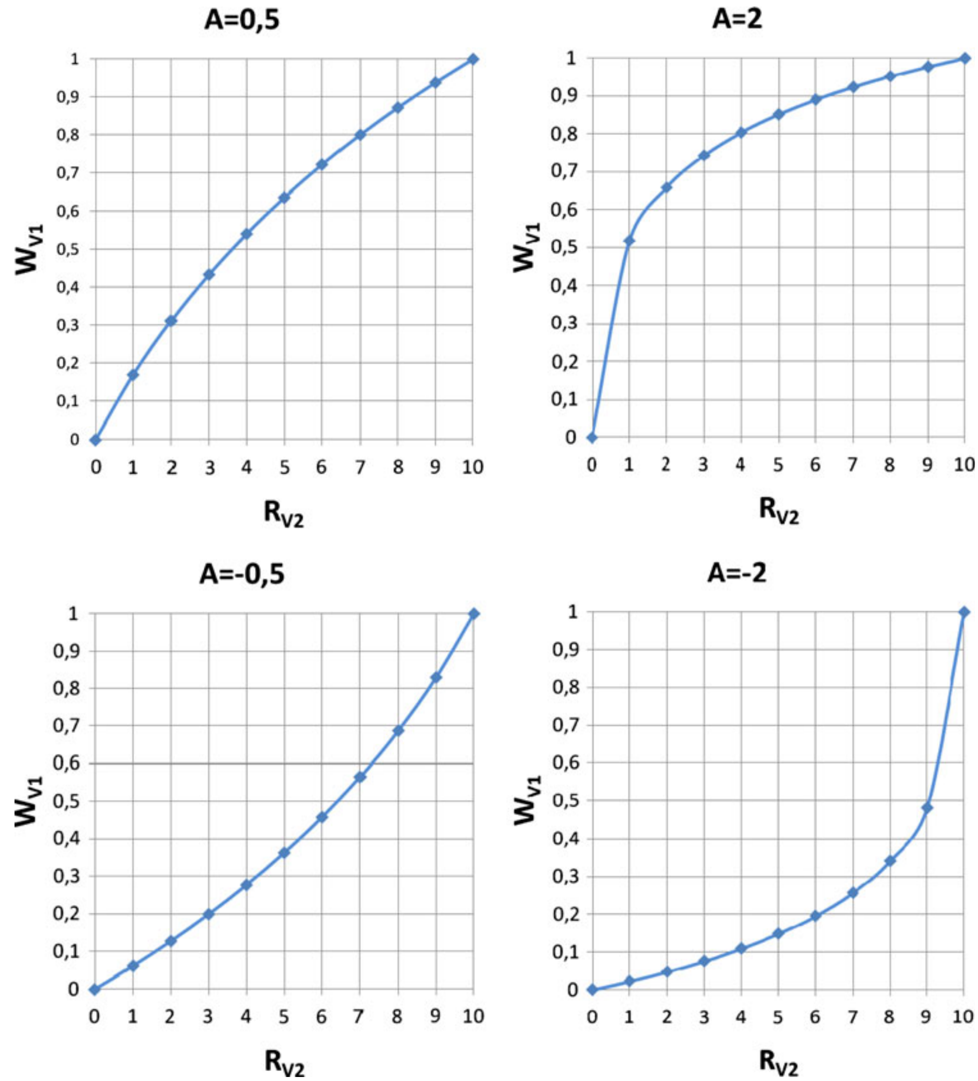

Fig. 6 Some examples of the functions for the weights definition, showing the changes in the curves shape with varying values of the constant "A"

The criteria to use in order to attribute ratings are reported in Table 1. Functions that relate parameters to weights cannot be fully reported and described here for the sake of brevity, but some significant example can be cited. The weight of the factor "drillholes quantity in an interval of 2 km" (Table 1) is related to the factor "m% of cored drillhole" by an Eq. 1-type function, with A = 2. This means that the weight of the former factor remains high, even when the rating of the latter decreases and that only for very low percentages of cored drillholes the weight tends to 0.

This relation has been set both intuitively and according to the experience, since it is evident that if many drillholes are available, even if only partially cored, it is possible to get a sound information anyway, while if only few drillholes are available, even if completely cored, the information is significantly less. On the contrary, the weight of the factor "m% of cored drillhole" has been defined by means of a function with A = −0,5 with respect to the factor "average distance from tunnel axis"; therefore, the relevance of the percentage of cored drillholes decreases rather rapidly as the distance from the tunnel axis increases. This can be understood if one thinks that drillholes provide punctual data, which cannot be easily extrapolated, even if the borehole is carefully executed. Full evidence of the "A" value used in defining the weights can be obtained by consulting the calculation spreadsheet cited in the introduction of Chapter 3.

3.2.2 Derivation of the Weights for the Investigation Parameters DPQ, MPQ and GPQ

Once the parameters DPQ, MPQ and GPQ are available, their relevance needs to be determined. The relative relevance, i.e. the relevance of each parameter with respect to the others, will be taken into account in this phase. For this

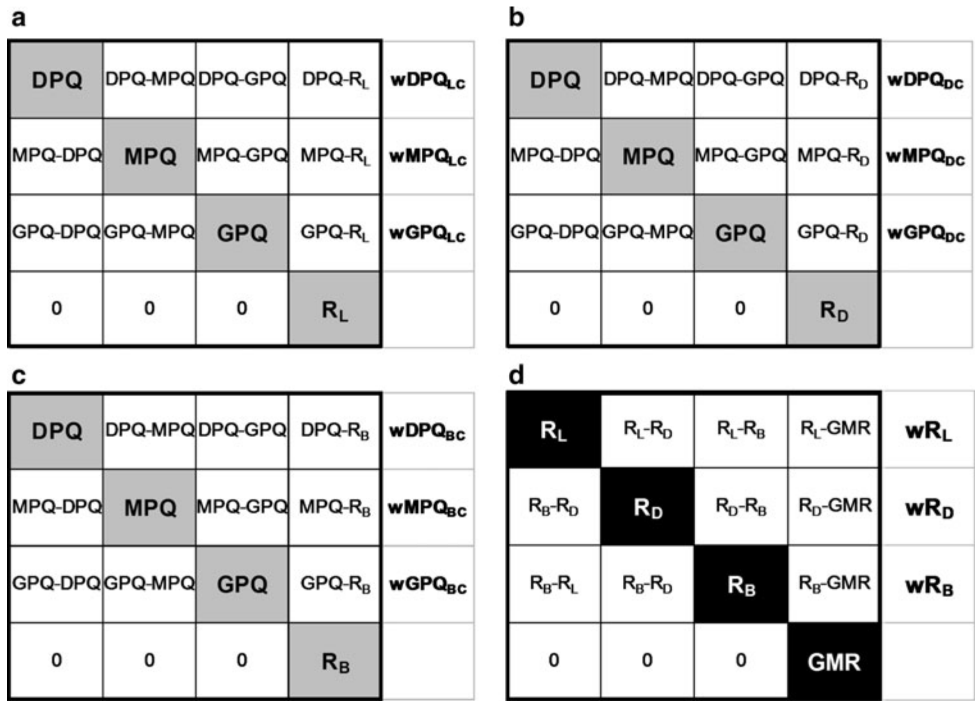

Fig. 7 **a–c** Structure of the global interaction matrixes used to evaluate the influence (weight) of the parameters DPQ, MPQ and GPQ on the forecasts reliability; **d** structure of the global interaction matrix used to evaluate the influence of R_L, R_D and R_B on the global reliability (GMR), where R_L, reliability of lithological forecasts, R_D, reliability of ductile deformations forecasts, R_B, reliability of brittle deformations forecasts

purpose, the two aspects cited at points 3.2 "c" (interactions among parameters) and "d" (influence of the natural setting) must be considered (step 2 in Fig. 5).

As far as point "c" is concerned, it is evident that the prediction quality provided by each considered investigation system can be improved by the existence of the other two types of investigations. It is a common procedure, for instance, to make one or more calibration boreholes as a support to a geophysical investigation campaign; predictions obtained with geophysics are therefore more effective if boreholes are available. Similarly, the results obtained by field geological mapping are by far more reliable if validated by drillholes. The opposite is also true, in the sense that the structural and lithological elements observed punctually in a borehole are easily interpreted when a 3D observation network is made available by mapping.

Therefore, mutual influences among different investigation types are evident, but it is also evident that such influences are not constant, varying from site to site according to changes in the geological complexity: the benefit that MPQ (mapping) gives to DPQ (drillings) is greater in a complex structural context, since in this case borehole logs can be correctly extrapolated only if the complex geological setting is fully understood by means of a structural mapping work. On the contrary, in an extremely simple geological setting, geological mapping could even be unnecessary to extrapolate drillholes data, because the geometric (structural) rules are very simple and can be mostly deduced by the drillholes themselves. Similar geological complexity-related relationships can be established among the other parameters.

As far as point "d" is concerned, it is noteworthy that the relative influence that each investigation type has on the forecasts reliability, also varies with the geological complexity of different contexts. As an example, seismic surveys effectiveness in providing reliable predictions rapidly decreases with increasing geological complexity as, in the presence of multiple folding or faulting, reflectors become so complex and numerous that their correct interpretation is extremely difficult. On the other side, information provided by geological mapping, even if decreasing in complex geological settings, remains rather effective. Therefore the relative weight of geophysical methods compared to geological mapping decreases with increasing geological complexity.

In order to derive the relative influences (weights) that each of the parameters DPQ, MPQ and GPQ has on the forecasts reliability by considering both their mutual influence and the variation of their influence with the complexity of the geological setting, the interaction matrix proposed by Jiao & Hudson (1995) is used. The leading diagonal of the matrix include the influence that the quantities DPQ, MPQ, GPQ and the searched parameter, i.e. the forecasts reliability (R), have on themselves, which is always zero. The off-diagonal cells of the matrix include representative values of the influences that each of the four parameters in the leading diagonal has on the others (see Fig. 7). Despite some simplification, it is assumed that the mutual influences between the quantities in the matrix are described by linear functions; the values reported in the off-diagonal cells are the angular coefficients of these linear functions (Jiao and Hudson 1995).

How does geological complexity enter this matrix? The geological complexity is the element that defines the system in which the variables interact, controlling how such variables interact with each other. The coefficients (angular coefficients) in the matrix cells assume different values in response to different degrees of geological complexity, i.e. in response to different ratings of the system parameters. These are rated with a value in the range 0–1, according to the standard concepts exposed in Table 2.

Moreover it must be considered that the geological complexity can be defined with reference to the three different parameters LC, DC, BC (Sect. 3.1.3). Each of them varies independently from the others from site to site: somewhere a great lithological complexity (LC) can cope with geometric complications induced by a complex ductile deformation (DC), whereas somewhere else LC can be higher and DC lower, and so on. This means that for each analysed context (each tunnel project), the effect of the three parameters on the relations among DPQ, MPQ and GPQ has to be considered separately and that to define the relationships among DPQ, MPQ and GPQ it will be necessary to create three matrixes: (i) one addressed to the lithological reliability (R_L); (ii) one addressed to the reliability of predictions concerning the ductile structural

Table 2 Criteria for the definition of the system parameters

LC grade	Description of the lithological setting	Rating
Criteria for the definition of the LC rating		
Low complexity	Etheropies: no	0.25
	Significant changes in strata thickness: no	
Medium complexity	Etheropies: no	0.5
	Significant changes in strata thickness: yes	
High complexity	Etheropies: yes (km scale)	0.75
	Significant changes in strata thickness: yes	
Very high complexity	Etheropies: yes (km scale)	1
	Significant changes in strata thickness: yes	
DC grade	**Description of the ductile deformation setting**	**Rating**
Criteria for the definition of the DC rating		
Low complexity	Superposed folding phases: no	0.25
	Transpositive phenomena: no	
	Ductile shears: no	
Medium complexity	Superposed folding phases: yes, two phases	0.5
	Transpositive phenomena: no	
	Ductile shears: no	
High complexity	Superposed folding phases: yes, three phases or more	0.75
	Transpositive phenomena: yes, for one folding phase	
	Ductile shears: possible presence	
Very high complexity	Superposed folding phases: yes, three phases or more	1
	Transpositive phenomena: yes, for more than one folding phase	
	Ductile shears: diffused presence	
BC grade	**Description of the brittle deformation setting**	**Rating**
Criteria for the definition of the BC rating		
Low complexity	Number of fault systems: 1	0.25
	Maturity of fault systems: mature	
Medium complexity	Number of fault systems: more than 1	0.5
	Maturity of fault systems: mature	
High complexity	Number of fault systems: more than 1	0.75
	Maturity of fault systems: some low -maturity system	
Very high complexity	Number of fault systems: more than 1	1
	Maturity of fault systems: all systems with low maturity	

setting (R_D); (iii) one addressed to the reliability of predictions concerning the brittle structural setting (R_B). The main output of the three matrixes will be represented by three coefficients wDPQ, wMPQ and wGPQ (step 2 in Figs. 5, 7a–c), representing the weights or influences that each of the three quantities DPQ, MPQ and GPQ has on the three types of forecasts reliability (R_L, R_D, R_B). Therefore at the end of the process nine coefficients will be obtained.

In all computations described in this section a crucial role is played by the ratings of LC, DC, BC and by the angular coefficients of the functions that correlate DPQ, MPQ and GPQ depending on these ratings. The basis for the definition of ratings rules, as for the case of the investigation parameters (Sect. 3.2.2), has been at first an empirical one and secondly a refinement through a trial-and-error process. Ratings rules are reported in Table 2; their principle is that the lower the complexity the lower the rating. With this principle in mind, in order to establish the rating rules, for each parameter two end-member situations have been at first defined. These have been attributed the minimum and maximum ratings (i.e. 0 and 1). Subsequently, the intermediate situations have been rated, according to a principle of linear increase with increasing complexity. For instance, in the case of ductile structural complexity (DC), the two end-members are (a) no folding and (b) many (three or more) superposed folding phases; experience indicates that in the first case the interpretation of investigation-derived data is practically straightforward, while in the second case it is very problematic. A number of intermediate situations exists (one folding phase, two folding phases, etc.), that have been used to regularly subdivide the interval between the two extreme situations.

The dependence on rating of the angular coefficients of the matrixes functions has been established according to a similar principle. Nevertheless, it must be emphasised that in this case the subjective feeling of the author and its personal experience have a greater weight. Some example will clarify this aspect. The influence of MPQ on DPQ has been inferred to increase consistently with the increase of ductile complexity (DC), since with increasing complexity a good knowledge of the general geological setting, obtained mainly by field mapping, becomes more and more necessary in order to interpret the drillholes. Conversely, the influence of GPQ on MPQ has been inferred to decrease with increasing ductile complexity, since geophysical investigations largely lose effectiveness when the geological context becomes very complex. In the first example the angular coefficient of the linear function that correlates the influence of MPQ on DPQ and the rating of DC increases with increasing DC and the function has always a positive slope; in the case of GPQ-MPQ influence, the angular coefficient increases with increasing complexity as well, but this time the function has a negative slope. The variation of these two angular coefficients is obviously strongly dependent on the author's feeling, since the correlated quantities are not measurable and it is difficult to have direct evidence of their relationships but that coming from personal experience. A description of all functions is beyond the scope of this paper, but the whole set of used relationships can be deduced by consulting the calculation spreadsheet cited in the introduction of Chapter 3; this should contribute to make more transparent the process of the GMR derivation.

3.2.3 Derivation of Partial Reliability Indexes

Once the matrixes are solved, the nine coefficients obtained can be used to calculate the weighted values of DPQ, MPQ and GPQ. Since these coefficients are grouped in three sets, representing the three parameters LC, DC and BC, describing the geological complexity, it will be necessary to derive three weighted sums, each describing a different aspect of the predictions reliability: R_L for the lithological setting, R_D for the ductile structural setting and R_B for the brittle structural setting (step 3 in Fig. 5).

Nevertheless, it has to be noticed (Sect. 3.1.1) that the derivation of the three partial indexes R_L, R_D and R_B cannot be obtained by simply weighting DPQ, MPQ and GPQ, because these quantities, that parameterise the potential qualities, need to be transformed in quantities that define an effective quality. This step is achieved by introducing corrections to the weighted sum according to the system parameters and the interpretation parameters (step 3 in Fig. 5; Sect. 3.1.2, points "e" and "f" respectively).

As far as system parameters are concerned, it is evident (Sects. 3.1.3 and 3.2 point "e") that the greater the system complexity, the lower the forecast precision obtainable by the investigations. In a more complex system the extrapolation and interpretation of investigation-derived data is less effective. To take into account this aspect, reduction factors must be applied to the investigation parameters weighted sums, which are linear functions of the same ratings used to define the angular coefficients of the matrixes functions, indicated as LC, DC and BC in step 3 of Fig. 5.

As far as the interpretation parameters are concerned (Sects. 3.1.3, 3.2 point f), the effective capacity that each type of investigation has in providing information about the geological setting, depends on the quality of the data interpretation. An estimate of the interpretation quality IQ (Sect. 3.1.2) is therefore necessary. The principle used is that if the interpretation quality was the best possible, all potential information contained in the investigations would be converted into effective information, while if the interpretation quality was very poor, no effective information would be derived. IQ is used therefore as a further

Table 3 Criteria for the definition of interpretation quality (IQ) rating

Parameter	Description	Rating
EC (extrapolation criteria)	Genetic interpretation based on well documented observations	1
	Genetic interpretation sometime not well documented	0.9
	Geometric extrapolation prevalent with poor genetical interpretation	0.8
CM (conceptual models)	All elements of the model included in the frame of one or more structural or lithostratigraphic association; conceptual models for associations used are well documented and well described in literature	1
	Partial use of the structural or lithostratigraphic associations concept	0.9
	No use of the structural associations concept; conceptual models use unclear	0.8
IE (interpreter experience)	Experience in geology for tunnelling >10 years	1
	5 years < experience in geology for tunnelling <10 years	0.9
	Experience in geology for tunnelling <5 years	0.8

factor applied to the weighted sums of DPQ, MPQ and GPQ (step 3, Fig. 5). The rating of IQ is derived by rating the three parameters described in Sect. 3.1.2 according to simple pre-determined criteria (Table 3).

The rating of extrapolation criteria (EC) can vary in the range 1–0.8 whether a genetic or purely geometric extrapolation has been applied. A high rating should be applied whenever in the baseline report it is exhaustively described how data from drillholes, mapping and geophysics have been correlated. Drillholes and geophysics data should be extrapolated according to genetic rules deduced from the mapping campaign, taking into account intersection and superposition relationships between different geological structures, and stratigraphic significance of the different lithological boundaries.

Similarly, the rating of conceptual models (CM) can vary in the range 1–0.8, depending on the effort to reconstruct the 3D rock mass geometries, according to adequate reference models. The choice of the adopted reference models should be described in detail in the baseline report; the models should make reference to the concept of “structural associations” (as described, for instance, by Hobbs et al. 1976; Forlati and Piana 1998; Perello et al. 2003a) and should be derived from literature cited in the baseline report.

The interpreter’s experience (IE) will be rated as follows: 1 if the geologist charged of deriving the RGM has more than a 10 years experience in engineering geology applied to underground works in contexts similar to that being studied, 0.9 if his experience dates back to 5–10 years and 0.8 if it dates back to less than 5 years.

The value of IQ is obtained by summing up the EC, CM and IE ratings and dividing the sum by 3 to normalise it and finding a value once more ranging between 0 and 1, which is suitable to be used as a multiplicative factor. The sum is used because it is supposed that each parameter contributes linearly and independently from the others to determine the value of IQ.

The basis for establishing the rating rules of EC, CM and IE is intuitive and is adjusted by means of a trial-and-error process; it has been chosen to use always high ratings, assuming that the geologist involved in the project is a professional acting according to a diligence criterion, meaning that he will make reference to correct interpretation principles. This does not imply that a rating of less than 0.8 cannot be applied, if in the judgement process one feels that the interpreter has been applying wrong models or extrapolation criteria, but in principle, this should not be the case. The application of values lower than 0.8–0.7 proved to return GMR values too low, if compared to real experience. An IQ range between 0.8 and 1 seems to grant the best complementarity with the other parameters contributing to the GMR.

3.2.4 Derivation of a Single Index

In order to obtain a global reliability quantification (i.e. the GMR), R_L, R_D and R_B need to be combined. It is easily understood that among R_L, R_D and R_B mutual influences also exist. As an example, to a greater detail in describing lithostratigraphic variations in the geological model will correspond a greater possibility to correctly interpret brittle structures superimposed on the stratigraphic sequence, in other words it will be easier to calculate the faults displacements.

Therefore, the influence that R_L, R_D and R_B have on the GMR must be deduced by means of a further interaction matrix (step 4 in Fig. 5). In this case the interaction functions, i.e. the coefficients in the matrix cells, are fixed, because it seems reasonable to suppose that the reciprocal influences between R_L, R_D and R_B are mostly independent from the geological context. For instance, the knowledge of the lithological setting has more or less always the same influence on the knowledge of the brittle faulting context, the knowledge of ductile deformations has more or less always the same influence on the knowledge of lithological setting etc.

The matrix assumes the form shown in Fig. 7d. The coefficients in the cells have been attributed relatively low values (0.2–0.3 in most cases), which means that influences among the different quantities are moderate. This is due to the fact that each part composing a geological model (lithostratigraphy, ductile and brittle deformation), even if it certainly benefits of contributions from the others, is mainly the result of specific analysis on investigation data and therefore, its relevance, as derived from the previous steps of the GMR calculation process, can not change very much.

At the end of this process of coupling through the global interaction matrix, the value of the global geological reliability (GMR) can be deduced. The matrix is assumed to provide the individual contribution (weight) that R_L, R_D and R_B give to the definition of a partial reliability and of the global GMR. In this sense, the GMR is defined as a parameter originated by the joined contribution of the three different types of partial reliability and therefore as the weighted sum of R_L, R_D and R_B, where the weights are represented by the outputs of the global interaction matrix (step 4, Fig. 5):

$$\mathbf{GMR} = wR_L \times R_L + wR_D \times R_D + wR_B \times R_B. \quad (3)$$

where wR are the weights of the three reliabilities.

It has been said that the coefficients in the global interaction matrix are fixed and independent from the geological context. Despite this, there are some special cases in which they may change. Let's consider, as an example, a geological context with a granite intruding a gneiss, where extremely complex and chaotic contacts occur between the two rocks having a similar rheological behaviour. In such a case, R_L would be probably high, but it would not have a significant influence on the reliability of the geological predictions aiming to choose the best excavation technique; neither it would have a significant influence on R_D and R_L and vice versa. "Lithological complexity" may not always mean "rheological complexity" as well, therefore the mechanical properties of the rock mass may not necessarily be influenced by a complex geological setting.

Similar cases could be found in contexts with frequent etheropies between marls and siltstones, or within a multiphase-folded metamorphic unit composed of interlayered ortho- and paragneisses, etc.; in all cases, the homogeneous mechanic behaviour of the rock mass as a whole prevails on the lithostratigraphic complexity.

Therefore, when managing tunnelling problems, the concept of lithological complexity should not only take into account the lithostratigraphical aspects, but also the geomechanical ones. For practical tunnelling purposes, the geological complexity is strictly correlated to heterogeneities in the rheological and mechanical behaviour of the rock mass. Owing to this subtle distinction, if one considers that, for simplicity, the coefficients of the global interaction matrix have been defined at first by thinking about a geological context with rheologically heterogeneous lithotypes, in order to include cases where different lithotypes have quasi-homogeneous rheological properties, it is necessary to remember that the interaction rules among the matrix cells can change, sometimes, and to include in the method some correction factor.

To do this, the role of rheology has been added as a last refinement of the GMR, by rating some typical extreme situations (Table 4). This rating has then been used to provide adjustments to the role played by R_L in defining the GMR. When the rating of Table 4 is high (value 3), i.e. if the lithological anisotropy is high, the original GMR matrix (Fig. 7d) is maintained unvaried. When the rating of Table 4 is low (value 1) the matrix coefficients defining the influence of R_L on R_D and R_B are reduced consistently, so as to reduce the role of R_L.

4 Discussion and Case Histories

Although it may appear as a rather complex and time-consuming process, defining the GMR for the different sections of a tunnel is relatively quick, just needing the evaluation of the 19 ratings resumed in Tables 1, 2, 3, 4, most of which do not need to be derived for each section as, once established, they are often valid for the whole layout. The GMR calculation is easily obtained by a pre-structured electronic spreadsheet written with a software of common use, freely available on the author's website (http://www.gdpconsultants.eu).

The GMR index significance is synthesised in Table 5. It has been defined empirically, by refining the coefficients in the functions governing the GMR, according to observation of already excavated tunnels. Any unforeseen event occurring during excavation in one of the examined tunnels had to fall in one of the four GMR classes, according to its nature and entity; if not, the internal coefficients of the GMR were revised.

With reference to the concepts discussed in Sect. 2, it is evident that the GMR aims at a better definition of uncertainty in a general sense, irrespective of its epistemic or stochastic nature. Its main goal is to discriminate between states of bounded and unbounded uncertainty, moreover implicitly admitting that absolute certainty is

Table 4 Criteria for rating the mechanical heterogeneity and defining the interaction rules in the matrix of Fig. 7d

Grade of mechanical etherogeneity of the rock mass	Description of the lithological setting	Value
Estimate of BIM coefficients for GMR		
Low	Both new and literature data allow to attest with very high probability that lithologies in the examined stretch display very similar mechanical properties	1
Intermediate	Both new and literature data allow to attest with very high probability that lithologies in the examined stretch display variable mechanical properties but no soluble lithologies (carbonatic or evaporitic) are present	2
High	Both new and literature data allow to attest with very high probability that lithologies in the examined stretch display different mechanical properties and there is the possibility that soluble lithologies (carbonatic or evaporitic) are present	3

Table 5 Significance of the GMR

Class	GMR	Reliability	Description
A	10–7.5	Good	(1) to be excluded; (2) possible: imprecision order of magnitude 0–50 m; (3) possible: imprecision order of magnitude 0–25%; (4) to be excluded; (5) to be excluded
B	7.5–5	Fair	(1) to be excluded; (2) possible: imprecision order of magnitude 0–100 m; (3) possible: imprecision order of magnitude 0–50%; (4) possible but not probable; (5) to be excluded
C	5–2.5	Poor	(1) possible but not probable; (2) possible: imprecision order of magnitude 0–200 m; (3) possible; imprecision order of magnitude 0–100%; (4) possible; (5) possible but not probable
D	2.5–0	Unreliable	(1) possible; (2) possible: imprecision order of magnitude >200 m; (3) possible: imprecision order of magnitude >100%; (4) possible; (5) possible

Points 1–5 in the description field refer to the following items: *1* significant deviation with regard to the RGM; *2* imprecision in the position of lithological or fault zones contacts; *3* imprecision in the thickness of lithological levels or fault zones; *4* presence of further critical geological elements of secondary importance besides the forecasted ones (metric to decametric faults/levels with poor geomechanical conditions); *5* presence of further critical geological elements of primary importance besides the forecasted ones (decametric to pluri-decametric faults/levels with poor geomechanical conditions

never possible. For cases falling in classes A and B of Table 5, the knowledge of the geological model can be ascribed to the field of bounded uncertainty. This means that when the GMR assumes values in the range 5–10, collected data are enough to draw all possible geological models along the tunnel; unknowns are mostly "imprecision" (Bieth et al. 2009) and unforeseen events can be excluded. Cases falling in this range mostly show relevant investments in investigations.

When classes C and especially D are concerned, the geological model is in a state of unbounded uncertainty and unforeseen events become possible. In class C the consequences of uncertainty are mostly "imprecision" or "unexpected events", but unforeseen events cannot be excluded as well, even if the risk that they occur is low. Class C can be rather common a condition in tunnelling, since it includes cases where the geological model is relatively well constrained, by means of a good deal of investigations, whereas the geological context is very complex (e.g. in multiphase-folded and faulted domains). When the GMR value falls in class D, we must consider the model only as a rough indication of what the geological situation could be. The probability that some geological elements did not emerge from the investigations and their interpretation is high. This case is not so common in advanced design stages and usually implies a significant lack of investigations.

GMR has positive aspects but also suffers of some intrinsic limitation. As a positive aspect it represents a structured approach to the analysis of a reference geological model reliability, trying to embrace in a unique logical framework most of the factors that contribute to the prediction of a tunnel geological setting. In this sense, it may be useful since it makes these factors evident and forces the engineering geologist to be aware that all of them play a role and that this role can change according to the geological context complexity.

As for limitations, GMR is based on empirical rules (especially those controlling ratings and weights) resting on personal experience. From this point of view, two main problematic issues remain: (i) the functions governing the influence of each parameter can be validated with difficulty, since they are often somehow related to the influence of other parameters; a certain alea must then be accepted; (ii) it is difficult to have experience of all possible tunnelling situations, therefore attention should be paid when using GMR in contexts not fully tested; at the moment GMR is relatively well tested for tunnels excavated in folded and faulted metamorphic domains, while it is poorly tested for tunnels excavated in soft ground and/or very simple geo-structural settings.

We may expect that GMR will benefit of future use-derived refinement. It cannot be excluded that some improvement to its structure will be necessary too. Therefore it must presently be intended as a tool whose testing is in progress.

For actual purposes the GMR could have various applications in design and contractual practice. One of such applications is related to the tendering phase of tunnelling projects, when identifying by the GMR the tunnel sections affected by the lowest reliability would permit to place in space and time the main construction risks deriving from geological aspects. GMR could be therefore a practical tool for contractors, optimising the tender strategy by means of a better calibration of the economical proposal or, at least, of a conscious acquisition of construction risks related to a poorly constrained geological model. Meanwhile, clients, by knowing which parts of the tunnel present the greatest aleas, could decide to adopt more flexible contractual tools.

Other applications could be related to the tunnel design process, where construction strategies are often chosen by means of probabilistic tools (Einstein et al. 1978; Ashley et al. 1981; Grasso et al. 2000; Chiriotti et al. 2003), based upon probability attributions to different hypotheses of geological model. They assume implicitly, therefore, a knowledge of the geological model of "bounded uncertainty" type, which could not always be the case; in facts, situations of unbounded uncertainty are frequent in tunnelling design, even if they are difficult to identify. The association of the GMR analysis to the classical risk analysis tools could allow a more exhaustive risk definition, also encompassing very critical situations of unbounded uncertainty that often lead to the worst accidents, with great increase of construction times and costs.

Therefore, in the frame of a risk analysis process, when considering the rock mass geomechanical behaviour of tunnel sections characterised by low to very low GMR classes (C and D, see Table 5), particular care should be taken as to include extreme scenarios. If, for instance, the Hoek and Brown (1980b) failure criterion, commonly used for the definition of the rock mass behaviour, is considered, a wide range of possibilities should be assumed in presence of low GMR values, due to the fact that both the Geological Strength Index (GSI; Hoek et al. 1995) and some intact rock properties (σ_c and m_i; Hoek and Brown 1980a) can be subject to strong deviation from the average estimated value. Similar considerations are also valid for other rock mass properties parameterisation systems, as the RMR index (Bieniawski 1989) or the Q-index (Barton et al. 1974).

The GMR could be used in the tunnel design process for an adequate planning and refining of investigation campaigns as well, in order to obtain the needed accuracy degree in the forecasts reliability. This purpose is obtained by means of simple diagrams, outlining which investigation type should be implemented to obtain the maximum benefits. For instance, Fig. 8 shows the essential diagrams for the case of a hypothetical tunnel section, where R_B is by far the most important type of reliability, which is due to the fact that its weight (0.67) in the calculation of the total reliability is approximately three times the weight of R_L (0.16) and R_D (0.17). R_B is therefore the factor we can try to optimise in order to obtain better forecasts.

In this example, the optimisation can be defined by examining the diagram of Fig. 8d, which illustrates the actual value and weight that each of the investigation parameter has on R_B. For this specific case, the geological mapping potential quality (MPQ) has a high weight of 0.6 but a low value (2.2). Further geological mapping would therefore be needed to increase consistently the geological model accuracy and reliability. Diagrams of Fig. 8b and c in this example are less important, since they make reference to R_L and R_D, whose weight is secondary.

In order to provide a clearer description of the use of GMR, two case histories are briefly presented. The chosen examples refer to already excavated tunnels, where one or more sections encountered unfavourable geological conditions, sensibly different from the design-predicted ones. For each case history, a sketch of the reference geological map is provided, together with a sketch of the longitudinal geological section used for the design and, finally, a sketch of the as-built section drawn after the excavation.

4.1 The High Speed Railway Link between Turin (I) and Lyon (F): Saint-Martin-La-Porte Access Tunnel

The 2 km long Saint-Martin-La-Porte tunnel (France) is part of the Turin-Lyon railway link, presently in an advanced design phase, that will cross the axial zone of the western Alpine chain, connecting Italy and France; it has the function of both exploration tunnel and access tunnel to the future 54 km long railway base tunnel. The excavation started in 2003 and ended in 2010, after meeting some relevant problems related to a geological/geomechanical situation not fully predicted in the design phase. The adopted excavation method was a mix of D&B and hydraulic impact hammer.

The tunnel is located on the right side of the Arc river valley and is excavated at a maximum depth of 400 m. The geological context is pretty complex and field interpretation is difficult because of the low outcrop percentage, most of the pre-quaternary basement being covered by

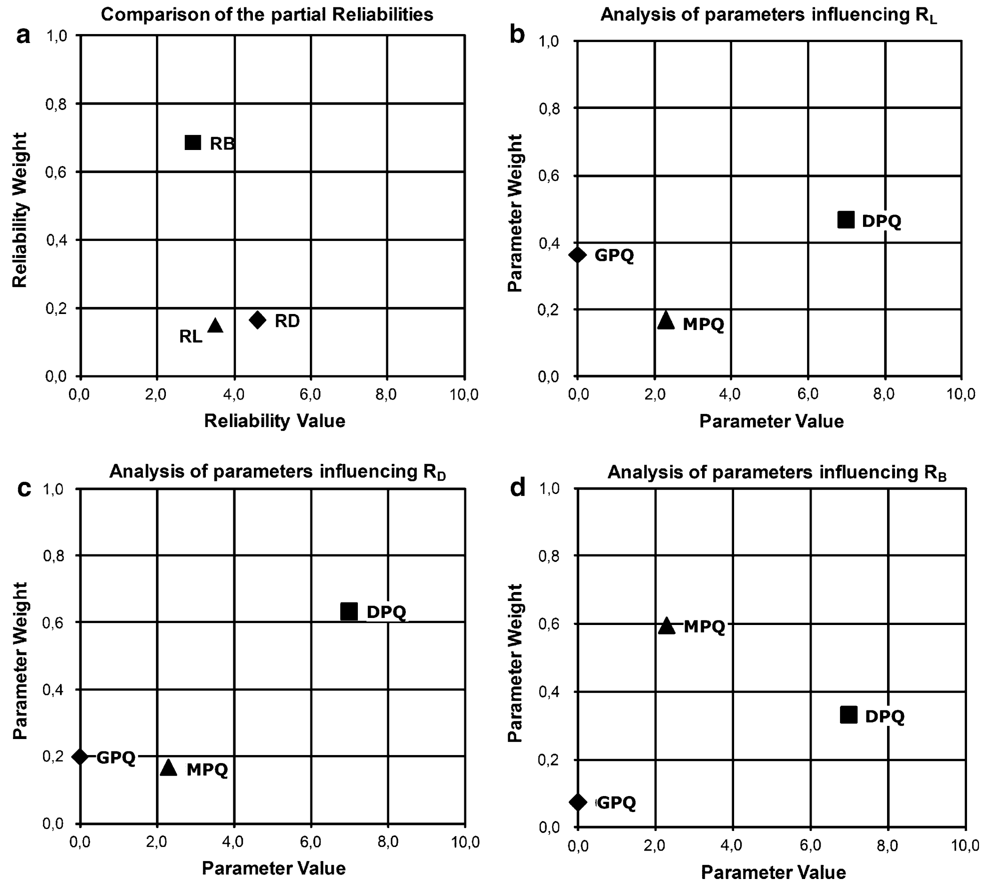

Fig. 8 Diagrams obtained from the GMR derivation process; **a** Relevance of the different reliability types versus their ratings; **b–d** Relevance of the different investigation parameters versus their ratings for the three different reliability types

extensive landslide deposits. Figure 9 shows a sketch map derived from the constructive design documents. The tunnel crosses the tectonic contact between two main alpine units, the carbonatic/evaporitic Perron des Encombres Unit and the siliciclastic “Zone Houillère”. Both units display a multiphase ductile deformation story, with three main superposed folding phases, one of which, at least, transpositive. The lithostratigraphic setting is very complex as well, owing to both pre-quaternary stratigraphy of the metamorphic basement and to the unclear basement/quaternary deposits relationships.

In cases like this, the GMR estimate should preferably be provided every 50 m of tunnel section. Attention will be focalised here on the zones comprised between 850 and 900 m (section 1) and between 1,250 and 1,300 m (section 2). In section 1, Liassic limestone and gypsum were expected; a palaeo-valley filling made of alluvial deposits was encountered instead, which caused considerable excavation problems (Perello et al. 2003b; Martinotti 2009). In section 2, a brittle to ductile shear zone was met inside the “Zone Houillère”, whereas moderately fractured siliciclastic meta-sediments were expected; squeezing problems and convergences greater than 1,000 mm were encountered (Barla et al. 2007). Figure 10 illustrates a comparison between the design and the as-built geological sections. Both accidents can be numbered among the unpredicted events, due to the difficulty of producing a reliable geological model, owing to intrinsic limitations to the possibility of constraining the model variability.

The GMR photographs rather well the low reliability of the pre-excavation geological model (Fig. 10a). As a matter of fact, despite the relatively high number of investigations, which might lead to the conviction of having a good geological model, the GMR value is about 4, indicating the existence of a residual possibility of some relevant unforeseen event. Table 6a, b shows the rating attributed to the GMR parameter in the two tunnel sections: most of the factors contributing to DPQ have relatively good ratings; one could question if the “average distance from tunnel”, especially for section 1, should to be set to 4 (i.e. 500 m) or to a higher value, since a drillhole exists (F18) not too far from the section; anyway, even if a greater value, e.g. 6, was chosen, the GMR would fall in class C (lower than 5: 4.08 for section 1 and 4.34 for section 2). Since the field mapping was very detailed, the MPQ factors are all high, with the important exception of the “outcrop percentage” that is very low (among 1 and 2), thus considerably reducing the contribution of MPQ to the reliability, that in such a context would be very important, especially for the extrapolation of borehole data.

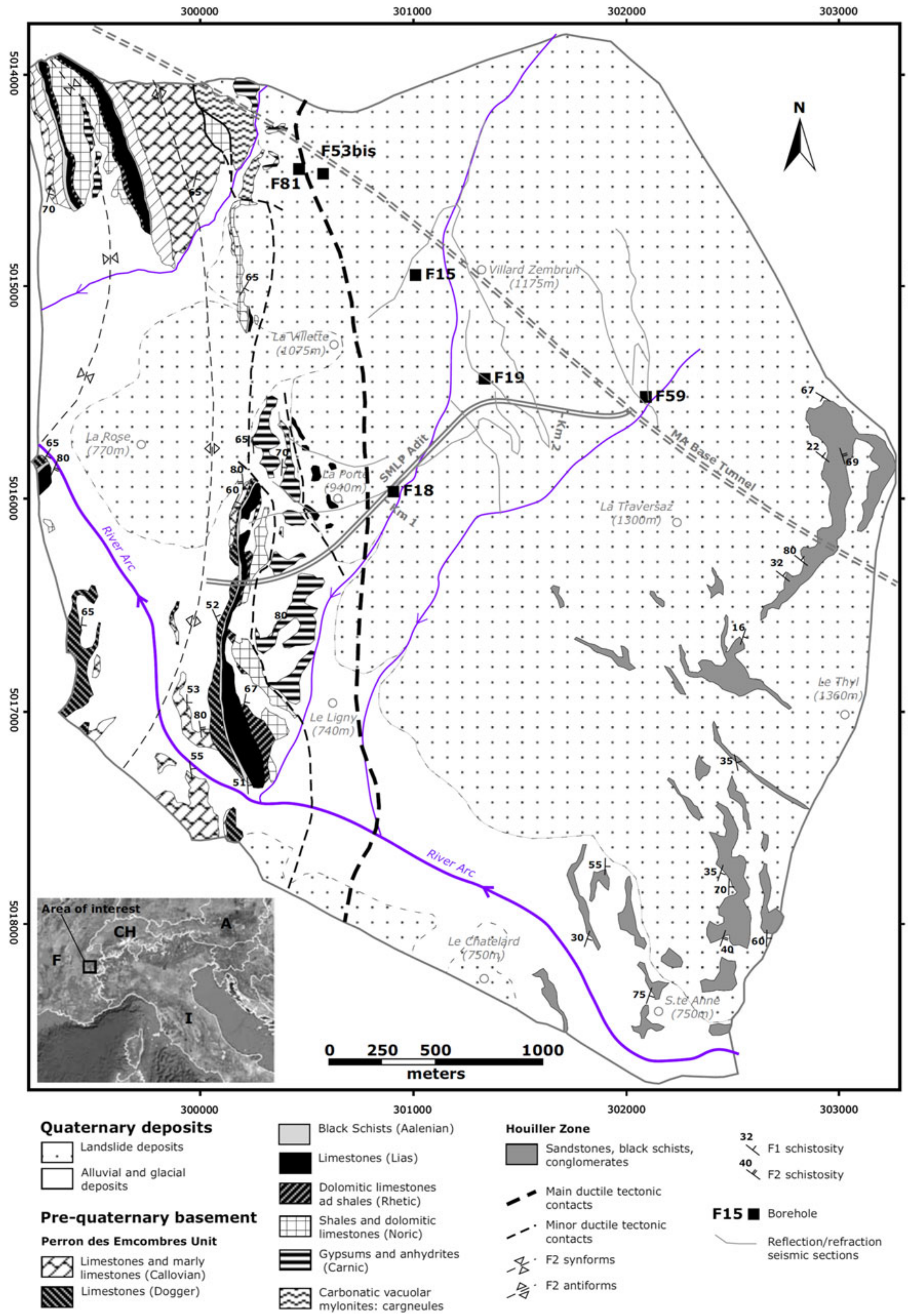

Fig. 9 Geological sketch map in the area of the Saint-Martin-La-Porte access tunnel (redrawn from Perello et al. 2003a)

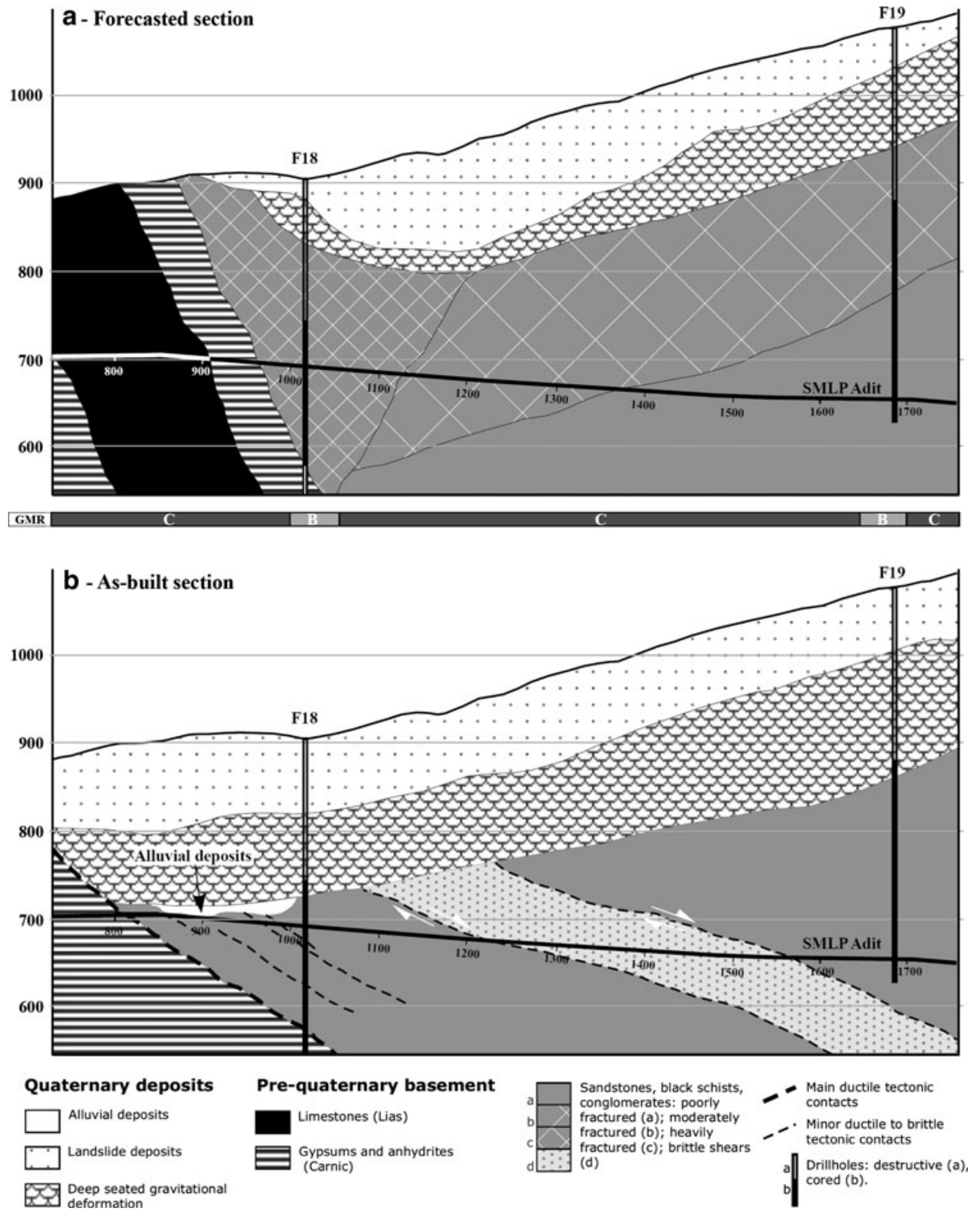

Fig. 10 Geological sketch sections along part of the Saint-Martin-La-Porte access tunnel. **a** Expected geological model (redrawn from Perello et al. 2003a); **b** As-built geological model (redrawn from Martinotti 2009)

Table 6 GMR parameters ratings for the Saint-Martin-La-Porte access tunnel: (a) section 850–900 m; (b) 1,250–1,300 m; (c) 1,000–1,050 m

			Rating	
Investigation Parameters	DPQ ratings	Drillholes quantity	6	5,9
		% cored drillholes	5	
		Distance from tunnel	4	
		drillholes depth	10	
	MPQ ratings	Mapping scale	8	4,5
		Mapped area	10	
		% Outcrop	1	
		Data collection method	10	
	GPQ ratings	Sampling lines length	9	8,2
		Method's resolution	5	
		Distance from tunnel	9	
		Investigation depth	10	
Inrerpretation Parameters		Extrapolation criteria	0,9	
		Conceptual models	0,9	
		Interpreter experience	0,9	
System Parameters	LC		1	
	DC		0,75	
	BC		0,75	
Grade of mechanical etherogeneity			3	
		GMR	**3,35**	

a

			Rating	
Investigation Parameters	DPQ ratings	Drillholes quantity	6	5,9
		% cored drillholes	5	
		Distance from tunnel	4	
		drillholes depth	10	
	MPQ ratings	Mapping scale	8	4,5
		Mapped area	10	
		% Outcrop	1	
		Data collection method	10	
	GPQ ratings	Sampling lines length	9	8,2
		Method's resolution	5	
		Distance from tunnel	9	
		Investigation depth	10	
Inrerpretation Parameters		Extrapolation criteria	0,9	
		Conceptual models	0,9	
		Interpreter experience	0,9	
System Parameters	LC		1	
	DC		0,75	
	BC		0,75	
Grade of mechanical etherogeneity			2	
		GMR	**4,18**	

b

Investigation Parameters	DPQ ratings	Drillholes quantity	10	9,7
		% cored drillholes	9	
		Distance from tunnel	10	
		drillholes depth	10	
	MPQ ratings	Mapping scale	8	4,5
		Mapped area	10	
		% Outcrop	1	
		Data collection method	10	
	GPQ ratings	Sampling lines length	9	8,2
		Method's resolution	5	
		Distance from tunnel	9	
		Investigation depth	10	
Inrerpretation Parameters		Extrapolation criteria	0,9	
		Conceptual models	0,9	
		Interpreter experience	0,9	
System Parameters	LC		1	
	DC		0,75	
	BC		0,75	
Grade of mechanical etherogeneity			3	
		GMR	**5,54**	

c

The factors contributing to GPQ have good ratings, but GPQ has a low weight in this complex tectonic and stratigraphic setting (this is also an output of the computations). The system parameters have all high ratings, owing to the complicated geological situation. In this case, the interpretation parameters could be easily evaluated, as the author was a consultant of the design team. All the parameters show an intermediate, not high, quality; this is due to the fact that: (i) the extrapolation of geological features was not always supportable by well constrained criteria, (ii) the adequacy of the adopted conceptual model was not always tested and (iii) the interpreters team had members with variable experience.

As a last consideration about this case history it is interesting to notice that the GMR calculation in the section 1,000–1,050 m, where a drillhole was available, provides a value of 5.5 (Table 6c), meaning that the model is rather reliable but some imprecision may be present anyhow. This is reasonable if one considers that the interpretation parameters are not the highest possible and that DPQ too is not the highest possible, due to the fact that the mentioned drillhole was only partially cored.

4.2 The High Speed Railway Link between Verona (I) and München (D): Aicha–Mauls Exploration Tunnel

The 10.4 km long Aicha-Mauls exploration tunnel was constructed for investigation purposes in the frame of the Brenner Base Tunnel railway project, part of the future Verona-München high speed railway connection (52 km length). It was excavated between 2007 and 2010 by a double-shield TBM. The tunnel is located in a steep-sided alpine valley and runs under a topographic cover ranging between 300 and 1,200 m.

Unlike the Saint-Martin-La-Porte tunnel, the lithological context is very simple, as the pre-quaternary basement is

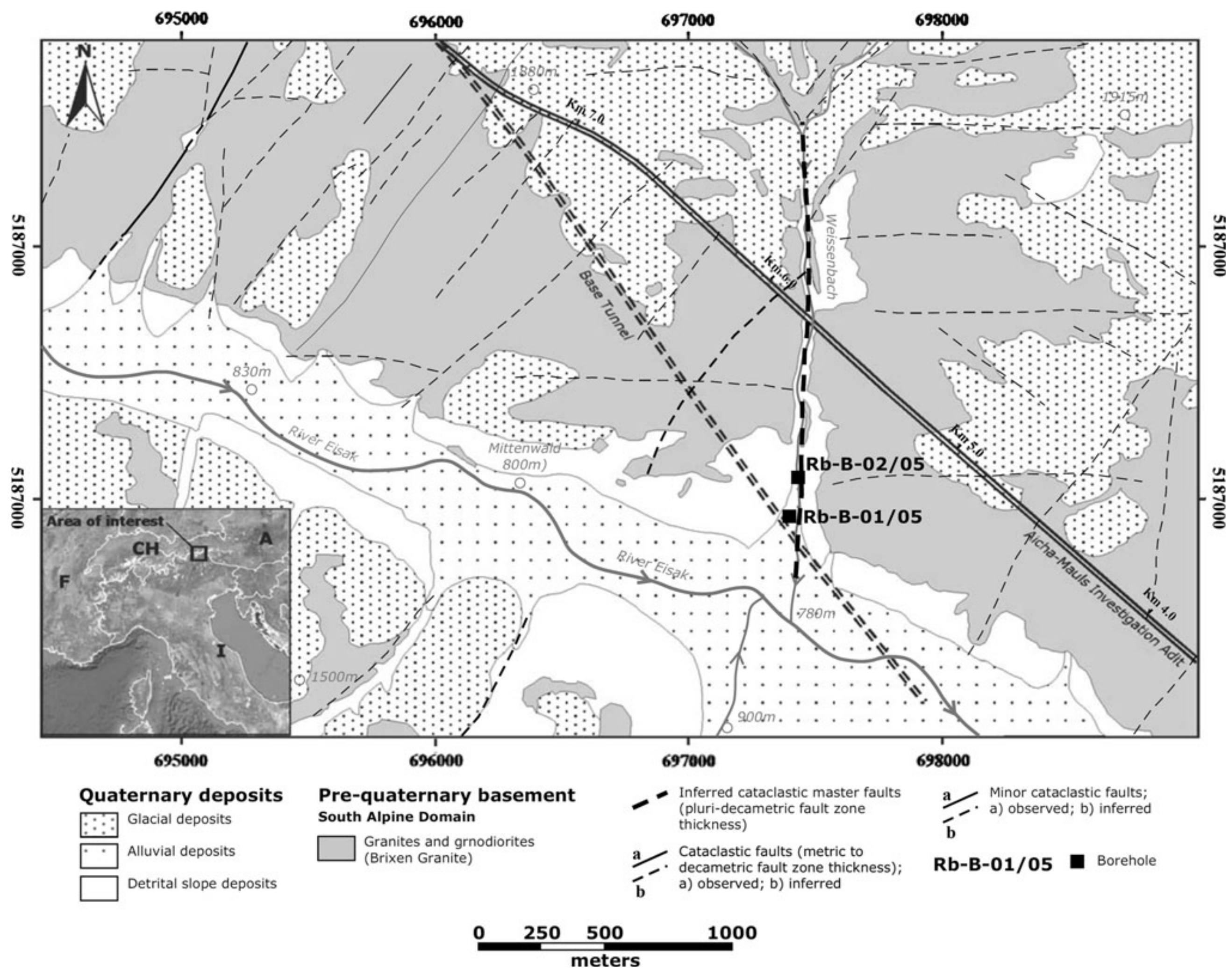

Fig. 11 Geological sketch map in the area of the Aicha-Mauls exploration tunnel (redrawn from Dal Piaz et al. 2005)

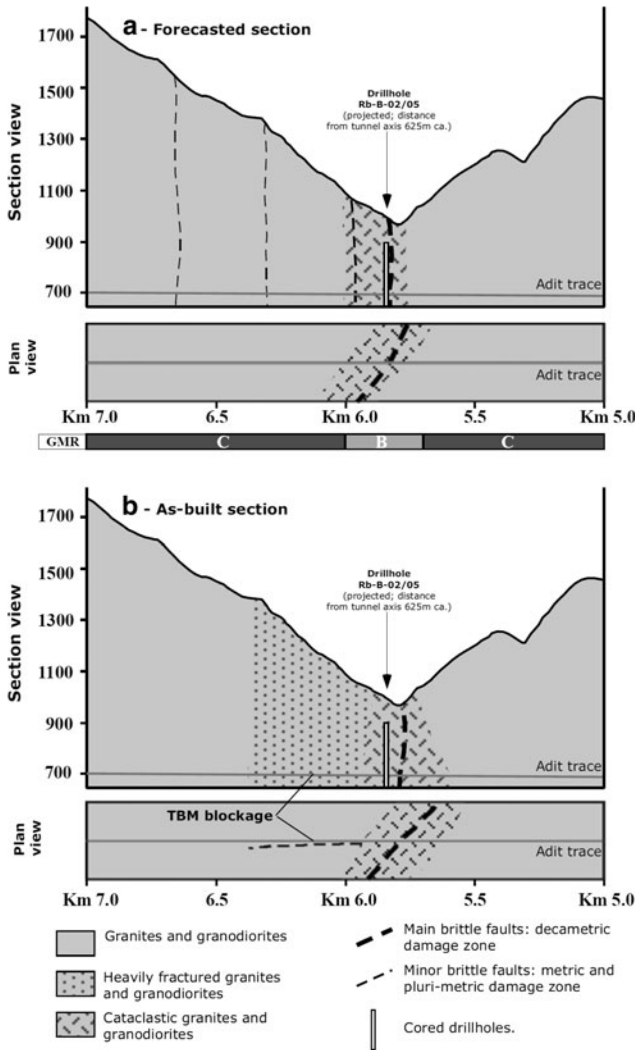

Fig. 12 Geological sketch sections along part of the Aicha-Mauls exploration tunnel. **a** Expected geological model (redrawn from Dal Piaz et al. 2005); **b** As-built geological model (redrawn from Perello and Baietto 2010). Note that in the vertical section (*b*) the trace of the fault that caused the TBM block is not visible, since the fault runs parallel to the section, in turn located in the fault damage zone; in the plan view the fault trace is visible, while the damage zone has not been represented because it is too thin

composed of monotonous granitic and granodioritic rocks with negligible compositional variations in space; quaternary deposits are very thin and there is no possibility that they reach the tunnel depth (Fig. 11). The granodiorites are affected by a very weak ductile deformation causing the sporadic appearance of a schistosity and of thin ductile shear zones. On the contrary, the brittle tectonic setting is very complicated, with different low-maturity fault sets, most of which are segmented and associated to damage zones with cataclastic rocks of variable thickness, all along the fault zone.

The excavation experienced a main accident at km 6 + 150 from the southern portal, due to the presence of a relatively small fault (10 m thickness) running for approximately 100 m sub-parallel to the left tunnel wall (Barla et al. 2010). The excavation has been stopped for 3 months owing to strong convergences and breaking of the concrete lining segments. The appearance of the small fault was an unexpected event, not forecasted in the baseline geological report and annexed tables (compare Fig. 12a, b).

The possibility that some geologically critical elements escaped to the geological model emerges from the GMR. In the tunnel section comprised between km 6 + 100 and 6 + 200, the GMR is 4.58 (class "C"), meaning that the presence of unpredictable critical geological elements is possible. Table 7a shows the ratings attributed to the GMR parameters. DPQ is rather low, mainly owing to the fact that drillholes are far from the examined tunnel section. MPQ is relatively high, but the low rating attributed to the "outcrop percentage" reduces its value; in facts, even if in the tunnel area there is a high outcrop percentage, most of the outcrops are not accessible, being located on steep mountain walls.

Therefore, according to the GMR rating standards (see Table 1, DPQ ratings, note 2), a 50% reduction was applied on the "outcrop percentage" rating. GPQ was set to 0 since no data of this type are available. As for the system parameters, both LC and DC are low, due to the simple lithological and ductile setting, while BC was given the maximum value (1), because of the complex and heterogeneous distribution of fault systems. The interpretation parameters were attributed an intermediate quality. The fault systems extrapolation was not always well constrained, owing to the scarcity of data concerning the kinematics and rheological behaviour of faults, which prevented a clear genetic interpretation of the different sets; a conceptual model comprehensive of all brittle tectonic elements was not defined; the interpreters team was composed of members with variable experience.

As a concluding remark, Fig. 12 shows that the only section where the GMR falls in class B and the forecasts can be considered relatively reliable, is comprised between km 5 + 800 and 6 + 000 (Table 7b). The geological model is here dominated by a main fault, explored by drillholes that can be extrapolated with certainty, even if they were not executed directly on the tunnel axis. In these cases, as defined by the GMR rating procedure, the factors called "Drillholes quantity in an interval of 2 km" and "Average distance from tunnel axis" were increased according to the rule of adding to the ordinary rating a quantity equals to (10-Rating) · 0.5. This leads to a final GMR of 5.14 (see Table 7b).

Table 7 GMR parameters ratings for the Aicha-Mauls exploration tunnel: (a) section 6,100–6,200 m; (b) 5,800–5,900 m

Investigation Parameters	DPQ ratings	Drillholes quantity	4	4,9
		% cored drillholes	8	
		Distance from tunnel	3	
		drillholes depth	10	
	MPQ ratings	Mapping scale	7	6,6
		Mapped area	10	
		% Outcrop	4	
		Data collection method	7	
	GPQ ratings	Sampling lines length	0	0
		Method's resolution	0	
		Distance from tunnel	0	
		Investigation depth	0	
Inrerpretation Parameters		Extrapolation criteria	0,9	
		Conceptual models	0,9	
		Interpreter experience	0,9	
System Parameters	LC		0,25	
	DC		0,25	
	BC		1	
Grade of mechanical etherogeneity			1	
		GMR	**4,58**	

a

Investigation Parameters	DPQ ratings	Drillholes quantity	7	7,7
		% cored drillholes	8	
		Distance from tunnel	6,5	
		drillholes depth	10	
	MPQ ratings	Mapping scale	7	6,6
		Mapped area	10	
		% Outcrop	4	
		Data collection method	7	
	GPQ ratings	Sampling lines length	0	0,0
		Method's resolution	0	
		Distance from tunnel	0	
		Investigation depth	0	
Inrerpretation Parameters		Extrapolation criteria	0,9	
		Conceptual models	0,9	
		Interpreter experience	0,9	
System Parameters	LC		0,25	
	DC		0,25	
	BC		1	
Grade of mechanical etherogeneity			1	
		GMR	**5,19**	

b

5 Conclusions

When the design and construction of linear underground structures is considered, the reliability of costs and time forecasts greatly depends on the reliability of the available reference geological model/s. Up to now, the engineering geology world experienced a difficulty in providing effective tools and processes for directly and objectively evaluating the reliability of the reference geological model. The GMR method, by defining the factors playing a key role in the construction of the model, allows to obtain a more structured and standardised approach to the evaluation of its reliability.

A geological longitudinal cross-section along a tunnel alignment is subdivided in parts of homogeneous length and a rating ranging from 0 to 10 is then attributed to each of them. According to the obtained rating, different reliability degrees for the predicted geological setting (faults, lithological boundaries, strata thickness, etc.) are deduced. The identification of the tunnel sections where some, or all possible models, are deemed unknown, is one of the most important potential results of the proposed method. When these sections are analysed by the GMR, the possibility of occurrence of unexpected events, critical for costs and time increase, can be constrained to a better degree and can be subsequently managed by implementing the investigations or by studying specific contractual tools.

The index derivation is achieved through a simple process of key parameters (e.g. drillholes number/depth, scale of available geological mapping, etc.) ratings. The results can be easily graphically represented by a descriptive row below the tunnel geological cross-section where the tunnel trace is divided in homogeneous sections, each described by one of the four classes associated to the index.

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