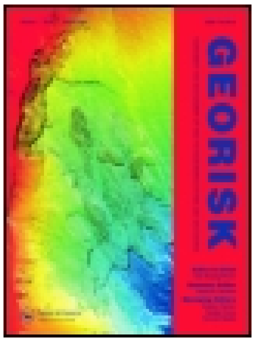

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The geological and geotechnical design model in tunnel design: estimation of its reliability through the R-Index

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ABSTRACT
In this paper recent improvements of the R-Index method are presented, based on its application on several projects in various geological and geotechnical contexts. The R-Index derives from a probabilistic procedure conceived for estimating the reliability level of the Geological and Geotechnical Design Model used to design underground structures, especially tunnels. The R-Index takes into account the geological complexity of a site and recommended empirical scores (based on expert judgement) for different quality levels of geological surveys and geotechnical and geophysical investigations.

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Geological hazards; geological reliability; probabilistic methods in rock mechanics

1. Introduction

The underground space offers unparalleled assets for managing successfully the growth of cities or crowded regions and reduces the distance between countries with long international tunnels. In addition, it supports and drives economic growth while reducing environmental pressure. To gain the maximum benefits from these assets it is necessary to reduce as much as possible the risks associated with the tunnel construction, which can cause potential damages to structures and/or people. To this end, tunnel design can be described as depicted in Figure 1 where three main steps are pointed out: the first step is to identify the potential hazards represented by the excavation process. After that it is needed to evaluate the likelihood of hazard occurrence and its potential consequences through the monitoring activities. The third step is to decide whether or not to apply mitigation countermeasures against certain identified risks. To address a rational tunnel design process closely related risks to its construction should be considered in a formal and uniform manner (Chiriotti, Grasso, and Xu 2003). Different authorities developed methodologies for incorporating risk-based processes into the conception, design, construction and operate and maintenance chain. The International Tunnelling Association (ITA) set up a Working Group to report on these systems and make proposals for a unified approach. This was achieved in 2004 with the publication of the "Guidelines for Tunnelling Risk Management" (ITA Working group 2004).

Within the Tunnelling Risk Management procedure it is well known that from an inadequate knowledge of geological and geotechnical conditions sources of potential hazards can be disregarded and risks may arise: several geological, hydrogeological and geotechnical aspects can remain unknown, partially or completely, prior to actual construction of a tunnel. In 2009 the Italian Section of the International Association for Engineering Geology and the Environment published recommendations for "Reliability quantification of the geological model in large civil engineering projects" (Dematteis 2009), followed by the "Recommendation on the characterization of geological, hydrogeological and geotechnical uncertainties and risks" (AFTES 2012).

Uncertainties usually exist in inverse proportion to the amount, types and quality of the geological and geotechnical investigations (USNCTT 1984; Consiglio Nazionale delle Ricerche 1997; Site Investigation Steering Group 2007). Many literature references and rules of procedure underline the importance of a complete and proper investigation campaigns (USNCTT 1984; AFTES 2012). Based on the analysis of 89 underground projects the USNCTT observed that in more than 85% of the cases the inadequate level of investigation led to claims and time/cost overruns. The USNCTT issued recommendations to pose minimum requirements for any project, especially considering the different order of magnitude (as percentage of capital cost) between investigation levels (<1%) and claims levels (12–20% and upwards). It is not worthless to observe that the expenditure on site investigation as a percentage of total project cost is often low, frequently ranging from 0.1% to 0.3%. Furthermore, in the recent years ground investigations

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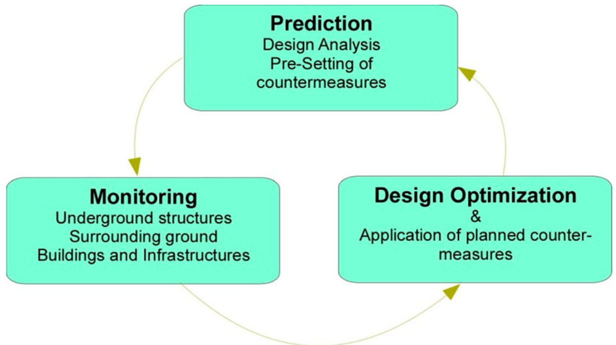


Figure 1. The principles of a rational and safe construction procedure.

seem to be inspired by the following principle: "minimum cost and maximum speed".

On the other hand it is experienced that sometimes, because of the intrinsic complexity of the geological context, also rigorous investigation approaches are affected by several possible sources of uncertainty related to the heterogeneity, inherent randomness, imperfect interpretation of *in situ* investigations, measurement inaccuracies and sampling limitations. Random or partially random geological features or events such as, for example, karstic caves, gas and underground water flow network are difficult to be predicted.

2. Geological and geotechnical design model

Some crucial points of tunnel design are listed below:

(1) the engineering design must maximize the quality of the project, fulfil the requested Standards and Norms and balance the budget constraints, in terms of both construction time and cost expenditure. It also must be rational, transparent, with a clear definition of its reliability,
(2) the design and construction of tunnels frequently deals with uncertainty and complexity that increases the designing-related risks,
(3) the main source of complexity and uncertainty is the geological and geotechnical context, which remains partially or completely unknown until the excavation.

Considering the above listed points, geological and geotechnical investigations and studies must be based on sound, transparent and verifiable approaches in order to identify project-specific critical geological features. In the past years several authors (Soldo 1998; Venturini et al. 2001; Knill 2002; Dematteis 2009) have progressively proposed the concept of the Geological Reference Model (GRM) as a tool capable of addressing the aforementioned requirements. In this respect, the Design Geological and Geotechnical Model (GGDM) underlies the bi-univocal relationship between GRM and the project, and hence it has a relevant role in the design procedure.

The result of the geological studies primarily consists in the evaluation of the geometry of geological bodies and characteristics at depth, at various scales. From this a design model can be derived, which can be focused on some particular aspects such as lithology, groundwater, geomorphology or rock structure and properties, described in the GRM.

The geotechnical model is built on the GRM describing the range of engineering parameters and ground conditions (with their variation and reliability) that must be considered in the design (Knill 2002). Simultaneously, the geotechnical model could eventually simplify the GRM by grouping geological formations with similar engineering properties, and identifying boundaries (with their variability, see e.g. AFTES 2012) where changes of geotechnical conditions may occur.

Then GGDM represents a conceptual framework composed of two main steps: the first is devoted to store all the collected data; the second consists of model reconstruction derived from the input data interpretation. Engineering projects are developed progressively deepening the design accuracy, at subsequent stages, and are also updated during the construction. At every stage of the project more data became available and enable the updating and improving of the GGDM.

The GGDM must be focused on the engineering needs of the project. The provided information must be disclosed and comprehensible to all the specialists in the design team, and eventually to the project stakeholders (non-specialists) as much as possible. The GGDM must be suited to and fulfil the current laws, norms, standards and procedures, together with requirements of the Owner or Third Parties. There is no universal protocol for its construction. Somewhere the reliability of the model can be high, for example, because supported by a good field mapping, also without many boreholes. The complexity of the geological context must also be considered: monotonous sequence of horizontal, homogeneous, rock or soil layers can be effectively studied also with few boreholes. Thus, GGDM can then be described as the framework in which the weakness of the geological and geotechnical model (derived from the lack of accuracy and completeness of the reconstructed subsurface conditions and soil and rock inherent variability and investigation uncertainties) can be highlighted. Furthermore GGDM provides the basis for planning additional site investigation and improving the design procedure. Finally, the GGDM includes an assessment of its effectiveness and reliability (with the evaluation of the associated uncertainties):

some approaches consider the quality of the investigation procedures, some others of the data and the model (e.g. in terms of extension of the geological mapped area, number and length of boreholes).

Such a model is conceived as a tool to understand, define, quantify, visualize and simulate the most relevant aspects of the natural conditions encountered in tunnel design.

Furthermore, the reliability of the model must be assessed after each update is carried out whenever changes in the natural system are detected. This last, crucial, step is the main focus of this paper, and will be discussed further in detail in the following chapters.

In this paper the R-Index method is proposed for assessing the effectiveness and the reliability of the geological model after the estimation of the contributions of different sources of uncertainties. It can be incidentally noted that this assessment is less than simple exactly because of the complexity and intrinsic, unavoidable, incompleteness of the GGDM itself.

3. Estimating the reliability of a geological model through the R-Index method

3.1. Uncertainties related to GGDM

Sometimes the collected data from *in situ* measurements can be used for describing the conditions and behaviour of points quite distant from the investigated ones. Instead, it is true that the effectiveness and reliability of a geological and geotechnical model strongly decrease with distance to the investigations points and it is strictly related to the number and quality of the collected data compared with the complexity of the studied context. In a very few cases (in a relatively homogeneous context, e.g. a shoreline sand deposits) limited number of measures enables an exhaustive description of the geological context.

Among the uncertainties related to underground model description, the intrinsic variability in time and space of geomaterials must be recognized. This natural variability (also called aleatory uncertainty) is associated with the inherent complexity of the natural material genesis and evolution through processes suffered alongside time.

Another category of uncertainties is the "knowledge" uncertainty, which can be divided into two subcategories:

- site characterization uncertainty is related to the exploration data uncertainties: measurement errors, inconsistency or inhomogeneity of data, data-handling and transcription errors, inadequate representativeness of data samples (due to limited number of observations);
- model uncertainty is related to the correspondence of the model derived by the data measured to the actual subsurface geology: it derives from the inability of a model to describe accurately the physical system conditions and predict its behaviour.

Considering the GGDM for a tunnel design, it is typically divided into homogeneous sectors.

A reduced number of samples are used to measure the various geomaterial properties. Only a small volume can be directly explored, and the most part will remain completely unexplored.

Regarding the underground volume that can be considered satisfactorily investigated, limitations of the investigation techniques in term of inconsistency, inhomogeneity or ambiguity of data or measurements errors must be taken into account. If direct investigation techniques (samples from boreholes, penetrometer tests) are point representative and precisely describe the actual geomaterial characteristics at that point, indirect geophysical methods or *in situ* stress measurements show a lower precision although they investigate larger portions of underground volume involved by the tunnel design. In any case it is obvious that assumptions must be made in assuming measurements from a direct investigated point (usually less than some centimetres large) to the surrounding rock masses (for metres up to 10s or 100s of metres).

Therefore, as affirmed by Smallman (1996), even when information is perceived as complete, uncertainty is present: more information from *in situ* tests does not automatically generate less uncertainty. Furthermore, model uncertainty reflects the needs for simplification in a design model compared with the real world whose behaviour changes in time and space.

Hereafter the knowledge uncertainties will be managed according to the R-index method, especially related to the (1) quality of geological investigations and (2) complexity of the geological model.

3.2. Introduction to the R-index method

The reliability of the GGDM is conditioned by some characteristic aspects (USNCTT 1984; Soldo 1998; Soldo et al. 2005; Perello et al. 2005; Dematteis 2009):

- the intrinsic natural complexity that generates an inherent variability of geo-material properties,
- the project depth (limiting the effectiveness of the investigations, increasing their cost and time expenditure),
- the intrinsic limits of the investigation techniques,
- the available time and monetary budget, together with the specialist team competency.

It must be emphasized that a robust programme of investigation may reduce the knowledge uncertainty but it will not reduce the aleatory uncertainty.

For reducing model uncertainties the effectiveness of the GGDM must be improved. Thus, the preceding task can be accomplished through the reduction of the knowledge uncertainty. In order to estimate the reliability of the GGDM the R-Index method was proposed in the past 10 years (AFTES 2012; Bianchi et al. 2009; Dematteis, Mancari, and Marini 2007; Perello et al. 2005). Hereafter, it is briefly introduced and its recent improvements based on its application on several projects in various geological and geotechnical contexts are illustrated.

The R-Index is a probabilistic approach method, considering the intrinsic complexity of the site and all relevant components influencing the reliability of the geological model GRM. The immediate, continuous relations with the GGDM are more than evident, for example, any geological investigation on the rock mass discontinuities has direct effects on its geomechanical characterization.

A reliable geological model prediction carried out through the R-Index method takes into account the following aspects:

- the quality of available geological investigations,
- the intrinsic complexity of the geological model, which is related to a series of geological parameters, the so-called System Parameters.

3.2.1. Quality of the geological investigations

The investigation approaches for setting up the geological design model typically include:

- geological mapping, including aerial photo interpretation and remote sensing,
- geophysical investigations (indirect investigations),
- borehole drilling and logging, site borehole tests and laboratory tests (direct investigations).

None of these types of investigation alone can lead to the definition of a satisfactory geological model. Therefore it can be assumed that the best knowledge of the natural environment will be attained only by the combination of data derived from these three different methods. Each one of these investigation parameters is, in its turn, influenced by a certain number of variables (Table 1). The quality of the variables is given in terms of a numerical score. It is evident that the greater the outcrop percentage, the greater the quality of information obtained from the geological mapping; the higher the number of boreholes, the greater the quality of the gathered information.

The quantification of the investigation quality is based on giving weights or ratings to the variables influencing this quality (Table 2). The weights range from 0 to 1. Each variable gives a contribution to the quality; therefore each investigation parameter results from the average of the ratings sum. The weight (importance) of each variable will be combined with the weight of other related variables. As an example, for the boreholes (Table 2), the weight of the number of available boreholes is greater if the average distance from the examined stretch is lower. Again, where the quantity of available boreholes is the same (identical rating) the weight of this aspect is greater if the boreholes are closer to the considered tunnel stretch. The quality of the investigation parameters is then the weighted average of the ratings sum. The quality of the investigation parameters is expressed as investigation effectiveness (IE) for boreholes (IE_{BH}), geological mapping (IE_{GM}) and geophysical investigations (IE_{GE}).

This version of the R-index method does not include the evaluation of the interpreter skill, because of its subjectivity.

3.2.2. Complexity of the geological model (System Parameters)

The geological model depends on the complex interactions of natural phenomena occurring alongside the life of the buried geological structures. Thus, the

Table 1. Synthesis of the main variables influencing the quality of Investigation Parameters.

Investigation parameters	Geological mapping	Geophysical investigations	Boreholes drilling, logging and tests
Variables influencing the quality of investigation parameters	Mapping scale	Number of available geophysical cross-sections	Number of available boreholes
	Extension of the mapped area	Quality of the survey (e.g. high vs. low resolution, etc.)	Quality of investigation (core-recovery, destructive)
	Accuracy of the survey technique	Average distance of the sections from the examined stretch	Tests and loggings
	Outcrop percentage	Depth reached by the investigation	Average distance from the examined stretch
			Depth reached by the investigation

Table 2. Classification of the parameters' weights for all types of geological investigations (boreholes, geological mapping and geophysics).

Boreholes (BH)	
Quantity	
Values	Weight
Number of boreholes = 0	0.1
Number of boreholes = 1	0.5
Number of boreholes = 2	0.8
Number of boreholes = 3	1.0
Quality	
Values	Weight
Drilling with core destruction	0.1
Drilling with core recovery	1.0
Test and logging	
Values	Weight
No tests, and no logging	0.1
1 test and/or logging up to 50% of the BH	0.5
Many tests and/or logging	1.0
Average distance from the tunnel axis	
Values	Weight
More than 1000 m from deep tunnels or 200 m from shallow tunnels	0.2
500 m from deep tunnels or 100 m from shallow tunnels	0.8
Less than 100 m from deep tunnels or few m from shallow tunnels	1
Depth	
Values	Weight
0.25 of the target depth	0.1
0.5 of the target depth	0.3
BH reach the target depth	1.0
Geological survey or mapping (GS)	
Quantity	
Values	Weight
Lenght of sections up to 50 m	0.2
Lenght of sections up to 500 m	0.4
Lenght of sections up to 1 km	0.6
Lenght of sections up to 2 km	0.8
Lenght of sections more than 4 km	1.0
Quality	
Values	Weight
Low-resolution geophysical survey	0.2
Tomography	0.6
High-resolution geophysical survey	1.0
Average distance from the tunnel axis	
Values	Weight
more than 1000 m from deep tunnels or 200 m from shallow tunnels	0.2
500 m from deep tunnels or 100 m from shallow tunnels	0.8
less than 100 m from deep tunnels or few m from shallow tunnels	1
Depth	
Values	Weight
0.25 of the target depth	0.1
0.5 of the target depth	0.3
BH reach the target depth	1.0
Geological survey or mapping (GS)	
Scale of the geological mapping	
Values	Weight
1:50.000	0.1
1:25.000	0.4
1:10.000	0.6
1:5.000	0.8
1:1.000	1.0
Extension of the area	
Values	Weight
Ext. area (Km^2)/Prof. (Km) = 1	0.1
Ext. area (Km^2)/Prof. (Km) = 2	0.2
Ext. area (Km^2)/Prof. (Km) = 10	0.6
Ext. area (Km^2)/Prof. (Km) = 20	1.0
Survey technique	
Values	Weight
Few dip and dip/dir measures of stratigraphic and structural surfaces, and no genetic interpretation of structures and stratigraphic sequences	0.2
Many dip and dip/dir measures of stratigraphic and structural surfaces, without genetic interpretation of structures and stratigraphic sequences	0.6
Many dip and dip/dir measures of stratigraphic and structural surfaces, with genetic interpretation of structures and stratigraphic sequences	1.0
Outcrop percentage	
Values	Weight
Less than 10%	0.1
Up to 50%	0.5
Up to 70%	0.7
100%	1.0

complexity of the geological model can be described by means of three System Parameters:

- complexity of the lithostratigraphical setting (LC),
- complexity of structures related to ductile deformations (DC),
- complexity of structures related to brittle deformation (BC).

The LCs vary from site to site and depending on the scale of analysis. Two cases studies are illustrated in Figure 2. Figure 2(A) shows the lithostratigraphic scheme of the south central part of the Catanzaro basin (Italy), crossed by SS106 Jonica. The black rectangles indicate the lithostratigraphic context in which tunnels were excavated in this stretch of the expressway. Figure 2(B) shows the complexity at the tunnel excavation face in another basin, equally complex, crossed by the Salerno Reggio Calabria highway. This second example shows how the complexity may vary according to the scale of analysis.

Similar considerations can be considered for the complexity of structures related to ductile deformation (DC). It can be demonstrated that a different degree of reliability can be obtained in a natural context characterized by a single and simple folding event (Figure 3(A)) if compared to a context where three or more folding events are superposed (Figure 3(B)). Much more input data are necessary for case b in order to obtain the same reliability as case a.

For complexity of structures related to brittle deformation (BC) Figure 4 provides an example of how this aspect can influence the reliability of the drawn geological model. In the case study presented highly segmented fault systems generate more uncertainty because they are difficult to be predicted if compared to a simpler linear fault system.

As it was done for the investigation parameters, the system complexity parameters have to be quantified to evaluate the reliability of the geological model.

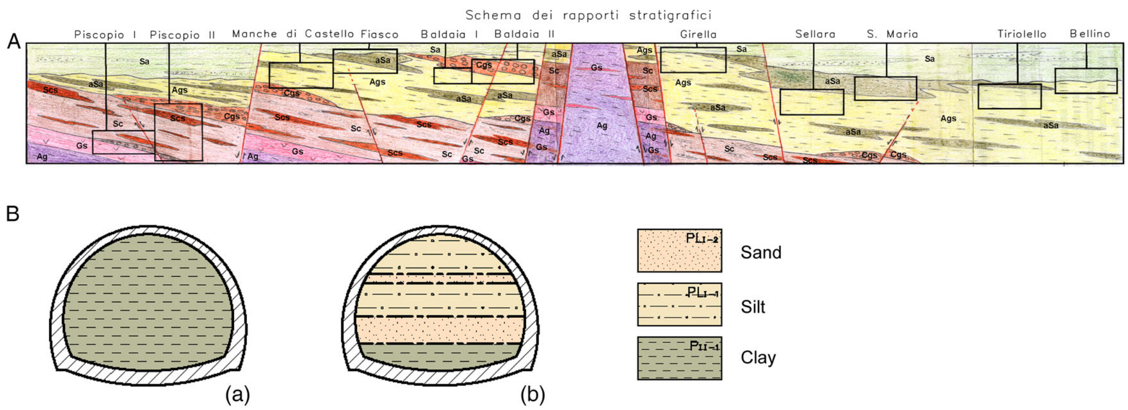


Figure 2. Examples of natural systems with different lithostratigraphical complexities (LC): (a) basin-fill succession made by Plio-Pleistocene sediments in a tectonically confined basin (SS106 Jonica, Calabria, Italy, not in scale) and (b) two typical scenarios at the excavation face in the Tarsia tunnel digging the upper-Pliocene to lower-Pleistocene pro-deltaic to deltaic deposits (Salerno Reggio Calabria highway, Calabria, Italy).

3.3. Computation procedure

The first step is to provide the longitudinal geological section of the tunnel. Commonly, the tunnel alignment is divided into 100 m stretches that will be evaluated through different R-Indexes. A standard length of 100 m has been used since usually geological structures of interest for tunnels maintain a certain homogeneity at this scale, based on practical experiences. Anyway, this length can be reduced where complex geological conditions are met.

Then the investigation quality (R_{BH}: rating for boreholes, R_{GS}: rating for geological mapping, R_{GE}: rating for geophysics) and the complexity of the natural system (LC, DC, BC) for each stretch of the tunnel has to be evaluated according to parameters and their weights listed in Tables 2 and 3. With those values, Equations (1)–(3) give the reliability of the knowledge of three components of the natural system (R_L, R_D, R_B), for each stretch.

$$R_L = (IE_{BH-L} \times R_{BH}) + (IE_{GS-L} \times R_{GS}) + (IE_{GE-L} \times R_{GE}) \tag{1}$$

$$R_D = (IE_{BH-D} \times R_{BH}) + (IE_{GS-D} \times R_{GS}) + (IE_{GE-D} \times R_{GE}) \tag{2}$$

$$R_B = (IE_{BH-B} \times R_{BH}) + (IE_{GS-B} \times R_{GS}) + (IE_{GE-B} \times R_{GE}) \tag{3}$$

where IE_{BH-L} is the investigation effectiveness of a borehole assumed for assessing the lithostratigraphic complexity of the stretch; IE_{BH-D} is the same for ductile deformation complexity and IE_{BH-B} for the brittle deformation complexity. And then the same for the other two types of investigations, that is, geological survey or mapping (GS) and geophysical investigations (GE). The *IE* must be considered as the potential capacity of each investigation parameter to affect the reliability of the geological model, matched with the complexity of the natural system, that is, with the system parameters mentioned above.

The investigation quality rating for boreholes, geological mapping and geophysics are calculated according to equations 4, 5 and 6.

$$R_{BH} = ((A_{BH} \times LC) + (A_{BH} \times DC) + (A_{BH} \times BC))/3, \tag{4}$$

$$R_{GS} = ((A_{GS} \times LC) + (A_{GS} \times DC) + (A_{GS} \times BC))/3, \tag{5}$$

$$R_{GE} = ((A_{GE} \times LC) + (A_{GE} \times DC) + (A_{GE} \times BC))/3, \tag{6}$$

where A_{BH}, A_{GS}, A_{GE} are the average of the parameter weights for each type of geological investigation (BH: boreholes, GS: geological survey and GE: geophysics, see Table 2), and LC, DC and BC are the values for lithostratigraphic, ductile and brittle deformations complexity, respectively (assigned to each stretch according to Table 3).

Then the R-Index is calculated with the following equation:

$$R_{INDEX} = (W_{RL} \times R_L) + (W_{RD} \times R_D) + (W_{RB} \times R_B) \tag{7}$$

W_{RL}, W_{RD} and W_{RB} are the weights to be applied to the lithostratigraphical, ductile and brittle deformation components of the reliability index. These weights are estimated by the method illustrated in the following section.

A

B

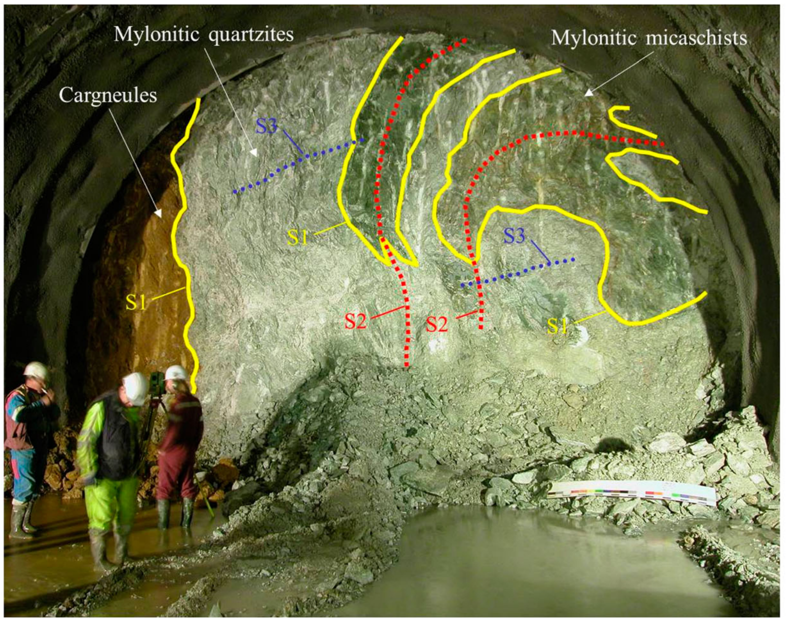


Figure 3. Example of two natural systems with different complexities of ductile deformation (DC). (A) marly limestone in Algeria, affected by one single ductile deformation phase and (B) micaschists in Modane adit (LTF project) affected by almost three ductile deformation phases (S1, S2, S3). S1 is the original stratigrafic layering, now folded, S2 is the axial plane of the subsequent ductile deformation phase and S3 is the axial plane of the latest ductile deformation phase.

3.3.1. System approach

Because many parameters involved in the calculations are related to each other, it is impossible to evaluate the influence of a single parameter without taking into account their reciprocal interaction.

For this reason the “Interaction Matrices” or “Fully-Coupled Model (FCM)” has been used (Hudson 1992; Jiao and Hudson 1995) with the relevant parameters (variables) along the leading diagonal. First the binary interactions between the variables are fixed. In this fashion an “uncoupled” matrix is compiled without taking into account multiple interactions. This is the binary interaction matrix (BIM). Then, by means of the graph theory, the contributions of all the mechanisms in all their possible interactions, with a “fully-coupled” interaction matrix (GIM), are identified.

Figure 5 shows 4×4 interaction matrixes defining the reliability of the system parameters (the first three matrixes that provide the indices R_L R_D R_B). Along the main diagonal are included the variables IE_{BH}, IE_{GM}, IE_{GE}, and R_L, R_D and R_B are the searched parameters. The better the information provided by IE_{BH}, the better the information provided by IE_{GM}, because the interpretation of geological mapping data benefits from the

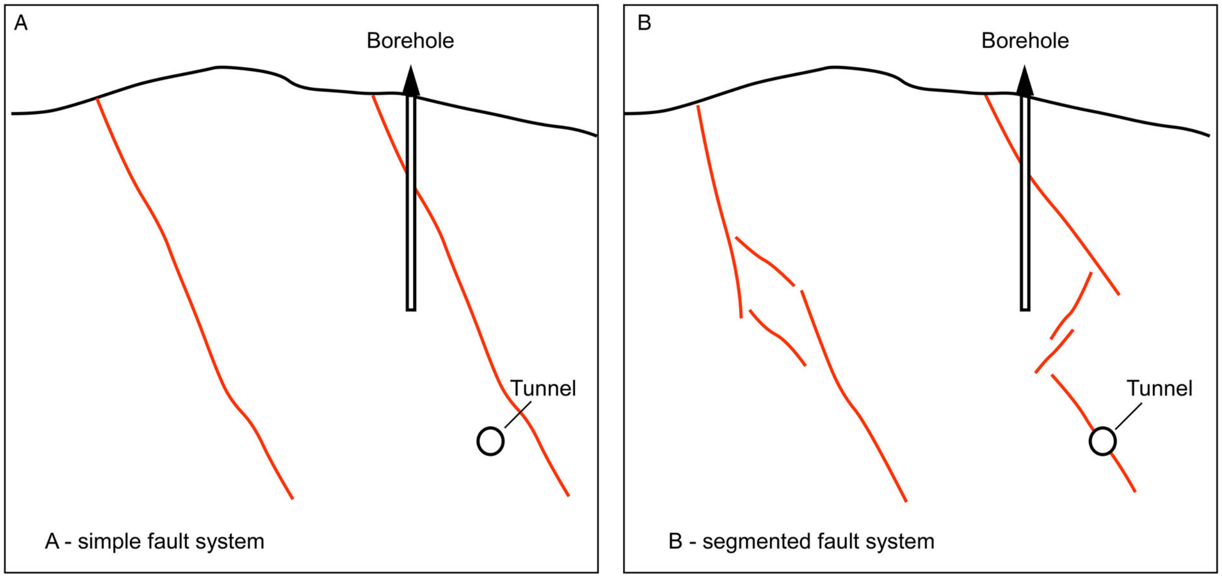


Figure 4. Example of two natural systems with different complexities of brittle deformation (BC) (from Perello et al. 2005).

underground information derived from IE_{BH}. The vice versa is also true and similar interactions exist among the other two parameters.

The BIM values assumed in the GIM calculation matrixes described in Figure 5 (respectively, for R_{L}, R_{D} and R_{B}) are the following:

$$\mathrm{GIM_{RL}} = \begin{bmatrix} 0.0 & 0.5 & 1.0 & 0.7 \\ 0.4 & 0.0 & 0.3 & 0.6 \\ 0.1 & 0.1 & 0.0 & 0.5 \\ 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

$$\mathrm{GIM_{RD}} = \begin{bmatrix} 0.0 & 0.3 & 0.8 & 1.5 \\ 0.8 & 0.0 & 1.0 & 1.5 \\ 0.1 & 0.1 & 0.0 & 0.2 \\ 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

$$\mathrm{GIM_{RB}} = \begin{bmatrix} 0.0 & 0.3 & 1.0 & 0.9 \\ 1.0 & 0.0 & 1.0 & 1.5 \\ 0.1 & 0.1 & 0.0 & 0.8 \\ 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

As a second step the three reliabilities (R_{L}, R_{D}, R_{B}) are in their turn combined in the last matrix showed in Figure 5, in order to obtain the total reliability of the geological model, or R-Index. Among the three reliabilities mutual influences exist: The greater the goodness of the geological model, the greater the capacity to interpret the brittle structures superimposed on the stratigraphical succession (e.g. is easier to calculate the faults displacements). On this basis, the following values have been assumed for BIM and therefore for GIM calculation:

$$\mathrm{GIM_{R-index}} = \begin{bmatrix} 0.0 & 0.5 & 0.2 & 1.0 \\ 0.2 & 0.0 & 0.2 & 1.0 \\ 0.1 & 0.4 & 0.0 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

The system weights for reliability of lithostratigraphy, ductile and brittle deformation complexity, which are the final results of the previous matrix calculation, are W_{RL} 38%, W_{RD} 30% and W_{RB} 32%.

4. Discussion about the application of the R-Index

The R-index value ranges from 0 to 10. It results from the evaluations of non-physical variables (e.g. quality evaluations or complexity evaluations): its significance in terms of possible variations of the forecasts has been deduced by the examination of relevant case histories. It has been applied, for example, to the 57 km long Lyon-Turin base tunnel through the western Alps between Italy and France, the 52 km long tunnel named Corridor Bioceanico Aconcagua, through the Andes between Chile and Argentina, the 8 km long tunnel Aburrà Oriente at Medellin, Colombia.

The significance of the R-Index can be expressed in four classes (A, B, C, D) as in Table 4.

The R-Index can be used in different design phases. Based on the most recent experiences of the authors, Table 5 summarizes the suitable R-Index class for the design phases of a project.

Table 3. Definitions of values for lithostratigraphic complexity (LC), ductile deformation complexity (DC) and brittle deformation complexity (BC).

Rating	Degree of complexity
Lithostratigraphic complexity	
0.2	*Very high complexity*: Lateral facies variation and significant variations in the thickness of layers are recorded at the hectometric scale
0.4	*High complexity*: Lateral facies variation and significant variations in the thickness of layers are recorded at the kilometric scale
0.6	*Medium complexity*: No lateral facies variation, and possible significant variations in the thickness of layers are recorded at the kilometric scale
0.8	*Low complexity*: No lateral facies variation, and no significant variations in the thickness of layers are recorded at the kilometric scale
Value for lithostratigraphic complexity (LC)	
Ductile deformation complexity	
0.2	*Very high complexity*: Evidence of three or more folding phases, evidence of transposing phenomenon for more than one of the folding phases, evidence of many ductile shear zones
0.4	*High complexity*: Evidence of three or more folding phases, evidence of transposing phenomenon for more than one of the folding phases
0.6	*Medium complexity*: Evidence of two folding phases, no evidence of transposing phenomenon
0.8	*Low complexity*: No evidence of folding phases or transposing phenomenon
Value for ductile deformation complexity (DC)	
Brittle deformation complexity	
0.2	*Very high complexity*: Many fault systems, all with low maturity degree
0.4	*High complexity*: Many fault systems, some of them are with low maturity degree
0.6	*Medium complexity*: Many fault systems, with a high maturity degree
0.8	*Low complexity*: A single fault system with a high degree of maturity
Value for Ductile deformation Complexity (BC)	

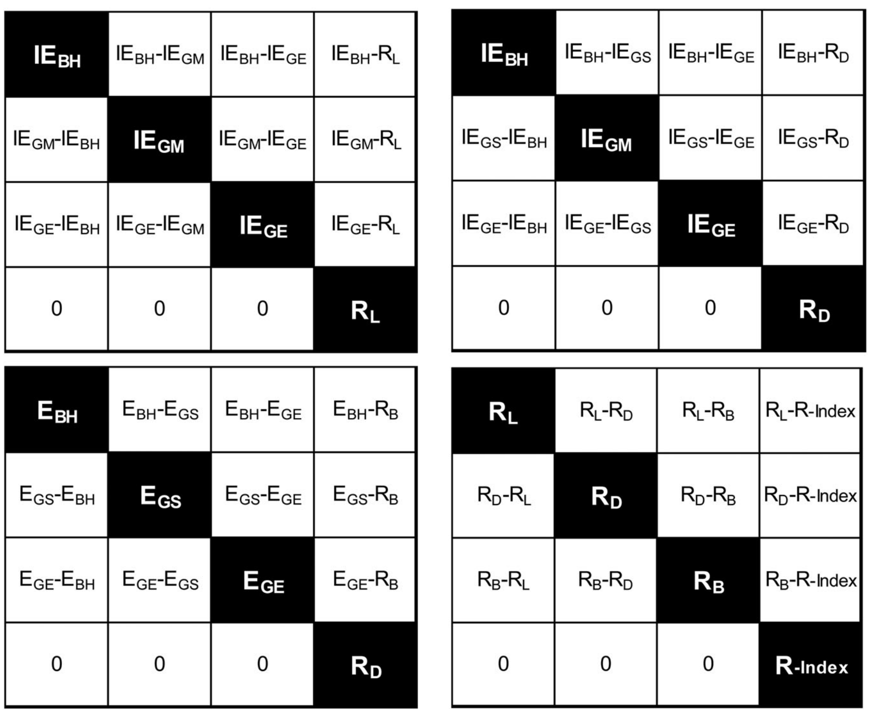


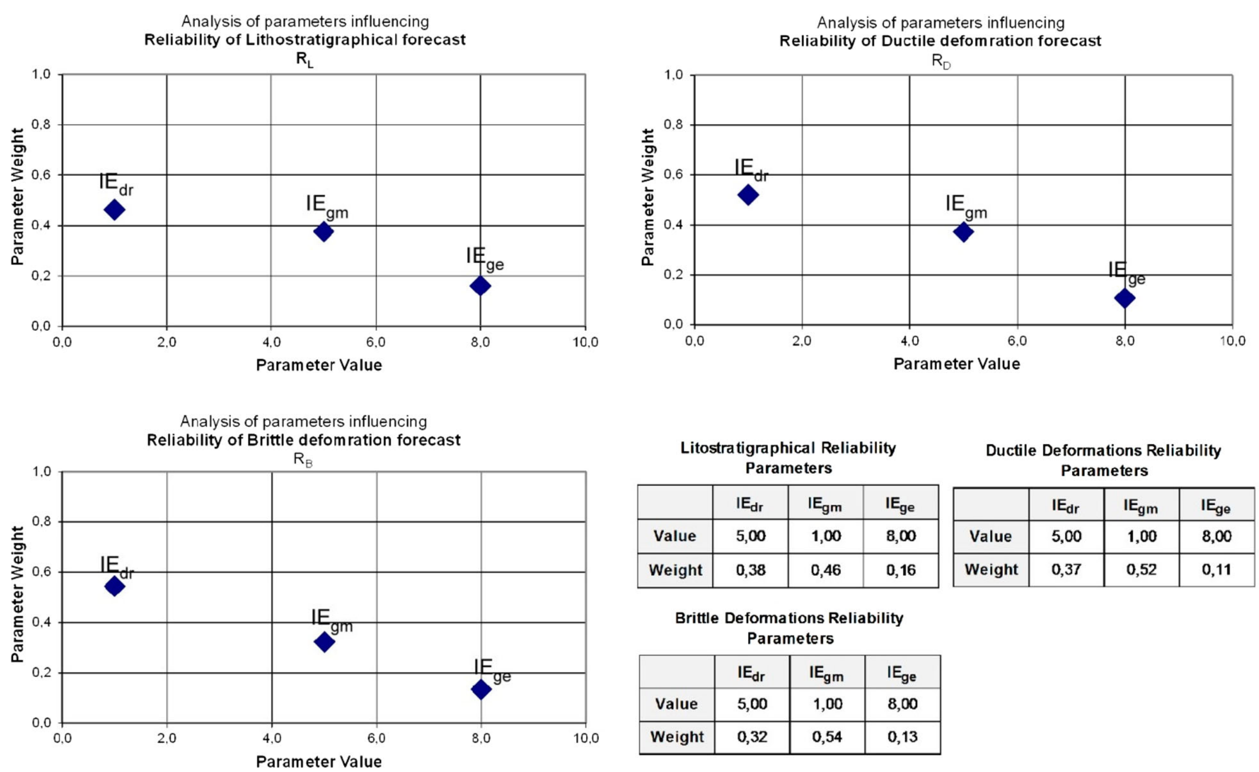
Figure 5. The first three interaction matrixes are referred to for the definition of R_L, R_D, R_B (see text for acronyms); B: interaction matrix for the definition of reliability of the geological model, the R-Index.

Table 4. Classification of the reliability of GRMs for tunnel projects using the R-Index.

R-Index			
Class	Value	Reliability	Description
A	10–7.6	Good to very good	Limits and faults reported in the section are definitely present and will be encountered within an interval of ± 25–50 m; the margin of error for the thickness of lithological layers may be between 10% and 20%
B	7.5–5.1	Average to good	Limits and faults reported in the section are definitely present and will be encountered within an interval of ± 50–100 m; the margin of error for the thickness of lithological layers may be between 30% and 50%. In addition to those indicated, other minor faults could be present
C	5–2.6	Poor to average	Limits and faults reported in the section are definitely present and will be encountered within an interval of ± 100–200 m; the margin of error for the thickness of lithological layers may be between 50% and 100%. In addition to those indicated, other major faults could be present
D	2.5–1	Not all reliable or unreliable	Limits and faults reported in the section may be absent, and other elements may be present. The thickness of lithological layers is not defined. Geological elements other than those forecasted may be present

Table 5. The grey diamonds depict the distribution of the most common R-Index classes according to the various phases of development of a project.

R-Index		Design phases (as defined in various countries)		
		Schematic Design, Pre-feasibility, *Avant Projet Sommaire, Progetto Preliminare*, analisis of alternatives	Design Development, Feasibility, *Projet, Progetto Definitivo*, Total cost definition	Construction Documents, Final design, *Projet d'Exécution, Progetto Esecutivo*
A	Good to very good			
B	Average to good			
C	Poor to average			
D	Not all reliable or unreliable			



Litostratigraphical Reliability Parameters

	IE_{dr}	IE_{gm}	IE_{ge}
Value	5,00	1,00	8,00
Weight	0,38	0,46	0,16

Ductile Deformations Reliability Parameters

	IE_{dr}	IE_{gm}	IE_{ge}
Value	5,00	1,00	8,00
Weight	0,37	0,52	0,11

Brittle Deformations Reliability Parameters

	IE_{dr}	IE_{gm}	IE_{ge}
Value	5,00	1,00	8,00
Weight	0,32	0,54	0,13

Figure 6. Example of application of the R-Index for the evaluation of the IE and for supporting the decision-making of further investments for investigations.

Low R-Index values can claim the necessity for further investigation. The three diagrams in Figure 6 can support the decision about the type of investigation that is most suitable for improving the reliability of the geological model. Particularly, all of the three diagrams indicate that the investigations related to boreholes (IE_{BH}) always have the highest weight, and the lowest rating value, indicating a low quality. It is evident therefore that in this example, in order to improve the reliability it is worthy to improve the data coming from boreholes (e.g. core recovery, drilling deeper up to the tunnel depth, etc.) and from the geological mapping (e.g. more detailed surveys, enlarge the area of survey, etc.), rather than geophysical investigations that have already reached an almost high quality.

The R-Index also is able to indicate which is the most critical section along the tunnel alignment. This is useful information during the tender phase and for undertaking the risk assessment procedures.

5. Conclusions

Given the intrinsic complexity of the geomaterials and the knowledge uncertainties related to investigation methodologies and the limited investigated underground volume compared to the volume involved in the tunnel construction, the reliability of the geological model used in tunnel designs must be estimated. To this end this paper proposed and illustrated the formulation of the R-Index method. The empirical ratings based on expert judgement have been introduced to weigh various geological features influencing the underground conditions and the quality of the geological model due to the complex interaction among many unknown aspects of the natural environment in depth. However, in tunnel construction, the relationship between geological and geotechnical models is evident. Thus, improving the first will have beneficial effects on the geomechanical characterization of the second one. Furthermore the R-index capacity of rating geological models reconstructed for tunnelling purposes has been improved by its application to relevant case histories. The R-index method allows the engineers to check the weakest sections of the geological model along the tunnel alignment. Finally, this method enables to improve the geological model by indicating which type of investigations must be further performed. A future development of the R-index method for reliability estimation of both geological and geotechnical models will be attempted based on new case studies of tunnelling constructions drawn from professional experiences of the present authors.

Disclosure statement

No potential conflict of interest was reported by the authors.

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