Determination of reliability in geological forecasting for linear underground structures: the method of the R-index

PERELLO PAOLO, VENTURINI GUIDO, DEMATTEIS ANTONIO, BIANCHI GIANPINO W., DELLE PIANE LUCA, DAMIANO ANTONIO
SEA Consulting s.r.l., Via Cernaia 27, 10121,Torino, Italy
perello@seaconsult.it

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Abstract
The knowledge of geological conditions is one of the most important aspects for risk assessment in tunnelling. Therefore the definition of a geological model is always one of the first steps before pursuing in tunnels design. Unfortunately these models implies variable uncertainty, due to the complex behaviour of natural environment. Underestimation of uncertainty is probably the main reason for economical and constructive problems, but quantifying the reliability of a geological model is a hardly attainable objective. This paper proposes a new computation method that aims at defining the reliability of geological models for tunnelling with a low degree of subjectivity. Reliability is expressed by mean of an R-Index and it can be used from clients, design engineers and contractors in order to minimise both constructive and economical risks related to tunnels excavation.

1. Introduction

Tunnels are linear underground structures that often have to be confronted with a natural environment characterized by high mechanical and geometrical complexity. For this reason the knowledge of the natural rules which control the distribution of physical properties in the rock mass is at the base of a successful design and excavation strategy. A proper study of geological conditions is therefore one of the most important aspects to be managed. Geological models related to underground linear structures should represent important aid decision tools in order to optimise projects costs.
Unfortunately geological structures in mountains chains as the Alpine belt are extremely complex. For this reason a geological model able to give totally reliable forecasts of geomechanical and hydrogeological underground conditions is not even attainable. A certain degree of uncertainty is always attached to geological models and it can bring clients or contractors to wrong risk evaluations, i.e. to the choice of wrong construction methods and to unreliable evaluations of construction's costs and times.
Since a total elimination of uncertainty is not possible, a correct approach in the design of underground linear structures should point to quantify the reliability of the model. This quantification is often difficult and includes some subjectivity. In the frame of studies for tunnelling it is a consolidated practice for geologists to attaching an evaluation of reliability to their forecasts. In many instances longitudinal geological sections classify the confidence level of forecasts as good, fair, sufficient or bad, but this information often sound as obscure and useless for engineers that have to provide the plan. Particularly it is often incomprehensible which parameters are determinant for the evaluation and, more important, which consequences a bad or good quality of geological forecasts may have on the construction of the structure. These misunderstandings between engineers and geologists may lead to serious risks underestimation.
As consequence an effort should be made by geologists in order to better constrain the uncertainty of their forecasts, by identifying some standard and key parameters whose quantification allow to define the possible variation of the real geological situation if compared to the forecasts.

This work aims to present a relatively simple computational method that allows to quantify the range of variability of geological/geomechanical conditions along tunnel alignments. The objectives of this method are firstly to define an index (R-Index) able to express the quality of the interpretation for individual discrete stretches of a tunnel and subsequently to attach to this index a significance in terms of possible variations with respect to the forecasted situation.
The discussion is subdivided in three parts. The first one (section 2) is dedicated to the description of the key parameters. The second part (section 3) provides insights in the mathematical procedures

chosen for the computation. The third part (section 4) is a discussion of the applications and benefits that can be derived from the method.

2. Conceptual framework: parameters influencing the reliability of geological forecasts

Three types of parameters that influence the reliability of geological forecasts can be individuated:

1. *Investigation Parameters*, i.e. parameters which define the quality of the investigation methods used in order to explore the rock volume to be excavated;
2. *Interpreter Skill,* i.e. the capacity of the geologist(s) which creates the model to interpret the data;
3. *System Parameters*, i.e. parameters which define the geological complexity of the rock volume and therefore the system to be investigated;

By analysing the interactions between these parameters it is possible to understand the process which leads to the construction of a geological model. This consequently permit to reach a quantification of the reliability.

2.1. Investigation Parameters and Interpreter Skill

In tunnelling, the *investigation parameters* typically comprehends three different methods of investigation: i) bore-hole drilling ; ii) geological mapping; iii) geophysical investigations. According to the experience of the authors none of these methodologies alone may lead to the definition of a satisfactory geological models. 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. As a consequence, in order to quantify the quality of the parameters, it is firstly necessary to quantify the quality of the variables. The variables are listed in Table 1.

	Investigation parameters		
	Drillholes	**Geological Mapping**	**Geophysical investig.**
Variables influencing the quality	Number of available drillholes	Mapping scale	Number of available geophysical cross sections
	Type (recovery of the core, destructive, BHTV etc.)	Extension of the mapped area	Quality of the survey (e.g. high vs. low resolution etc.)
	Average distance from the examined stretch	Detail reached by the investigation technique	Average distance of the sections from the examined stretch
	Depth reached by the investigation	Outcrop percentage	Depth reached by the investigation
		Depth of the tunnel in the examined stretch	

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

The influence of the variables presented in Table 1 on the *investigation parameters* is easily illustrated by some examples. It is evident, for instance, that the higher the number of drillholes in the reference stretch, the greater the quality of information obtained by the investigation; the greater the outcrop percentage, the greater the quality of information obtained from the geological mapping.

From the former discussion it follows that in order to quantify the reliability of a geological model the first step is the quantification of the **investigations quality (IQ)**. How this quantification is done will be illustrated in section 3. It is important to underline here that the *investigation parameters* are nothing but the data set that the interpreter has at disposal. Thus, from a conceptual point of view, this data set doesn't give any contribution to the model, unless it is interpreted. Its effectiveness, or contribution to the model depends from the second parameter among those previously cited: the **interpreter skill (IS)**. The quantification of the interpreter skill represents the second step in the evaluation of the model reliability. Unfortunately this fundamental parameter has a high degree of subjectivity and is difficult to be judged. Despite this the problem of the interpreter skill quantification is a negligible one in many of the applications or the R-Index. This is due to the fact that usually the aim of the reliability quantification is deciding if investing more money in investigations and which type of investigations are the most appropriated (see section 4). In such a case the quality of data is by far more important than the interpreter skill, assuming that if the interpreter is not supposed to be good it can be changed.

Once the investigations quality (IQ) and the Interpreter skill (IS) are quantified, they can be combined them in order to deduce the **investigations effectiveness (IE)**, i.e. the potential capacity of each investigation parameter of forecasting the structure of the rock mass to be excavated (figure 1). It is important to underline that this capacity is only potential because it has to be confronted with the complexity of the natural system, i.e. with the *system parameters*.

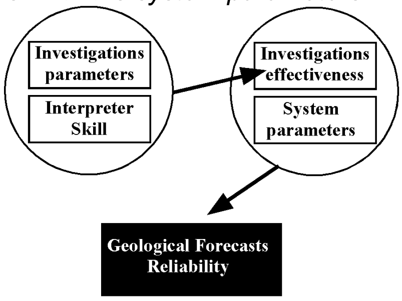

***Figure 1**. Sketch diagram illustrating the conceptual steps in the calculation of the geological forecasts reliability.*

2.2. System Parameters

The *system parameters* depend from the natural framework hosting the underground structure and comprehend three different categories: i) complexity of the lithostratigraphical setting, ii) complexity of structures related to ductile deformations, iii) complexity of structures related to brittle deformation.

The **complexity of lithostratigraphical setting (LC)** can vary greatly from a site to another. As an example two natural systems with different lithostratigraphical complexity aree shown in Figure 2. In the system of Figure 2A the extrapolation of punctual data is obviously more reliable than for the system of Figure 2B. This implies that the geological forecasts obtained in the two systems under the same condition for the *investigation parameters* (in this case the same number of drill holes) will have a different degree of reliability.

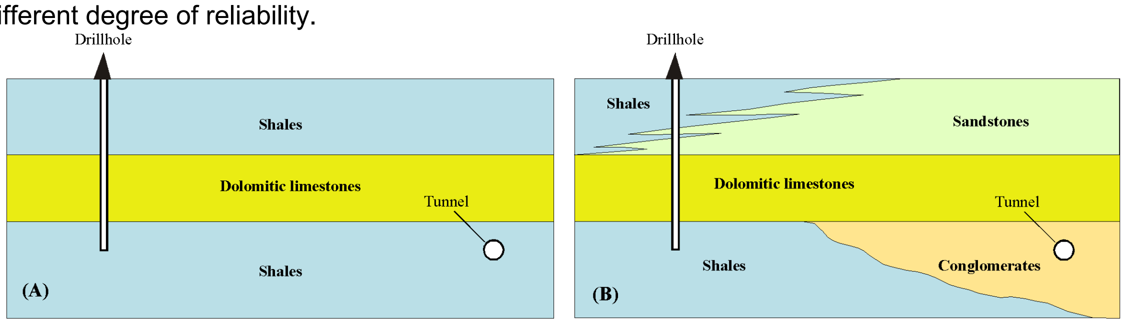

***Figure 2**. Example of two natural systems with different lithostratigraphical complexity.*

Similar considerations can be done 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 characterised by a single and simple folding event (Figure 3A) if compared to a context where two or more folding events are superposed (Figure 3B). Much more input data are necessary for the case of Figure 2B in order to obtain the same reliability of case 2A.

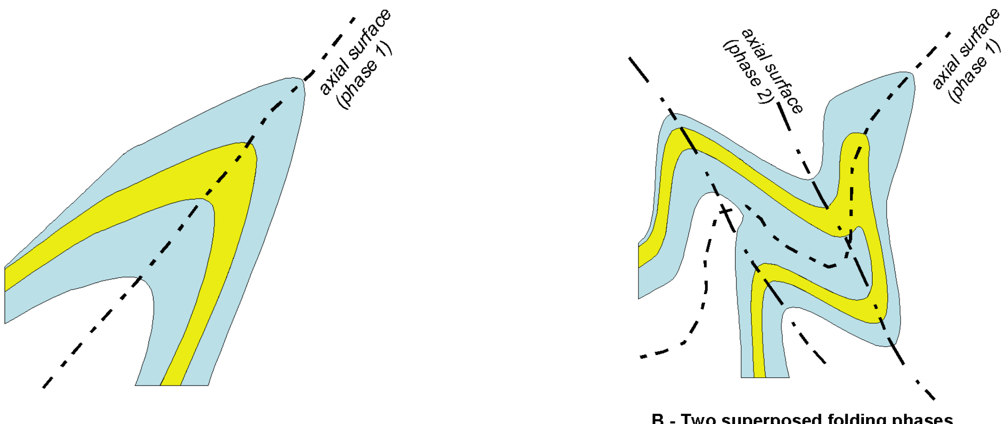

***Figure 3**. Example of two natural systems with different complexity of ductile deformation.*

For **complexity of structures related to brittle deformation (BC)** of Figure 4 provides an example of how this aspect can influence the forecasts reliability. In the considered case highly segmented fault systems are more difficult to forecast if compared to mature systems and generate more uncertainty.
As it has be done for the investigation parameters, the systemn parameters have to be quantified to evaluate the reliability of the geological model. After this it will be possible to combine the system parameters with the value of the investigations effectiveness in order to obtain the reliability (Figure 1).

3. Computation procedure

3.1 Generalities
Starting from the conceptual framework defined in section two, a computational procedure has been established which allows to define the R-index as a value ranging from 0 to 10. As it will be illustrated in this section, being this index the result of evaluations of non physical variables (e.g. quality evaluations or complexity evaluations) the significance of this value in terms of possible variations of the forecasts has been deduced by the examination of different case histories.
I
n order to proceed with the calculations, a longitudinal geological section of the tunnel has to be available. As a standard procedure the tunnel alignment has to be subdivided in 100m stretches that will be the subjects of individual R-Index evaluations. The standard length of 100m has been used since usually geological structures of interest for tunnels maintain a certain homogeneity at this scale. Anyway this length can be reduced in greatly complex environmentsor increased for simple situations.

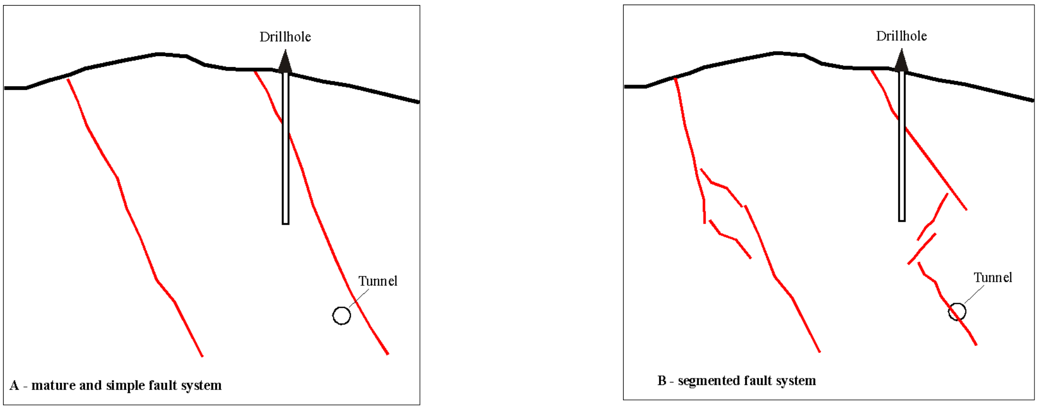

***Figure 4**. Example of two natural systems with different complexity of brittle deformation.*

It will be shown in the following paragraphs that many of the parameters involved in the calculations are interdependent, in the sense that the way they influence the reliability is also dependent from the effect of other parameters. For such situations it is very difficult to evaluate the influence of a single parameter without taking into account the multiple influences that the other parameters have on this one. In these cases a computational procedure must be found in order to deduce the correct weight that the parameters have in the calculation of the searched value (in our case the R-Index). This is a recurrent problem in engineering geology. In order to solve it the method of the “Interaction Matrices” or “Fully-Coupled Model (FCM)” is often used (Jiao & Hudson, 1995; Hudson & Jiao, 1996). This method will be applied also with reference to the present problems in addition to other simple mathematical relationships. For details about the FCM the cited references can be consulted. As a synthesis, 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 doesn’t take into account multiple interactions. Successively, by mean of the graph theory, the contributions of all mechanisms in all possible interactions paths is established and a “fully-coupled” interaction matrix is obtained.

3.2. Quantification of IQ
The quantification of IQ is attained by the attribution of a rating to the variables influencing the quality (table1). The rating ranges from 0 to 10, for coherence with the searched value of the R-Index. Each variable gives a contribution to the quality, therefore each investigation parameter results from the average of the ratings sum.

It must be noted therefore that the weight (importance) of each variable on the quality of the investigation parameter is not independent from the other variables. As an example, for the drillholes (table 1), the weight of the number of available drillholes is greater if the average distance from the examined stretch is lower. As a matter of fact if we consider two different situations where the quantity of available drillholes is the same (identical rating) the weight of this aspect is greater for the case where the drillholes are closer to the considered tunnel stretch. Similar examples could be shown for the other variables.
This means that the weights of each variable are functions of the other variables. These functions are difficult to be established, since the variables are not physical quantities; anyway, as a first approximation, it has been assumed that the functions are linear and of the following type:

$$W_{V1} = R_{V2}/10 \qquad \text{(eq. 1)}$$

Where V1 and V2 are two variables, W_{a1} is the weight of variable 1 and R_{V2} is the rating for V2. This means that the weight of V1 is comprised between 0 and 1 and increases with R_{V2}. For more than two variables the functions are multiplied:

$$W_{V1} = R_{V2}/10 \times R_{V3}/10 \times R_{V4}/10 \times \ldots R_{Vn}/10 \qquad \text{(eq. 2)}$$

Therefore the quality of the searched *investigations parameters* will be, more exactly than previously defined, the weighted average of the ratings sum.
At the end of this computational procedure we will obtain the values of the three cited IQ (Figure 5), i.e.: drillholes (IQ_{dr}), geological mapping (IQ_{gm}) and geophysical investigations (IQ_{ge}).

3.3. Quantification of IE
As stated in section 2 the potential capacity that each investigation parameter has to provide information about the geological setting, i.e. the effectiveness, depends from the interpreter skill (IS). To convert this relationship into mathematical terms it is possible to state that if the interpreter skill is the greater possible, all information provided by the investigations can be converted into interpretation; if the interpreter doesn't have capacity, no information can be converted into interpretation. For this reason if we attribute to IS a value ranging from 0 (minimum) to 1 (maximum), IE can be calculated as:

$$IE = IQ \times IS. \qquad \text{(eq. 3)}$$

This means that if the interpreter skill is the greater possible (IS=1) the rating obtained from the computation described in 3.1. is maintained, otherwise is linearly decreased with skill decreasing.
At the end of this computational procedure we will obtain the values of the three cited IE deriving from the three IQ (Figure 5), i.e.: drillholes (IE_{dr}), geological mapping (IE_{gm}) and geophysical investigations (IE_{ge}).

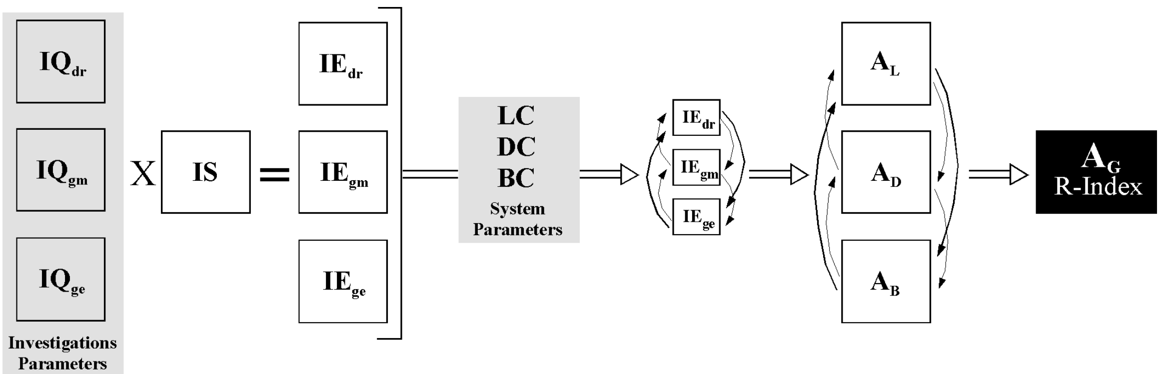

***Figure 5**. Sketch diagram showing the path followed in order to calculate the R-Index..*

3.4 Combination with system parameters
The reliability of the geological forecasts obviously depends from each one of the three calculated IE. Therefore these have to be combined. Furthermore the interpretations obtained from the investigations always have a local value, in the sense that, as an example, drillholes provide interpretation in their neighbourhood but this interpretation has to be extended to the more remote sectors of the rock

volume. This extrapolation will be the more effective for simple geological contexts. Therefore, in order to obtain a reliability quantification, among being reciprocally combined, the three IE also need to take into account the effects of three *system parameters*.
In order to include in the calculation process the effects of system parameters, a single computation step could be done. Anyway a single step implies a great logical complexity, due to the fact that among the parameters to be combined, there exists a considerable amount of interdependent relationships and mutual influences. Therefore instead of deducing in a single step the R-Index, a two steps procedure will be followed.

This implies, in a first step, the combination of the three IE with each-one of the three complexity parameters; thus obtaining three reliability for each one of these complexity parameters: Reliability of lithostratigraphical forecasts (RL), Reliability of ductile deformations forecasts (RD), Reliability of brittle deformation forecasts (RB; figure 5). As a second step the three reliabilities are in their turn combined in order to obtain the total geological reliability or R-Index (Figure 5).
In this paper the details of all the three reliabilities deriving from the first step will not be given. As an example it will be illustrated the procedure of calculation for the R_L, being the other ones similar.
R_L is calculated via a 4x4 interaction matrix (see 3.1), including as variables along its leading diagonal: IE_{dr}, IE_{gm}, IE_{ge} and R_L (the searched parameter). This procedure is necessary, due to the fact that there exist evident interactions between the three IE. As an example, the better the information provided by IE_{dr}, the better the information provided by IE_{gm}, because the interpretation of geological mapping data benefits of the underground information derived from IE_{dr}. The vice versa is also true and similar interactions exist among the other two parameters. The matrix form is the one shown in Figure 6A.

A

IE_{dr}	IE_{dr}-IE_{gm}	IE_{dr}-IE_{ge}	IE_{dr}-R_L
IE_{gm}-IE_{dr}	**IE_{gm}**	IE_{gm}-IE_{ge}	IE_{gm}-R_L
IE_{dr}-IE_{ge}	IE_{gm}-IE_{ge}	**IE_{ge}**	IE_{ge}-R_L
0	0	0	**R_L**

B

R_L	R_L-R_D	R_L-R_B	R_L-R_G
R_D-R_B	**R_D**	R_D-R_B	R_D-R_G
R_B-R_L	R_B-R_D	**R_B**	R_B-R_G
0	0	0	**R_G**

C

0,0	0,5	0,2	1,0
0,2	**0,0**	0,2	1,0
0,2	0,2	**0,0**	1,0
0,0	0,0	0,0	**0,0**

***Figure 6**. A: example of the interaction matrix for the definition of lithostratigraphical reliability (see text for acronyms); IE_{dr}-IE_{gm} = influence of drillholes effectiveness on geological mapping effectiveness; the same notation is used for other influences. B: interaction matrix for the definition of lithostratigraphical reliability (see text for acronyms; R_G reliability of the geological model, its value is the R-Index); C: coefficient of the binary interaction of "B".*

The influences among the variables in the leading diagonal are assumed to be linear. Therefore the values reported in the cells out of the leading diagonal are the angular coefficients of the equation line (see Jiao & Hudson, 1995).
How the complexity of lithostratigraphical setting (LC) enters in this matrix and is combined with the other parameters? The lithostratigraphical complexity is the parameter which defines the "system" where the variables interacts, i.e. LC controls the way in which the variables interacts each other. Changing the system LC changes, and therefore also the interaction values change. As an example it is evident that the benefits that the geological mapping effectiveness give to the drillholes effectiveness are much greater in a complex lithostratigraphical context, since the drillholes data are more easily extrapolated by mean of information deduced from geological mapping. On the contrary in an extremely simple lithostratigraphical context, at the limit, geological mapping could also be unnecessary in order to extrapolate drillholes data. Similar variations, related to complexity, can be established among the other parameters.
This implies that the values inside the non leading diagonal cells of the matrix will vary according to the lithostratigraphical complexity of the area where the tunnels are located. In order to define these values, first of all, LC has to be quoted. Second, a relationship has to be established which describes the variation of the influences among parameters when LC changes. In order to enter in this relationship a numerical value, LC is quoted, as the other parameters, via the attribution of a rating ranging from 0 (very low complexity), to 1 (extremely high complexity). The relationship of LC vs. the influence among variables is, once again, assumed to be linear, e.g., for geological mapping and drillholes (see before), the greater the complexity, the greater the influence of mapping on drillholes.

So in synthesis, once LC is quoted and the binary interaction parameter are consequently derived and inserted in the matrix (BIN, binary interaction matrix), applying a standard computational procedure (see Jiao & Hudson, 1995) we obtain, as a result, the same matrix but with the interaction values changed for taking into account the multiple interactions (GIM, global interaction matrix). Among these new parameters three are of particular interest: IE_{dr}-R_L, IE_{gm}-R_L, IE_{ge}-R_L. As a matter of fact these three parameters can be considered as the weights that each one of the three effectiveness have on R_L. Now, if for notation simplification IE_{dr}-R_L, IE_{gm}-R_L, IE_{ge}-R_L are re-named respectively as w_{dr}, w_{gm}, w_{ge}, R_L can be calculated by mean of the following expression:

$$R_L = w_{dr} \times IE_{dr} + w_{gm} \times IE_{gm} + w_{ge} \times IE_{ge} \qquad \text{(eq. 4)}$$

In this expression the *w* values obtained by the GIM are first normalised by their sum. By doing this, since the three IE can vary among 0 and 10, also the value of R_L will vary from 0 (forecasts non reliable) and 10 (forecasts totally reliable).
Two interaction matrices similar to the one where the interaction values are controlled by LC have to be created for the other two complexities parameters, i.e. DC and BC (see section 2.2.), thus obtaining a quantification for the reliability of these other two aspects of the geological complexity, i.e. R_D for DC and R_B for BC.

In order to obtain a total reliability quantification the three reliabilities calculated up to this point need to be combined. It is easily understood that among the three reliabilities mutual influences also exist. As an example, the greater the capacity the geological model has to forecast the lithostratigraphical variations, the greater the capacity to interpret the brittle structures superimposed on the stratigraphical succession (e.g. is easier to calculate the faults displacements).
Therefore the weight that each one of the three reliabilities has on the total reliability must be again deduced by mean of an interaction matrix. In this case the interaction parameters of the matrix are fixed and the matrix assumes the form shown in Figure 6B and 6C. At the end of this process the value of the total geological reliability (R_G) can be deduced by mean of a normalisation and a weighted sum as for eq. 4:

$$R_G = \textbf{R-Index} = w_{RL} \times R_L + w_{RD} \times R_D + w_{RB} \times R_B \qquad \text{(eq. 5)}$$

Where w are the weights of the three reliabilities.

4. Significance and use of the R-Index
As stated before the R-Index, or rather the quantification of parameters that contribute to its computation, have been calibrated according to well known case histories derived from tunnels directly studied from the authors. At the state of the art the calibration is not very fine, due to the limited number of examined case histories (approximately 50 Km of tunnels coming essentially from 5 different case histories). This calibration will be progressively refined by adding new case histories. In the present situation the significance of the R-Index can be expressed as in Table 2.

R-Index	Significance
10.0 – 7.6	**Good reliability**: the geological limits and faults reported in the stretch are certainly present and will be encountered within a range of ± 25-50 m; the thickness of lithological levels can have an error of 10-20%.
7.5 – 5.1	**Fair reliability**: the geological limits and faults reported in the stretch are certainly present and will be encountered within a range of ± 50-100 m; the thickness of lithological levels can have an error of 30-50%. Some minor fault out of those forecasted could be present
5 – 2.6	**Poor reliability**: the geological limits and faults reported in the stretch are certainly present and will be encountered within a range of ± 100-200 m; the thickness of lithological levels can have an error of 50-100%. Some main fault out of those forecasted could be present
2.5 – 0	**Not reliable**: the geological limits and faults reported in the stretch could be absents and other elements could be presents the thickness of lithological levels is unconstrained. Other geological elements out of those forecasted could be present.

***Table 2**. Significance of the R-Index.*

The uses of the R-Index are multiple and it is applicable to different stages of tunnels construction and design.
Clients can use the R-Index in order to establish if their investigation campaigns reach a satisfactory level, but above all they can use the R-index in order to correctly plan or refine the investigation campaign.

The proposed method allows, as a matter of fact, an easy analysis of investigation parameters, by mean of simple diagrams, owing to discover toward which type of investigation should be directed the economical investments in order to obtain the maximum benefits.
As an example Figure 7 shows the four essential diagrams for the formerly cited analysis in the case of an hypothetical tunnel stretch. By the diagram of Figure 7A it is possible to deduce that everyone of the three partial reliabilities (R_L, R_D, R_B) has approximately the same weight (0.3 – 0.4), and also their ratings are very similar (4.5 – 6.0). It follows therefore that, in order to obtain a better general geological reliability (R_G), no one of them should be preferentially increased by mean of new investigations, but rather all them should be ameliorated. The three diagrams of Figure 7B, C and D allow to decide which type of investigation it is necessary to improve in order to obtain a better R_G. Particularly, all three diagrams indicate that the investigations related to drillholes always have an important weight (except for R_B where the geological mapping has the higher weight), but they always have a low rating value, indicating a low quality. It is evident therefore that in such an example the choice to do in order to obtain a better reliability is to improve the drillholes quality, rather than investing in other types of investigations. This could be done, for instance, by doing new drillholes with good characteristics (e.g. core recovery, high length etc.).

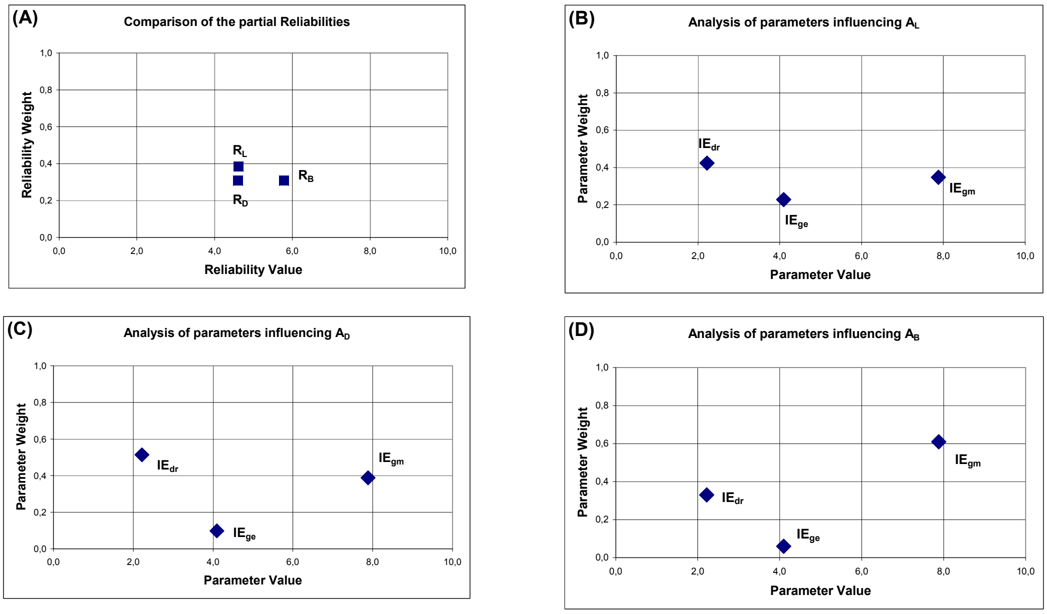

***Figure 7**. Example of output diagrams useful for planning and refining of investigation campaigns.*

Design engineers can use the R-Index in order to identify the more critical stretches, i.e. those where a wider range of possible design solutions should be applied. This will have many benefits in the construction phase since if the project include from the beginning a quantification of all possible design solutions a better information is given to the constructors. These consequently will optimally plan the site organisation with evident positive relapses on construction times and with minimisation of claims.
Constructors can have evident benefits from the R-Index. A detailed analysis of tender documents and of existing investigations leading to the application of the R-Index can potentially identify the main construction risks deriving from geological aspects. This consequently will allow a better calibration of the economical proposal or eventually a conscious acquisition of risks.

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