International Association for Engineering Geology and the Environment

Italian department

Recommendations for

RELIABILITY QUANTIFICATION OF THE GEOLOGICAL MODEL IN LARGE CIVIL ENGINEERING PROJECTS

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1 Introduction

These recommendations have been elaborated between 2007 and 2009 by the technical commission of the IAEG Italian Group, through two Workshops (in Torino in 2008 and in Milano in 2009) attended by commission members, and by field experts expressly invited and all people interested that submitted explicitrequest. On IAEG website (http://www.iaeg.it/comm_opere_sott.htm) are published the meeting interventions and the Commission interim reports.

Knowledge of the intricacy of subsurface geology is at the heart of any design and construction strategy during all major civil engineering projects, so the Reference Geological Model (defined below in § 1.1), is a particularly useful decision tool required to design. It reduce risk, and optimize and implement good working practice and operational costs.

Geological structures are normally complex and for the major part cannot be directly observed, for these reasons we can say that in most cases, a fully reliable prediction of the geological, hydrogeological and geotechnical conditions are not possible. Anglo-Saxon culture has stated for some time (Essex, 1997) that *"Mother Nature" did not create subsurface conditions in accordance with a materials properties handbook, nor do geotechnical engineers (or any other participants in the process) have magical predictive powers. The design and construction process must account for the variability of subsurface conditions, and potential for project costs associated with that variability.*

As the total elimination of uncertainty is not possible the definition of a correct approach for its quantification is required.

In the field of *engineering geology* this quantification is not a common practice as it is difficult to implement. In some cases a subjective assessment is supplied. For example, along a geological profile several sections are defined with a uniform reliability level of forecasts. It is normally divided into classes (e.g. good, medium, poor). However, this information often appears vague and not useful to those who have to carry out the project. It is not clear what the parameters are that govern this assessment, and more importantly, it is not easy to understand the effects that a good or poor reliability may have on the construction work. This lack of understanding can also lead to serious risks involving the overestimation or underestimation of implementation time and costs, environmental risks or incorrect design and methodological decisions implemented to carry out the works and financial activities involved.

Generally speaking, in fact, the reliability quantification of the geological, geomechanical and hydrogeological model is part of the work risk analysis process which must be undertaken with the cooperation of the geologist, designer and customer.

An example taken from the field of tunnelling shows how the reliability quantification of the geological model has already been aknowledged as a key preparatory step in the risk analysis. The guidelines for risk management in the tunnelling (International Tunnelling Insurance Group, 2006, *ITA/AITES*, 2004) plan for analysis, chronological order were:

- reliability quantification of the geological model;
- reliability quantification of the geomechanical and hydrogeological model;
- risk analysis (cost/time) according to economic criteria;
- identification of points to be investigated (risk review).

This process is not a one off event, but an ongoing process developed step by step. In fact it goes hand in hand with the design process development, ultimately defining the reliability level of the Reference Geological Model (RGM) based on the geological data (l.s.) available at each design development stage. Every stage of the development of the RGM should be based on the preceding stage, therefore deepening and enhancing all geological data available.

The objective, where possible, is to follow a quantification process that is traceable and transparent to all those participating in the design (designers, builders, financers, control institutions).

1.1 Recommendations and definitions

"Definition of guidelines for the reliability quantification of the Reference Geological Model in large engineering projects".

The guidelines should indicate the criteria and parameters required to assess and document the reliability of the Reference Geological Model and the criteria to verify compliance, during the construction process, between the forecasts and the actual situation. They need to be taking into account ISO regulations and recommendations proposed by the *International Society for Rock Mechanics* (ISRM) and the *International Society for Soil Mechanics and Geotechnical Engineering* (ISSMGE).

The quantification should be developed by applying well-defined and traceable methods. Methods such as: classification type (for example the classification of rock indexes commonly used in geomechanics, such as RQD, RMR, etc ...), or the probabilistic type, based on statistical data analysis and mathematical modelling (numerical). In quantifying the reliability of a geological model a correct reference between the two concepts of reliability and geological model must also be defined.

Reliability is the degree of compliance between a geological model and reality. During the design stage the reliability degree will be given on the basis of the analysis carried out and will be verified during the construction stage. The scale of the analysis is still to be defined. Reliability is the opposite of uncertainty, which is expressed in terms of existence, location and the significance of a particular geological element within the forecasting model.

The reference geological model (RGM) is a conceptual reconstruction of the three-dimensional geometric situation and a succession of time and space geological events characterizing a given portion of the subsurface. It has a logical meaning derived from the objective surface, subsurface and laboratory data available at the time it is formulated. RGM is subjective, as it is also derived from the interpretation given by the technicians concerned. The model is subject to change over time according to new data that is accumulated after its formulation. The new data can be integrated in a correct way or can justify a revision up to actual reformulation.

Major civil works typically include roads, railways, hydroelectric power plants, with particular reference to underground works. The adjective "major" distinguishes them from ones with current constructive importance, simple constructions, buildings, houses and other minor constructions. For example, for "major works" refer to the categories listed in the IV as defined by the Italian Ministry of Public Works.

1.2 Existing standards and recommendations

ISRM (1975). Recommendations on Site Investigation Techniques.

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2 Quantification process

It is necessary to divide the quantification process of the geological model reliability into the following logical steps, listed in chronological order:

- *data collection and organization*
- *data analysis*
- *RGM of the design*
- *reliability quantification of RGM*

All the stages of the process should be recorded in a suitable design report, distinguishing "facts", "interpretations" and "opinions". A classic example of facts is a geological map of outcrops, or a borehole core logging explorations. The interpretation of the facts that can also be enhanced by previous information taken from bibliographical data should be carried out to define the RGM of the project, typically explained, for example, by a geological profile; or an interpretative geological map. Based on the facts, interpretation and the experience the designer can also express judgments, such as, for example, the hydrogeological characterization of a fault zone not directly investigated. This kind of information needs to be provided for completeness sake, but should be highlighted as "judgments" to allow, if necessary, their omission, for example in an agreement documentation with a Customer, for lack of direct feedback and to prevent the contractor from taking them as reference.

3 Data collection and organization

Data collection and processing procedures need to be described, organized and distinguished from interpretations. Their traceability must be maintained, all ensuring that any data or data processing procedures can be traced and consulted retrospectively.

An example of this is the project *"Knowledge Base for representations and sharing of Geological information"* coordinated by F. Piana of the CNR-IGG Institute in Torino (http://www.csg.to.cnr.it/r22.html). From this example, useful information concerning data collection and interpretation can be drawn:

- to establish a concrete conceptual model, a hierarchical data structure, containing all relevant properties, the relationships between them, the rules, the axioms and constraints of the knowledgeable and descriptive approaches that the field geologist adopt during the collection of data (ontology);
- to develop a *Geological Knowledge Base* (GKB), a tool allowing the definition and description of geological data (objects), processes (concepts) and interpretations (e.g. geological maps, sections and, more generally, geological reference models);
- to develop the database and the GKB in a GIS environment, representing the ideal environment required for the intended purpose, namely the management of geological data directed towards the implementation of large civil works;
- to ascertain the quality of the data entered into the GKB it is necessary to take into account the uncertainty related to the acquisition and interpretation of the basic data.

This approach suggests the adoption of a structure organized with Metadata sheets in complying to the European standard ISO19115.

4 Data analysis

In order to assess the reliability of interpretation it is necessary that the all data and conceptual models taken as reference are clearly described. This will ascertain whether they are suitable for the purposes required.

The quality and reliability of the geological data must be clearly stated as they strongly influence the overall reliability of the RGM.

Obviously not all geological data has the same reliability. So, it is recommended that their qualification is based on their effectiveness to provide reliable information. Below are examples of various types of investigations, listed in order of reliability:

- boreholes with continuous core sampling, exploratory tunnelling;
- destructive boreholes;
- high-resolution geophysical investigations, calibrated with boreholes results;
- geophysical investigations, not adjusted by boreholes.

Also the reliability of the geological-structural projection adopted, and the distance between investigations and the designed work must be quantified.

5 Reference Geological Model (RGM)

The paragraph 1.1 states the definition of RGM. The geological structure is a product of nature, existing before the work itself; it is much more complex than any artificially produced material and varies extremely from site to site.

Despite the intrinsic difficulties of characterization, the interaction between work and ground must be studied using adequate ground "models". Such models must first identify the three dimensional geometrical structure and the time and space succession of geological events characterizing the site under investigation (RGM), secondly the mechanical behaviour of soils (Geotechnical Model) and the movement of underground water and gas (Hydrogeological Model).

An effective Geotechnical and/or Hydrogeological Model cannot exist if an effective Reference Geological Model is not available before hand.

Geological, Geotechnical and Hydrogeological model effectiveness is limited to the specific sites and therefore cannot be extended to other situations.

In addition, the RGM by definition evolves over time, with the progression of design stages, and its reliability varies accordingly with an increase of information available.

5.1 RGM stages

Since the moment an area where a certain work is to be carried out is defined a Preliminary Geological Model can be prepared. It needs to be adequately detailed to properly assess feasibility of the work, or to assess any alternative location. The setting up of an effective Preliminary Geological Model is a complex conceptual operation, essential for the subsequent development of the design. The current practice, which at best involves a feasibility study followed by a generic "geological report", usually purely descriptive, is definitely not the most suitable approach.

The compiler of the Geological Model, in addition to the geological aspects, must not ignore the following design points:

- the main design lines (e.g. layout, entrance area, intersection crossing the work),
- the constraints or opportunities that affect the implementation of a project in that specific site (e.g. work size, work functionality, interaction with the socio-economic fabric of the site);
- any possible flexibility in the project structure (possibilities for design optimization and improvement),
- the i constraints (technical, economic, temporal, etc..) related to the implementation methods of the works;
- the opportunity to consider alternative sites;
- environmental, economic, political factors that - even if not binding - can affect the final eligibility for financing of the work.

Moreover, as the RGM is a tool for the preliminary analysis of the design work, during hits initial set-up it is necessary that:

- the results achieved at each progressive stage of the geological study are discussed with the work designer and assessed in the light of the parallel design developments he has carried out at the same time;
- the criticalities revealed by the geological studies are promptly assessed with the designer;
- the geological investigation programme, at any stage, is shared and agreed with the designer;
- the geologist will say if it is necessary to obtain more specific details concerning criticalities, that may be useful to optimize the layout and improve any economic factors concerned with the Works.

This willingness to cooperate with the other parties concerned with the implementation of the work (particularly the geologists, engineers and builders), should not give rise to authority and responsibility confusion, but allow a <u>cultural</u>

sharing of problems and a full willingness to work together to produce the best outcome possible.

At the same time, the geologist should be able to enhance this logical process to led him to formulate the RGM through the correct interpretation of the data. The *Geological Knowledge Database* available to him should allow the description of every single point of the process, always clarifying what is data or interpretation.

Effective and continuous dialog and interdisciplinary communication specifically between the geological and engineering departments, especially the geotechnical one, are an essential prerequisite to set up an effective RGM.

5.2 Investigations plan

If we do not know what to look for, it is difficult to find what we need. For this reason, the in-depth survey should be guided by the RGM and must be designed to acquire the data that helps to reduce uncertainty and the number of possible interpretations.

It is deceptive to believe that it is possible, at the beginning of the process, to define a single definitive investigation plan; this plan must be flexible for type, size and duration and must provide one or more in-depth stages. These stages should be carried out along the timeline of the project, and will need an adequate economic budget.

The area to be investigated should be considered as the area within which the implementation of investigation is relevant in the RGM formulation. To this effect it can be bigger than that of the work site. Sometimes it is necessary to carry out direct investigations outside of the site concerned; for example to investigate a shear zone of great importance, by direct surveys on an area far from the work site. Also the phenomena of aquifer recharge, which may take place far from the work site, must be properly studied. In mountain regions in karst aquifers or in special folded structures having regional importance, the recharge could take place in neighbouring valleys.

Indirect surveys (e.g. geophysical surveys) may be very useful and lead to savings in cost and time; however in complex geological contexts the interpretation of the data obtained cannot be accepted without verification via a direct survey (e.g. boreholes).

The in-depth geological survey aims to the model reliability increase; however, improved reliability is not always directly linked to the amount of surveys carried out. For example, in some cases, new geological assessments or new surveys, will not lead to significant increases in the model reliability. In other cases, small investments in additional surveys may generate a significant improvement.

Every stage of the project development and relevant quantification of the RGM reliability should be followed by an analysis of scenarios (e.g. assessment of the likelihood of two different geological interpretations) and of the suitability of other surveys to be carried out or not. This will be done through a comparison between the cost of new surveys and the additional cost of the work related to the uncertainty of the RGM.

There cannot be a clear rule defining the threshold beyond which the costs for new surveys are no longer justified, however, it is reasonable to fix such a limit taking as a reference the relationship between the cost of new surveys and the cost variation of the work directly or indirectly depending on the RGM uncertainty. For example, when this ratio is lower than 0.1, additional investigations seem to be on the whole justified (Survey cost / uncertainty cost < 0.1).

6 Reliability quantification

6.1 Existing methods in literature

International scientific literature presents different methods for geological uncertainty quantification, which can be divided into three macro categories depending on the subject being analyzed.

1. Reliability of mechanical properties of rocks and rock masses (Gilles, 2005a; Gilles 2005b; Miranda, 2009; Ruffolo, 2009; Sari, 2009): is the inherent variability of geological materials defined with theirs geomechanical parameters (compressive strength, fracture density, permeability, abrasiveness etc..); those methods proposes for each analysis and/or parameter to define the following:
    a. the theoretical adopted model,
    b. the analysis methodology,
    c. the existence intervals and their statistical distribution.
2. Spatial reliability of geological investigations and surveys (Cetin, 2004; Demoungeot-Renard, Duncan, 2000; Perello et al, 2005; Pine, 2005): is the assessment of each specific parameter variability within the same geological homogeneous body defining its reliability and specifying:
    a. control points (outcrops, surveys, tunnels, etc.),
    b. structural data (outcrop measures, survey orientations, etc.),
    c. interpretations used for the spatial projection of data (geological sections, seismic lines and velocity model used, etc.),
    d. Interpolation and geostatistical procedures, variograms used.
3. 3D viewers and spatial numerical models (Mallet JL 1997; Bistacchi et.al, 2008; Lajaunie et al, 1997; Pomian-Srzednicki, 2001; Tonini et al, 2008). These approaches describe the methodology leading to numerical model construction and allow the quantification of the variable position of geological limits within the model itself. To achieve this result the following points are explained:

a. detailed description of the mathematical algorithm on which the software constructing the geological model is based;
b. list of input data (control points, geological sections defined by the operator),
c. verification of the quality level assigned to each input data,
d. definition of the uncertainty intervals of each input data (e.g. data derived from experimental data or assigned by the operator),
e. explanation of any construction routines performed by the operator
f. if the uncertainty intervals of the geological bodies limits are the result of modelling or provided by the operator.

6.2 General recommendations

The philosophy inspiring this recommendation suggests to implement several possible methods based on objective, transparent and traceable criteria.

Any objective method for quantitative assessment of the reliability must be based on a theoretical mechanism adjusted through objective analysis of real cases, in which the factors appear well documented. In this sense it is appropriate to proceed by trial and error during scientific research.

It is generally agreed that:

– the reliability of a RGM must always be referred to the level of detail of the design stage;
– to define the reliability it is crucial to use quantitative terms and check their compliance with all project documents;
– the elements that describe the reliability (or uncertainty) are three: existence, location and meaning;
– the reliability of the Geotechnical Model, or Hydrogeological Model, must be related to the reliability of the RGM.

Considering a more specific point of view, the formulation of the RGM must take into account the following aspects:

– from a conceptual point of view, the area to be investigated should be considered as the area within which geological investigations are useful for the RGM formulation. The survey area must always be extended in a direction parallel to the regional structures of the geological (e.g. large plicate structures), geotechnical (e.g. fault shear zones or fracture zones of a great importance), and hydrogeological (e.g., areas of aquifer recharge) models;
– in a dedicated geological study the macro areas with various uncertainty degrees must be clearly highlighted, explaining the reasons for each

causing them. The criteria to guide this classification must at least take into account the following aspects:

  - o availability and density of direct surveys (surveys, tunnels, etc.), indirect surveys (geophysical lines, covers and aerial photo scales , etc.);
  - o geological – structural complexity (e.g. deformed metamorphic complex or sedimentary structure not deformed);
  - o percentage of quaternary cover, geomorphological features, availability of detailed topographic map, etc.;

- finally, the possibility to interpret the underground geological features according to different conceptual models should be always considered, always taking into account the available data (e.g. the coexistence of different interpretations of the same sector).

6.3 Reports and drawings

The methodological approach must be the one indicating the range of variability and the uncertainty level of the RGM. At the same time, specifying which subsurface conditions is the most likely to be encountered, in order to finalize the contractual documents. This will allow the identification of the risks and the definition of their allocation between Owner and Contractor (see § 6.5).

Regarding the RGM, the drawings and reports describing the approach must be updated along with the increase in knowledge and it is suggested, where possible, to update documents by revisions and not create new ones.

The representation of the model must be supported by vertical and horizontal geological sections showing the geological hypothesis most likely. In these documents the different geological criticalities observed (e.g., fault zones, zones of intense fracturing, landslides, toxic gases, special mineralogical characteristics, water inlets, etc..) and their likelihood must be highlighted. Similarly the mechanical and hydrogeological property values, for each area of a tunnel, must be reported according to the most likely hypothesis.

Any alternative geological interpretations, plausible and consistent with available data, but considered less likely, may be shown separately, but always with horizontal and vertical geological sections, indicating the existence intervals of geological limits, of faults, etc., the rock and rock masses mechanical characteristics and the geological criticalities estimated.

The descriptive written report should describe in detail the process that led to drawings, the list of uncertainties and geological criticalities identified and must detail the temporal evolution of the RGM.

The *Joint Code of Practice for Risk Management of Tunnel Works (ITIG*, 2006) provides a procedure for risk management followed by sensitivity analysis (tests) on the costs and time to identify and assess the likely economic and temporal scenarios. This is done depending on the risks that each design choice requires. The procedure assigns to each risk a specific confidence level. In this sensitivity analysis also the consequences of possible measures to avoid or minimize the risk will be assessed.

6.4 Unexpected geological event

It is to be hoped that a cultural change will occur allowing the concept of "unexpected geological event", widely present in the Italian law and often quoted in legal and contractual fields to be abandoned.

The definition of predictability or unpredictability of a specific geological context becomes important and may be formulated in both a "technical geological" and “legal-contractual” point of view:

- technical approach (geological): A geological prediction totally free from uncertainties does not exist. Since the total elimination of uncertainty is not reasonably possible, the definition of a quantification is needed;
- managerial approach (legal-contractual): The reliability of the model does not exclude the geological principle of unpredictability, but rather enhances it. If the model considered in the project was demonstrated reliable and during construction cannot predict a geological element, the latter becomes actually unpredictable. The demonstrability of the assumption of reliability, therefore, becomes a key element in the design decision-making process not only in technical, but also contractual terms.

The RGM identified as a realistic construction hypothesis, together with the quantification of reliability, must be included in the contract documentation, to create the document to compare and audit the occurrence or not of "unexpected geological event" during the construction phase.

6.5 Shearing of geological risk

The RGM represents a contractual definition of what it is assumed will be met during excavation. The inclusion of RGM in the contract documents does not guarantee that the subsurface conditions will be exactly as planned, but guarantees that the real conditions will be compared with the RGM and, on that basis, the deviation from the predictions will be defined.

In this perspective, the level of RGM evolution and quantification of its reliability are the elements needed to assess the geological risk during construction. During the contract definition, the allocation of costs related to geological risk between the owner and the contractor (*risk shearing*), is made possible by the knowledge of these elements.

This approach is indicated in the aforementioned GBR (Essex, 1997), and is here noted because it allows for a better control of the operational time and costs for large civil engineering works.

7 Future work

This technical commission identified and recommends further studies to be carried out to improve and complete the work done so far:

1. to widen the Commission on an international level. To this regard the IAEG Council meeting of September 7, 2009, in Chengdu (China), approved the new Commission, known as *C28 - Reliability quantification of the geological model in large civil engineering projects;*
2. to define standards for collection, organization and analysis of geological data; to define quality control and certification procedures for collection, organization and analysis of geological data;
3. to develop new systematic and assessments methods to quantify the reliability of geological predictions. Within University, Research, Government Institutes, Professional Studies or Design Companies the practices and experiences for reliability quantification already used need to be analyzed. In this area the key factors affecting reliability must be separated and coded (e.g.. geologic complexity, survey quality and quantity, data interpretation);
4. to promote and encourage the comparison of real cases. The experiences and validations of existing methods must be based on real cases;
5. to examine and quantify how geological surveys and investigations could improve the knowledge and contribute to the RGM reliability. It would be useful to create guidelines for this specific aspect, to be adopted to support decision-making.

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