Commission 28 - Reliability quantification of the geological model in large civil engineering projects.

Written by Antonio Dematteis and Giovanna Vessia on Sept 07, 2022

1. Commission chairpersons and members

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All the listed chairs and members are currently active. The C28 is open to welcoming new active members, who are asked to send an expression of interest via email to the chairpersons.

Communication between the members over the past year took place via email. The next scheduled joint activity is a web-meeting to be held in October.

2. Activity developed in 2021-2022 of the Commission 28

In the last three months of 2021 and during 2022, C28 members cooperated with C25 members to reshape Chapter 7 now differently numbered (see Appendix A) of the publication "Guidelines for the Development and Application of Engineering Geological Models on Projects" promoted and developed by the Commission C25 "Use of engineering geological models". The final draft of this chapter is ready to be issued.

In Appendix A it is reported.

3. Future activities

ICOSSAR 2021-2022

The 13th International Conference on Structural Safety & Reliability will be held on 13-17 September 2022, Tongji University, Shanghai, China in an Hybrid form. Two members of C28 will take part in it with the following two contributions:

Multivariate geostatistics to build maps of regional rainfall thresholds for the shallow landslide initiation (authors: Giovanna Vessia, Diego Di Curzio)

Indicator Kriging method for liquefaction instability maps (Diego Di Curzio, Paolo Boncio, Francesco Iezzi, Linda Savini, Giovanna Vessia)

and will chair the session:

GS02: Machine Learning-based Uncertainty Quantification

ISGSR 2022

This is the 8th International Symposium for Geotechnical Safety & Risk and it will be held on 14 - 16 December 2022 - Newcastle, Australia. The main topic of this conference is "Geotechnical Risk: Big-data, Machine Learning and Climate Change". Here a few members of C28 will participate as contributors:

Multi-Criteria decisional analysis to assess the support class in TBM excavation: examples from snowy 2.0 pumped hydro project (Authors: Davide AGNELLA, Antonio DEMATTEIS, Damiano FRONTINI, Juan SILVA, Shivcharan GANGELE, Francesco DE SALVO, Giacomo ARMETTI).

Uncertainty propagation assessment in CPTu-based lithological modeling using stochastic co-simulation (Authors: Uncertainty propagation assessment in CPTu-based lithological modeling using stochastic co-simulation)

and chairmen of the following session:

IS4 - Reliability assessment of subsoil modelling in geoengineering applications (Conveners: Wojciech Pula, Giovanna Vessia, Diego Di Curzio, Marcin Chwała)

4. Commission meetings and publications

- C28 has planned a web-meeting in November to discuss the possibility to expand the content of the Chapter 5, on uncertainty in engineering geological modeling into an informative publication on how to apply methods and procedures to check the quality of the engineering geological model and then to quantify its uncertainties.
- Chapters of the Guideline on the reliability assessment of the geological model: "Part 1: Advisory clauses - 1.5 Reducing EGM uncertainty" "Part 2: commentary – C2.5 Reducing EGM uncertainty"

5. Self-evaluation of the performance of Commission 28 since 2015

Excellent	Good	Fair	Poor

6. Appendices

A. Contributions of C28 sent to C25 for the *Guidelines for the Development and Application of Engineering Geological Models on Projects.*

1.5 Reducing EGM Uncertainty

Introduction

Uncertainty within the EGM is caused by the imperfectly or unknown aspects of the knowledge framework that describes the ground conditions.

The reliability of the EGM is the degree to which the predicted engineering geological conditions can be relied upon to be an accurate and reasonable approximation of the actual conditions or performance.

Risk is the possibility of an adverse outcome and is often expressed in terms of a combination of the consequences of a series of events or scenarios and the associated likelihood of their occurrence.

Uncertainty within the EGM thus will reduce the reliability of the project engineering and increase the potential for project risks. Therefore, the uncertainty should be assessed and strategies developed to reduce that uncertainty and the associated project risks to agreed levels.

Increases in reliability and reduction of risk occur through the accumulation of both conceptual and observational knowledge within the EGM, usually through various stages of investigations that are carried out as the project progresses (Figure 1-8).

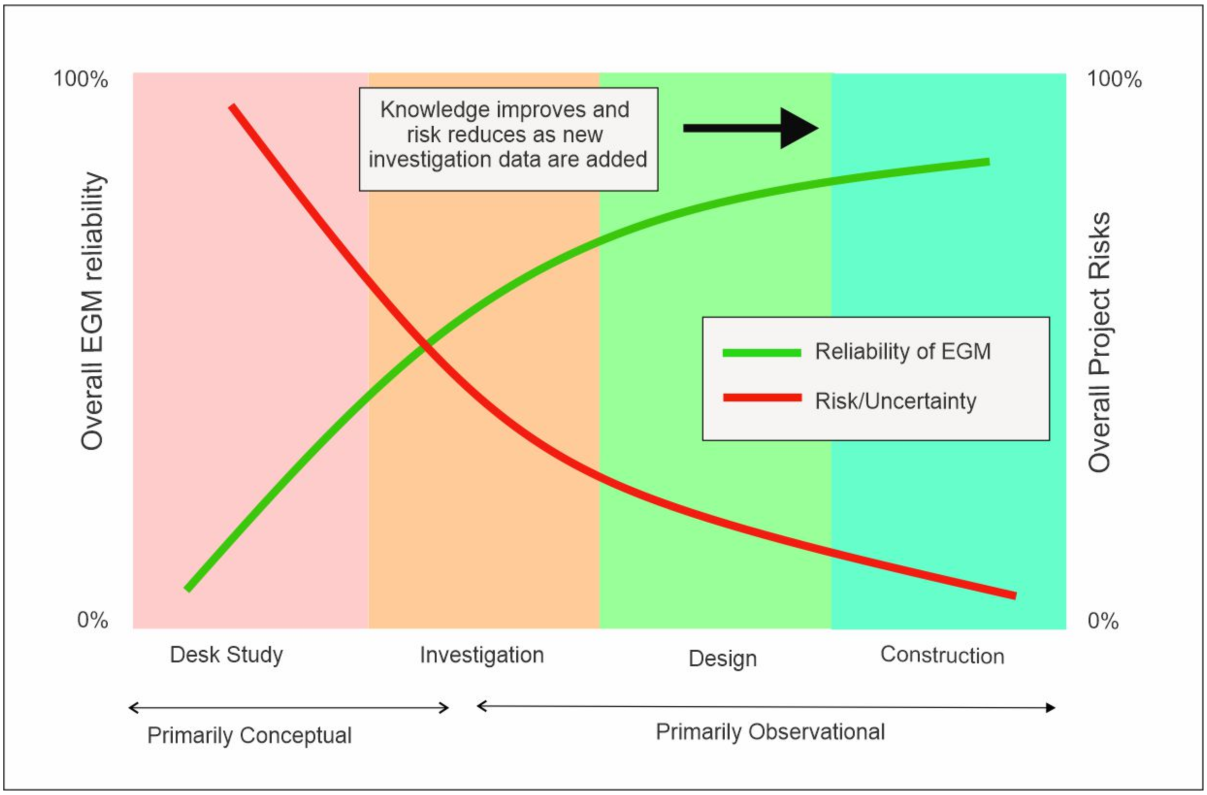

Figure 18 Improvements in EGM reliability as project progresses

The classic assumption that simple progressive risk reduction and reliability increase and an improved EGM will be created through sequential steps of investigation, then design, then construction, can be misleading. Meaningful reduction of risk and improvement of understanding requires feedback loops developed during staged investigation and review during design and construction. It is essential that as the project progresses the EGM can be verified and, where necessary, improved or altered (Figure 1-9). Improved reliability is achieved when conceptual ideas and observational data have been reconciled through an iterative process of comparison and improvement.

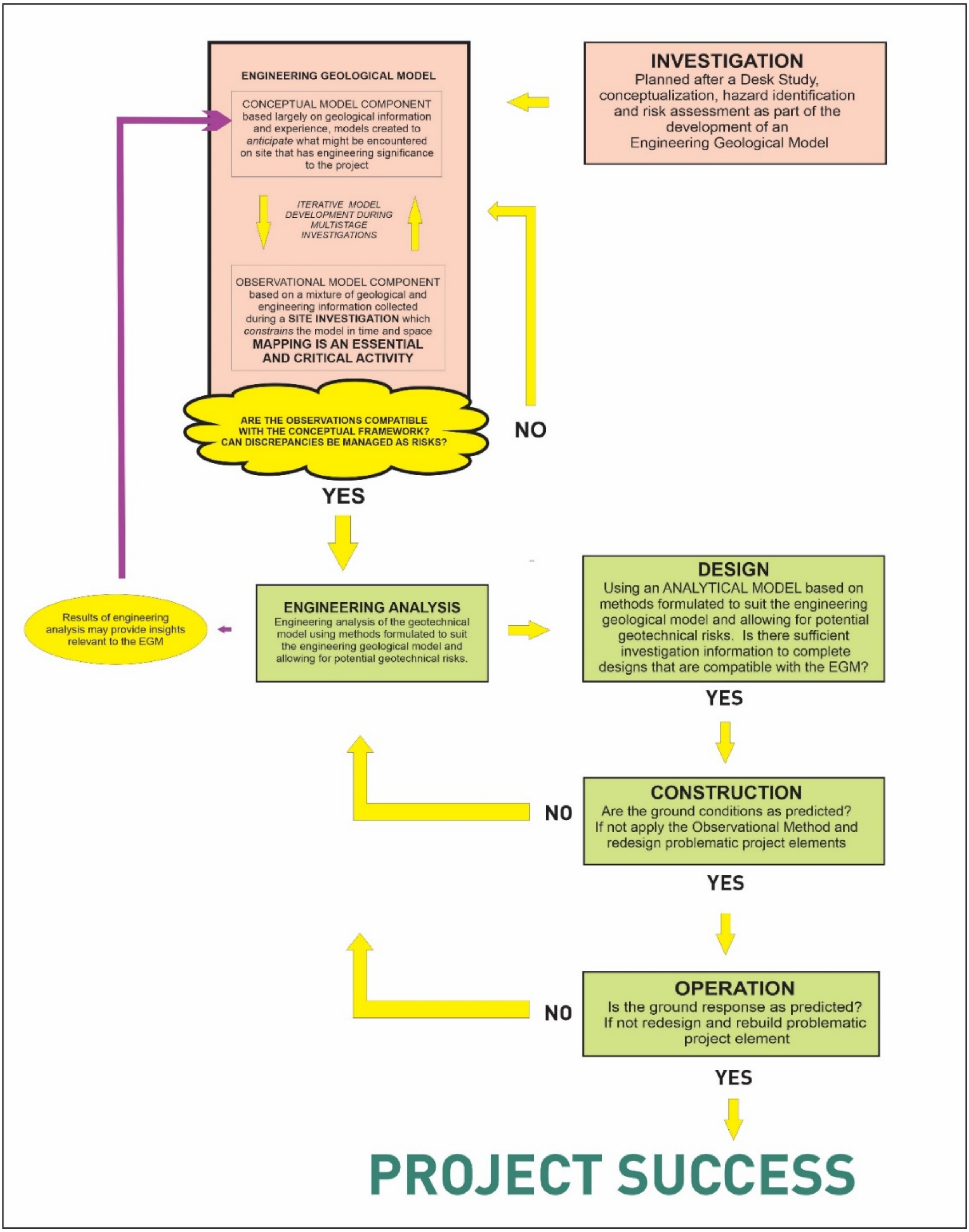

Figure 19 Feedback loops

What is an acceptable or tolerable level of risk should be defined early in the project as this ultimately guides the level of uncertainty that is acceptable within the EGM and thus the extent of the investigations that are required. The likely geotechnical complexity (primarily from the conceptual model) should also be assessed early on in the project's life as part of the definition of acceptable uncertainty, as an inadequate understanding of the true level of geotechnical complexity often leads to an inappropriate definition of the actual reliability of an EGM.

Sources of uncertainty

The way that the knowledge is accumulated within the EGM reflects the dynamic relationship between the conceptual component and the observational component. These two fundamental components of the EGM are characterized by very different sources of uncertainty: conceptual uncertainty and observational uncertainty.

Uncertainty in the Conceptual Model

Uncertainty in the conceptual model is due to a lack of knowledge or bias of the model developer. This is known as epistemic uncertainty but for ease of reference these Guidelines have adopted the term conceptual uncertainty.

Conceptual uncertainty primarily depends on the appropriateness of the concepts underlying the EGM which, in turn, is heavily dependent on the knowledge and experience of those involved. However, the following factors are also important:

- The spatial relevance of the data to the project – location and scale.
- The quality of the available data sources.
- The representativeness and volumetric adequacy (quantity) of available data.
- The geotechnical complexity.

Uncertainty in the Observational model

Uncertainty in the observational model is due to variability and randomness of the intrinsic properties of the ground. This is known as aleatory uncertainty but for ease of reference these Guidelines have adopted the term observational uncertainty.

Areas with sparse direct observations are likely to be more uncertain than areas with frequent direct observations. Provided that an adequate amount of observational data is considered within a robust conceptual model, the uncertainties in the observational uncertainty will be primarily data-related, encompassing:

(1) Inherent variability: natural spatial variability of the geological environment.

(2) Limited data: the impossibility of measuring geological and geotechnical properties at every point within the ground.

(3) Testing uncertainty: uncertainties related to the measurement accuracy of testing devices.

Inherent variability cannot be reduced and testing uncertainty cannot be removed without improving the quality of the instrument.

It is only the limited data uncertainty that can be reduced by increasing the number and distribution of measurements.

Methods of assessing the uncertainty and reliability of the EGM

All of the information that contributes to the EGM needs to be assessed and combined to evaluate uncertainty and reliability. For the data aspects of the EGM, such checks are relatively straightforward and can be undertaken either quantitatively or qualitatively. However, quantitative methods cannot realistically assist in reducing reliability errors stemming from inaccuracies in conceptual understanding. Only by checking the veracity of the concepts through qualitative approaches can this component of the EGM be assessed and, thus, its reliability increased.

Assessing the reliability of the Conceptual component

A method of assessing the conceptual component of the EGM is illustrated in Figure 1-10. This method should be adopted at all stages of the project by individuals, reviewers or expert panels. It is particularly useful if applied during the development of a digital 3D model because the modeller can directly review the veracity of the concepts underlying the visualisation.

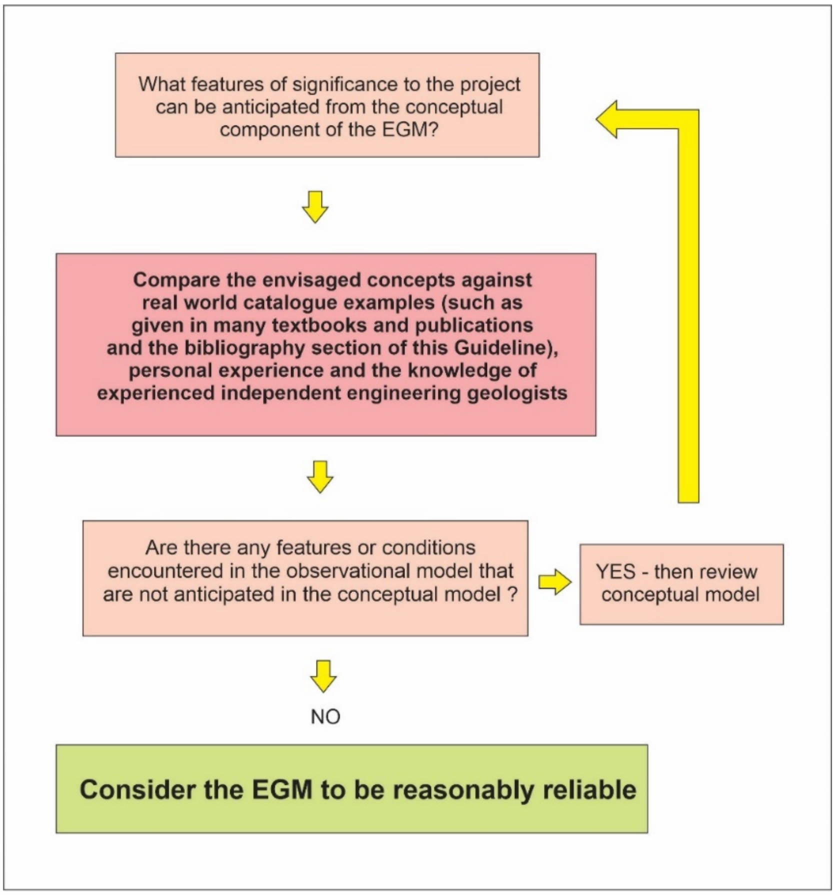

Figure 110 Suggested approach for verification of the EGM Conceptual Framework

Qualitative evaluation of the EGM

Consideration of Compatibility/Harmony

A reliable EGM can only be established when there is sufficient "compatibility" or "harmony" between the evolving conceptual model and the acquired observational data. It is the conceptual model that is used to measure this compatibility or harmony, as it embodies the fundamentally correct engineering geological thinking that needs to be developed for a site. This comparison also allows an evaluation of the adequacy of the conceptual model - if there are too many discrepancies between the conceptual model and the observational data and they are increasing as more observations are acquired, then the conceptual model should be reviewed and revised.

Such discrepancies are best identified through the use of feedback loops in the EGM development process (Figure 1-9). This methodological strategy of rechecking with real world data is essential. Overall reliability of the conceptual model will depend more on the level of experience and knowledge of the engineering geologist than the correctness of the input data.

For Level 1 projects (Section 3.2. – Tables 1-1 & 1-2) internal reviews will provide a basic check of conceptual reliability. It is recommended that the engineering geologist responsible for the EGM self-check their own work at sequential steps throughout development and refinement of the model, so that the reliability of the conceptual model is as best as possible benchmarked against appropriate conceptual analogues derived from education, experience and the literature.

For Level 2 projects (Tables 1-1 & 1-2) the review will be as for Level 1 but undertaken by external reviewers. These may be external to the project team or external to the organization itself.

For Level 3 projects (Tables 1-1 & 1-2) an expert review panel consisting of acknowledged experts should be used to assess the reliability of an EGM by independently reviewing and commenting on the content, completeness and reliability of the project documentation.

Calibration and Verification

The term 'verification' is used differently by different user communities. In some cases, it refers to 'calibration' of model responses using historical records prior to making predictions of future conditions. This is common in groundwater and pollution modelling. It also applies to predictions of ground support. The term 'verification' can also refer to the comparison of EGM predictions of ground conditions with the "as encountered" conditions as a project proceeds. If these comparisons show reliability, even though not always precisely accurate geometrically, then construction can often be completed more efficiently. This type of verification is an ongoing process.

Communicating the reliability of Observational Models

The reliability analysis of the observational component of the EGM may be communicated using thematic maps and the classification of the reliability of datasets.

Further details are provided in the Commentary.

Semi-quantitative approaches

Methods in which the components of the EGM are graded and the various scores combined to provide a numerical assessment of reliability have been devised.

Further details are provided in the Commentary

Quantitative approaches

Quantitative assessments are restricted to evaluating the Observational Model components of uncertainty that is, spatial variability, limited data uncertainty, systematic uncertainty and transformation uncertainties. Three families of tools can be employed:

- Random Field simulations and Random Finite Element Method (RFEM involves the use of random virtual ground combined with finite element analysis within a Monte Carlo simulation).
- Geostatistical methods (both stationary and non-stationary, such as Kriging methods),
- Stochastic simulations.

Further details are provided in the Commentary.

Incorporation of data uncertainty in design parameters

When the parameters of the EGM become input data for design, the adoptive parameter's uncertainty should be evaluated. In design practice, two methods are used to manage EGM's parameter uncertainty: Safety Factors and Reliability-Based Design (RBD) methods.

Further details are provided in the Commentary.

C2.5 Reducing EGM Uncertainty

Introduction

A major concern of C25 is the communication of information on uncertainty to different users of digital visualizations using methods that are relevant to them and their needs. Importantly, the methods used to communicate should be easily understood, as many of the users will have no technical knowledge on uncertainty quantification and, often, not even of the geological processes that formed the site.

Sources of uncertainty

Increases in reliability and reduction of risk occur through the accumulation of both conceptual and observational knowledge within the EGM, usually through various stages of investigations that are carried out as the project progresses (Carter 1992, Carter & Marinos 2020).

Uncertainty in the Conceptual Model

The decisions taken during the conceptualisation process can introduce bias and uncertainty into the model. Bond *et al*. (2008) noted several types of biases, the most relevant being:

- Availability Bias: an interpretation that comes most readily to mind and is familiar.
- Anchoring Bias: accepting 'expert' or dominant published opinion.
- Confirmation Bias: seeking only opinions or facts that support one's own hypothesis, or similarly interpreting the data to fit the hypothesis.
- Optimistic Bias: interpreting in a manner that produces a more positive outcome for a study, such as interpreting greater continuity of mineralization controlling structures, or preferring to ignore conflicting data that may reduce positive project outcomes.

Uncertainty in the Observational model

No further commentary provided.

Methods of Assessing the Uncertainty and Reliability of the EGM

No further commentary provided.

Assessing the reliability of the conceptual component

No further commentary provided.

Qualitative Evaluation of the EGM

Communicating the reliability of the Observational Model

There are multiple ways of communicating the reliability of the observational model to the users of the model, including thematic maps. Figure 2-11 shows a reliability diagram in the form of a heat map as an example of how to graphically communicate uncertainty in the observations.

Relative reliability of Geotechnical Observations

A qualitative approach assessing the relative reliability of data can be applied to EGMs to classify reliability of datasets (in order of certainty from least to most) under the headings 'Implied,' 'Qualified,' 'Justified' and finally 'Verified' as per Table 2-5.

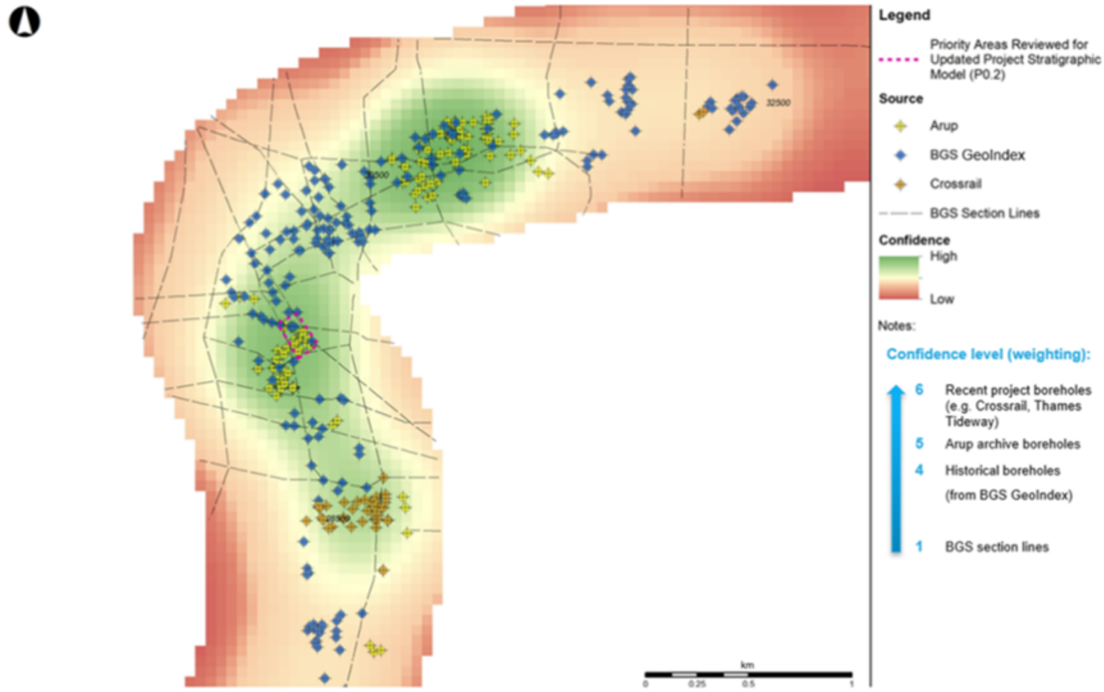

Fig. 10. Extract from confidence heat maps produced to inform viewers of the Project Stratigraphic Model of the level of confidence they should place on strata levels at particular locations along the proposed route.

Figure 211 Confidence heat map for strata levels (Ting *et al*. 2020)

Table 25 Uncertainty related to available information

Data Type	Requirements (adapted from Haile 2004) assuming that the EGM is being developed by competent practitioners
Implied	• No site-specific geotechnical data necessary or available. • EGM is primarily conceptual. • The EGM has a low level of reliability.
Qualified	• Project-specific data are broadly representative of the main engineering geological units and inferred geotechnical domains, although local variability or continuity cannot be adequately accounted for. • Observations broadly conform with conceptual model. Non-conforming areas identified. • The EGM has a moderate level of reliability.
Justified	• Project-specific data are of sufficient spatial distribution (density) to identify geotechnical domains and to demonstrate continuity and variability of geotechnical properties within each domain. • High degree of agreement between the conceptual and observational models • The EGM has a high level of reliability.
Verified	• Site-specific data are derived. All engineering geological boundaries/units have been mapped in the field upon exposure during construction. • High degree of agreement between the conceptual and observational models • EGM is based on exposure mapping for example foundation/tunnel and direct observation of in situ conditions. • The EGM has the highest level of reliability.

Semi-Quantitative approaches

Degree of complexity

One approach of assessing the degree of complexity (and hence helping define how much data might be needed to verify a specific conceptual EGM in early stages of development) is that of Keaton (2015) see Table 2-6.

Table 26 Geological model complexity rating system, rating criteria and scores (from Keaton 2015)

Component	Points	3	9	27	81
Regional-scale geoloigc complexity	Genetic - deposition or emplacement	Simple, uniform conditions	Generally simple, predictable conditions	Somewhat complex, generally predictable conditions	Highly complex and variable conditions
Regional-scale geoloigc complexity	Epigenetic - structural or deformational	No faulting or folding observed or expected	One episode of limited faulting and folding expected	Two episodes of limited faulting and folding expected	Multiple episodes of major faulting and folding expected
Regional-scale geoloigc complexity	Epigenetic - alteration or dissolution	Unlikely because of geologic setting	Possible because of geologic setting	Likely because of geologic setting	Known to exist
Regional-scale geoloigc complexity	Epigenetic - weather-ing and erosion	Uniform weathering profile; minor erosion	Generally regular weathering profile; some erosion	Irregular weathering profile; moderate erosion	Highly irregular weathering; extensive erosion, buried valleys
Site-scale geologic complexity		Vertically and laterally uniform over project site	Generally regular over project site	Irregular over project site	Highly irregular over project site
Terrain features		Some relief; many good exposures	Some relief; some good exposures	Strong relief; poor exposures	Heavy vegetation; very poor exposures
Information quality		Extensive data from multiple sources	Limited data from few sources	Reconnaissance level information	Existing information only; desktop study
Geologist competency level		Professional Geologist with local field experience	Professional Geologist with field experience in non-similar geology	Geology degree or equivalent with some field experience	No geology training or experience (engineer or non-earth scientist)
Alotted time or level of effort		Ample time; well-developed interpretation	Adequate time; thoughtful interpretation	Brief time; thoughtful interpretation	Brief time; rushed interpretation

The R-Index for tunnelling

The R-Index is a rating method that was developed for estimating the reliability of geological and geotechnical models prepared for tunnelling purposes (Perello *et al*. 2005, Dematteis and Soldo 2015, Venturini *et al*. 2019) but has been extended to application in the mining industry, particularly for open pit mine model validation (Carter & Barnett 2021). This method evaluates the quality of the geotechnical investigation data and the geological complexity of the site to qualify the reliability of the model.

Dematteis and Soldo (2015) provided detailed explanations for the application of the method, in a tunnelling context, based on a classification system developed to consider the following parameters:

i. Quality of geological and geotechnical investigation. The method provides rating tables for each one of the parameters, that are subdivided in:
   - Geological mapping, including aerial photograph and satellite image interpretation.
   - Geophysical investigation (indirect investigation).
   - Borehole drilling and logging, site tests and laboratory tests (direct investigations).

ii. Complexity of the site, which can be described by means of the three following geological parameters, called System Parameters (for the System Parameters as well the method provides a table with the ratings to be used for the anticipated geological conditions):
   - Complexity of the litho-stratigraphical setting (LC).
   - Complexity of structures related to ductile deformations (DC).
   - Complexity of structures related to brittle deformation (BC).

As many of the parameters (Quality Parameters and System Parameters) involved can be related to each other, the influence of a single parameter on all the others and vice versa is considered by means of binary and fully coupled interaction matrices.

The computation of the R-Index is provided along the longitudinal geological and geotechnical profile of the tunnel. The alignment is divided into homogeneous stretches, to which the ratings of the parameters described above are assigned, that allow the calculation of the R-Index for each stretch. The R-index values range from 0 to 10. Its significance in terms of reliability of the model has been deduced by the examination of several case histories and is expressed in four classes (A, B, C, D) as described in Table 2-7.

Table 27 Geological and geotechnical model reliability in 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

The method has a specific module aimed at addressing the geotechnical investigation plan to improve the reliability of the model (Perello *et al*. 2005, Dematteis and Soldo 2015). The method provides an assessment of the quality of each of the data of the model and the impact that the different types of geotechnical investigation can have to improve the rating. This is to support the decision on the most suitable type of geotechnical investigation to improve the reliability of the model.

Uncertainty Assessment

After a site investigation has been completed the level of uncertainty and reliability of different parts of the EGM knowledge framework can be systematically assessed and combined to identify project implications using a method devised by Paul (2018) (Figure 2-12).

Visualization of uncertainty

Uncertainty in geometric representation of models can also be documented and visualised by using techniques such as:

- Distance query (this shades the surface and subsurface based on distance from investigation points).
- Face dip of surface (this locates possible zones of interest, that is possible faulting observed as steeply dipping surfaces between investigation points).
- Contouring the boundary of the model to a maximum distance from investigation points so as to not model beyond the set limit.

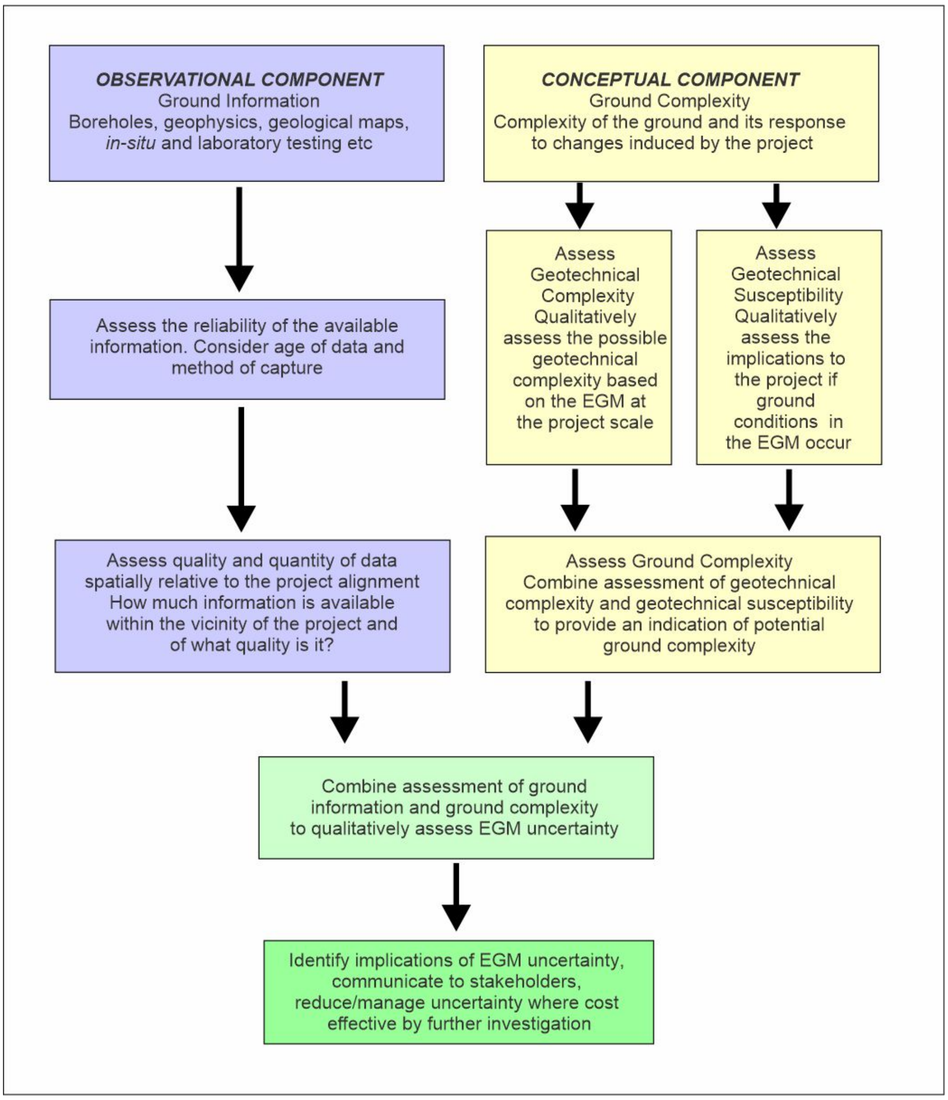

Figure 212 An example of documenting uncertainty in the development of the observational model (modified from Paul 2018).

Use of metadata statements

Uncertainty related to electronic data files that may include both data and interpretation can be documented as an independent metadata statement attached to files being exchanged within organisations or between different disciplines and software applications.

Quantitative approaches

There is uncertainty associated with the estimated distribution of the measured parameters that form the observational component of the EGM. In some cases, the input parameters for parts of an EGM are derived from a transformation of measured parameters that are dependent on the design purposes. Transformation uncertainty depends on the transformation model and variables and can be quantified by propagating the original uncertainty affecting the measured variables.

The following methods are also able to quantify and manage this type of uncertainty: random field approach, kriging and stochastic simulation, and these are discussed below.

Random field approach

This method enables the users to interpret the spatial variability uncertainty through a deterministic trend function and random fluctuations. By implementing the random fluctuation properties within a Montecarlo Simulation the users can calculate the spatial standard deviation related to the estimated values of the parameters over the whole domain of interest (Vanmarcke 1984).

Kriging Methods

Kriging methods are a set of univariate and multivariate techniques pertaining to geostatistics that allow mapping of the spatial distribution of quantitative georeferenced data, such as mechanical and hydraulic properties of soils and rocks, as well as contained fluids. These methods are based on the Regionalized Variable Theory that considers quantitative attributes of a certain domain (for example, subsoil), measured in a discrete way, as random and spatially dependent variables. In simple words, values related to close measurements are likely to be more similar than if they were more separated. These geostatistical techniques provide a quantification of the uncertainty associated with the estimates in terms of Kriging variance that, in turn, can provide a standard deviation value (that is, with the same unit) or required confidence interval limits (Fenton and Griffith 2008, Vessia et al., 2020).

Stochastic Simulation methods

Stochastic Simulation methods allow quantification of the uncertainty by providing a number of realizations, obtained using the spatial variability functions defined through the experimental measurements (that is, variogram, or LMC). These numerous equiprobable configurations of spatial distribution related to the subsoil property under study result in a statistical distribution of values at each location of the considered domain, representing an accurate estimation and quantification of local uncertainty.

Incorporation of data uncertainty in design parameters

The use of the Safety Factor follows a deterministic approach. The safety factor is the ratio between the resistance or the response of the system to the loads applied by the engineering structures or by the human activities. Such a factor has been calibrated empirically by technical experience. Thus, the acceptability of the values of the safety factors is not calculated or estimated but empirically assessed based on accumulated technical knowledge and legacy of the performance of different structures gained over time.

Reliability-based design (RBD) methods are currently recognized as the preferred approach in technical codes in many parts of the world instead of Safety Factor. Simplified RBD methods such as the Load and Resistance Factor Design (LRFD) with constant partial factors have now been used only for the coded design limit states. These factors have replaced the safety factors and can be calculated according to accepted fixed probability value of failure.

Further comments on these aspects of design are outside the scope of these Guidelines.