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Managing
Engineering Geological Model Uncertainty

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1 Introduction

The Engineering Geological Model (EGM) is the representation of the subsoil physical, mechanical, chemical and even thermo-dynamic characteristics into a unique model that shall be handled by the Geologists and Engineers for design purposes. The EGM is reconstructed by the Geologists according to both geological and geotechnical investigations (Baynes, and Parry, 2022)[1].. This report describes the nature of uncertainty within the EGM, how reliability and risk are related to that uncertainty and why it is essential to identify, assess or quantify, and manage that uncertainty to ensure project success.

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 and therefore can optimise engineering decision-making. Uncertainty within the EGM will reduce the reliability of the project engineering and therefore the uncertainty must be assessed, and strategies developed to reduce it.

Risk is the possibility of an adverse outcome. Risk 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. There is an inverse relationship between reliability and risk. That is an increase of model reliability should reduce project risks.

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, as captured in the right-hand diagram below.

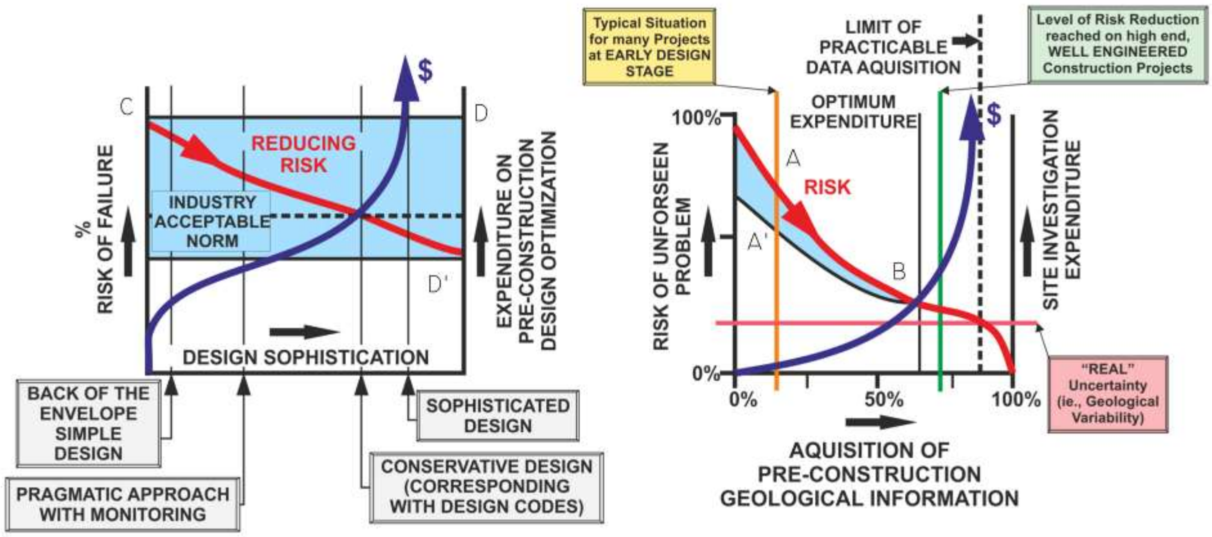

Figure 1 Progressive and relative reductions in uncertainty as knowledge increases versus that achieved solely through more sophistication in modelling (from Carter & Marinos, 2020, after Carter, 1992;)

For example, in the right-hand diagram in **Figure 1**, assuming a good quality conceptual model is developed, at the start of the ground investigation knowledge at Point A, once ground investigation is completed, knowledge is expected to reach at least Point B for most projects, with an associated reduction in both

[1] Baynes, F. J. and Parry, S. 2022. Guidelines for the development and application of engineering geological models on projects. International Association for Engineering Geology and the Environment (IAEG) Commission 25 Publication No. 1, 129 pp. Downloadable at https://www.iaeg.info/C25EGMGuidelines/

uncertainty and risk, as conceptually plotted as the red curve. The left diagram in **Figure 1** can be thought of as a section drawn at right angles into the page relative to the right-hand diagram, at any point along the x-axis time scale of increased data acquisition.

The blue band on both diagrams thus shows the relative reduction in risk and uncertainty that conceptually is all that can be achieved solely by greater sophistication in analysis and modelling at any stage along the path of knowledge acquisition, but with no more actual added hard data. As shown by the relative width of the blue band in the right diagram, in early stages of design great insight (with concomitant increase in understanding and reduction of uncertainty) can be achieved by significant modelling effort, reducing real risk from Point A to A' corresponding to moving from Point C to D' in the left-hand diagram. Conversely, there is very limited real reduction in risk achievable solely by undertaking increased sophistication in modelling when Point B has been reached. This conceptually matches the well-known adage that only through acquisition of additional hard data can real uncertainly be reduced and reliability increased (Hoek, 1994).

In addition to the fallacy that increased sophistication in modelling and analysis can reduce risk and uncertainty (Peck, 1976, Hoek, 2009), 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 also be misleading. True reduction of risk and improvement of understanding requires feedback loops for further investigation checking along the way so that model concepts can be verified and where necessary improved or altered.

It is important that what is an acceptable or tolerable level of risk is defined early in the project as this ultimately guides the level of uncertainty acceptable within the EGM. Complexity of the geology must also be assessed early on in project life as part of this definition of acceptable uncertainty, as inadequate definition of geological complexity oftentimes leads to inappropriate definition of the true reliability of an EGM. Properly domaining the rockmass for which the EGM is being built can help significantly in reducing such uncertainty (Carter & Barnett, 2021). Sophisticated EGM's that are not backed up by an appropriate level of solid site-specific data, matched to geological complexity, can give a false sense of accuracy that leads to a delusion of great understanding, with hidden deficiencies only surfacing once unexpected surprises occur during construction or operation stages. Erroneous perception of improved understanding gained solely through increased sophistication in modelling is also detrimental to assuring the reliability of the EGM. It must be appreciated that only through staged additional investigation to validate the EGM and implement concept verification checks, can real risk be reduced. The widespread delusional tendency nowadays of undertaking more and more sophistication in modelling, but without acquiring additional verification and validation data must be avoided.

The EGM thus needs to be built around a valid understanding of the site, its setting and its geological history.

In consequence, the two fundamental components of the EGM will be characterized by very different sources of uncertainty:

1. The Conceptual Model – is a model based mainly on geological concepts and interpretations that also incorporate the engineering purpose of the model. Associated uncertainty is due to a lack of knowledge and bias of the observer. This is sometimes called epistemic uncertainty but we will use the term conceptual uncertainty.

2. The Observational Model – is a model-based mainly on engineering and geological observations and measurements. Associated uncertainty is due to variability and randomness of the intrinsic properties of the system. This is sometimes called aleatory uncertainty, but we will use the term observational uncertainty.

The way that the knowledge is accumulated within the EGM reflects the dynamic relationship between the conceptual component and the observational component.

If the EGM does not allow a realistic understanding of how the ground will respond to the project with the required level of certainty, then more knowledge or data is needed. Improved reliability is achieved when conceptual ideas and observational data have been reconciled through an iterative process of comparison and improvement (**Figure 2**).

This iterative process of EGM Conceptual Model must be traceable and structured, trying to avoid as much as possible the subjective judgments of the authors of the model, replacing them with objective and measurable facts (e.g., models and case histories from literature, mapping, geotechnical investigation, geotechnical monitoring, etc.). Only in this way will it be possible to quantify the uncertainty of the conceptual model, with qualitative approaches as shown in section 5.3, and monitor the Conceptual Model's reliability improvements as new data become available. The refinement process of the Conceptual Model through Observational Model mustn't rely on subjective positions but on data to be provided in case of the occurrence of structural failure.

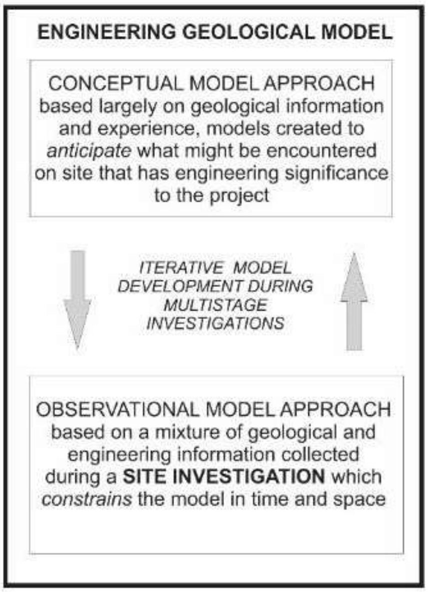

Figure 2 Iterative development of the EGM knowledge framework

2 Sources of uncertainty

2.1 *Uncertainty in the Conceptual Model*

Conceptual Model uncertainty primarily depends on the appropriateness of the concepts underlying the EGM., i.e., understanding of site conditions, 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 geological and geotechnical complexity, and geological history, including the deformation history and stress regime especially for deep underground engineering works.

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 is most readily to mind and are familiar with.
- 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 (after Krueger and Funder, D., 2004).

2.2 *Uncertainty in the Observational model*

Provided that an adequate amount of observational data is considered within a robust conceptual model, the uncertainties in the Observational Model will be primarily data-related, encompassing:

- Inherent (natural) variability: natural spatial variability of the geological environment.
- Limited data uncertainty: the impossibility of measuring geological and geotechnical properties at every point and in every different geological domain within the EGM.
- Instrument uncertainty: uncertainties related to measurement accuracy inclusive of field devices and laboratory testing devices.

Inherent variability and instrument uncertainty are systematic and cannot be removed without improving the quality of the instrument. Only the limited data uncertainty can be reduced by increasing the number and distribution of measurements.

2.3 *Uncertainty within digital models and visualizations*

A major concern is the communication of information on uncertainty to different users of software visualizations using methods that are relevant to them and their needs and that they can understand, 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.

Uncertainty varies within a software model representation of the geology. Areas with sparse direct observations are more likely to be more uncertain than areas with frequent direct observations.

In some cases, the input parameters for parts of a geological model are derived from a transformation of measured parameters, dependant on the EGM design purposes. *Transformation uncertainty* depends on the transformation model and variables and can be quantified by propagating the original uncertainty affecting the measured variables.

Qualitative, semi-quantitative, or quantitative methods can document the sources of uncertainty within software models (Cave and Wood 2002).

- Qualitative assessment of conceptual model interpretations can be undertaken by an adequately experienced peer reviewer's application of a quality rating system.

- Qualitative and semi-quantitative assessments of uncertainty can show the spatial variability and/or reliability of observations by reference to a reliable information source, such as a geological map; a process that is relatively easy to produce and understandable by many users.

- Semi-quantitative methods combine aspects of qualitative and quantitative methods; they typically employ statistics or stochastic procedures to evaluate software model uncertainties. See also section 5.3 on this regard.

Any uncertainty in geometric representation of models should be documented and visualised by creating any of the following using the appropriate modelling software:

- distance query (this shades the surface and subsurface based on distance from investigation points),
- face dip of surface (this locates possible zones of interest, i.e. 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.

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

3 Methods of assessing the uncertainty

All of the information that contributes to the EGM needs to be assessed and combined in order to define model uncertainty and reliability. For the data aspects of model construction, such checks can relatively straightforwardly be undertaken either quantitatively or qualitatively, as described in sections XX & YY. What is more problematic is checking the conceptual basis of the EGM to ensure that it matches the reality of actual site conditions. A flowchart approach to achieving this necessary check is outlined in this section.

3.1 *Qualitative and classification approaches*

A reliable EGM can only be established when there is sufficient "compatibility" or "harmony" between the evolving conceptual framework and the acquired observational data. It is the conceptual framework 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. However, this comparison also allows an evaluation of the adequacy of the conceptual framework - if there are too many discrepancies between the conceptual framework and the observational data, and they are increasing as more observations are acquired, then it is time to review and revise the conceptual model.

Such discrepancies are best identified through the use of feedback loops in the EGM development process. This methodological strategy of rechecking with real data is essential best practice. Where it does not occur – which is sometimes the case in current design practice – it can lead to sub-optimal design or even project failure, see **Figure 3**.

Improving Reliability of Structural Domaining for Engineering Projects

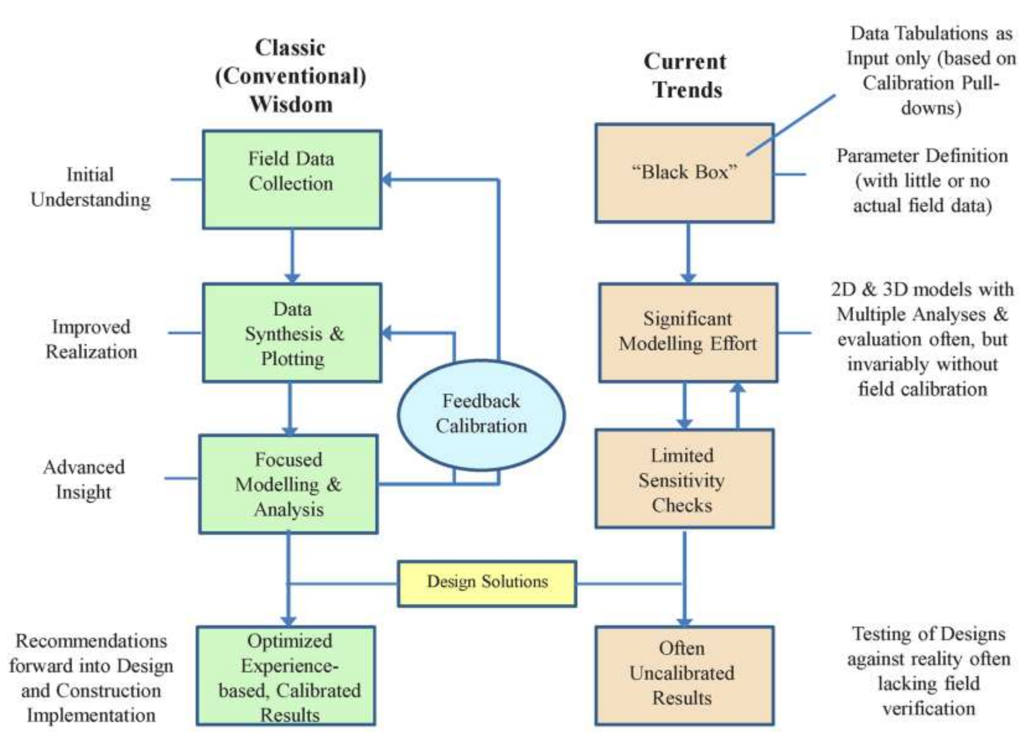

Fig. 4 Comparison of current design practice trends (right column) versus classic methodology (from Carter 2015)

Figure 3 Problems with current design practice.

While arguably the best means for validating a conceptual EGM is through expert panel peer review, as discussed subsequently, basic checks of the conceptual reliability of an EGM can and need to be made as it is developed. Often it is problems in incorrectly replicating the true geological conditions of a site that lead to the largest reliability errors in EGMs. In fact, reliability of the conceptual model that forms the framework of the EGM can almost universally be directly related with the degree of understanding that the modeller has of the environment in which he or she is working. As a result, overall reliability of the model will depend more on the level of experience and knowledge of the modeller than the correctness of the input data. In addition, while hidden reliability issues abound in many models where insufficient verification subsurface data is available, this is not just a problem for data verification but also a major problem for validating the conceptual framework around which the model is built. This is a particular concern where a modeller's experience in working in that sort of geological environment is limited. It is thus critical that the conceptual model for the EGM should be sketched up ahead of building a composite EGM and then checked against reliable natural analogue examples.

Once the reliability analysis of the EGM is completed, there are multiple ways of communicating it to the users of the model, including thematic maps. **Figure 4** shows a reliability diagram as an example of how graphically communicate uncertainty in the observations.

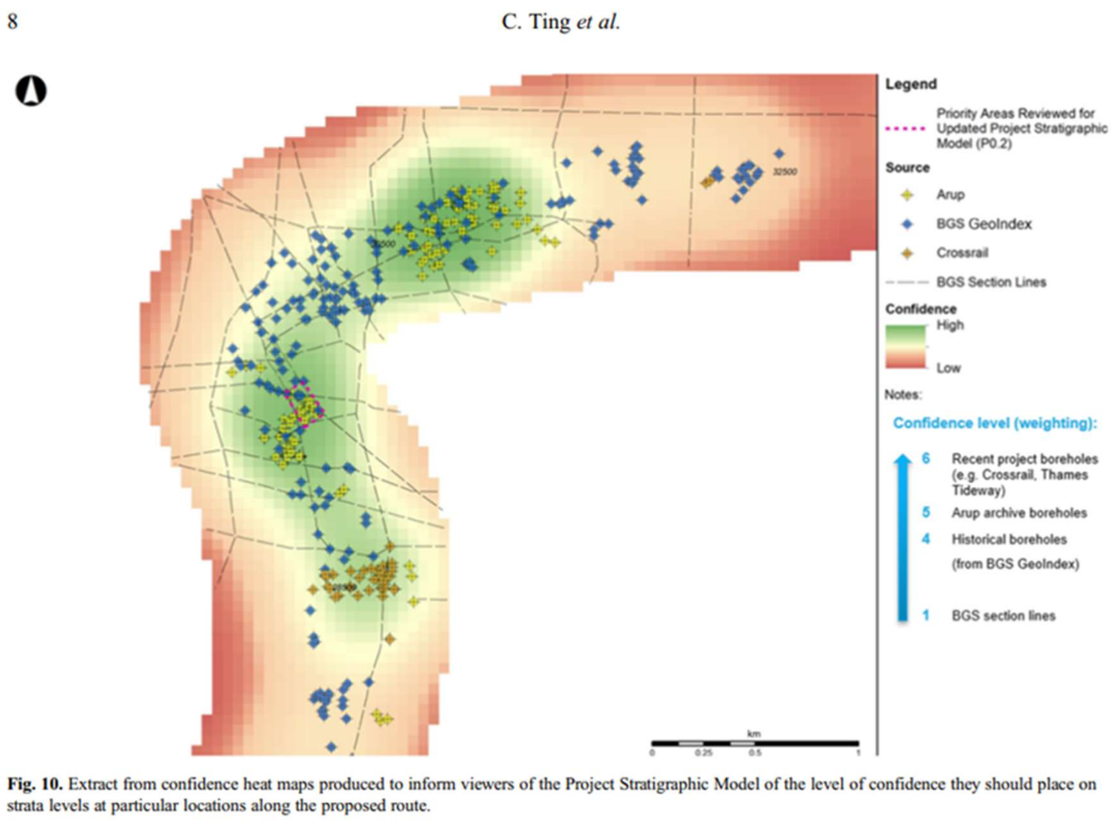

Figure 4. Confidence heat map for strata levels.

The following paragraphs report some examples of practical methods to assign the degree of uncertainty or reliability to the EGM. The first two paragraphs are more oriented to the evaluation and validation of the conceptual model, the following 3 offer examples for the complete evaluation of the EGM, including the conceptual and observational model.

3.1.1 ***Use of Expert Review Panels***

Convening an expert review panel consisting of acknowledged experts is a commonly used method to qualitatively assess the reliability of an EGM by independently reviewing and commenting on the content, completeness, and reliability of the project documentation. Typically, expert review will include evaluation of the conceptual components of the EGM, but often cannot delve into the integral details of the model construction sufficiently to unearth fundamental development issues that impact ultimate reliability. To resolve this the optimal approach for this process is to begin detailed expert review before the award of the contract to build an EGM and then continue such review regularly until project completion. However, in some circumstances where there are problems due to major risks eventuating after the project has commenced it is not unusual to instigate an Expert Review Panel in response to some major project failure.

3.1.2 ***Self-Checking of EGMs***

As discussed earlier, while expert review is probably the most suitable approach to assess uncertainty within a conceptual model, self-checking a conceptual model is a necessity. Self-checking should thus aim to compare the envisaged concept against real world catalogue examples, such as given in the IAEG Guidelines for the development and application of engineering geological models (Baynes and Parry, 2022), in the revised proposal for the Self-Checking the Reliability of Engineering Geological Models (Dematteis et al., 2023), and in many textbooks and technical papers (eg, Fookes, 1997). Many of these publications provide excellent illustrations, such as shown in **Figure 5**, that provide guidance on the typical geological conditions one can expect, that should conceptually frame the EGM.

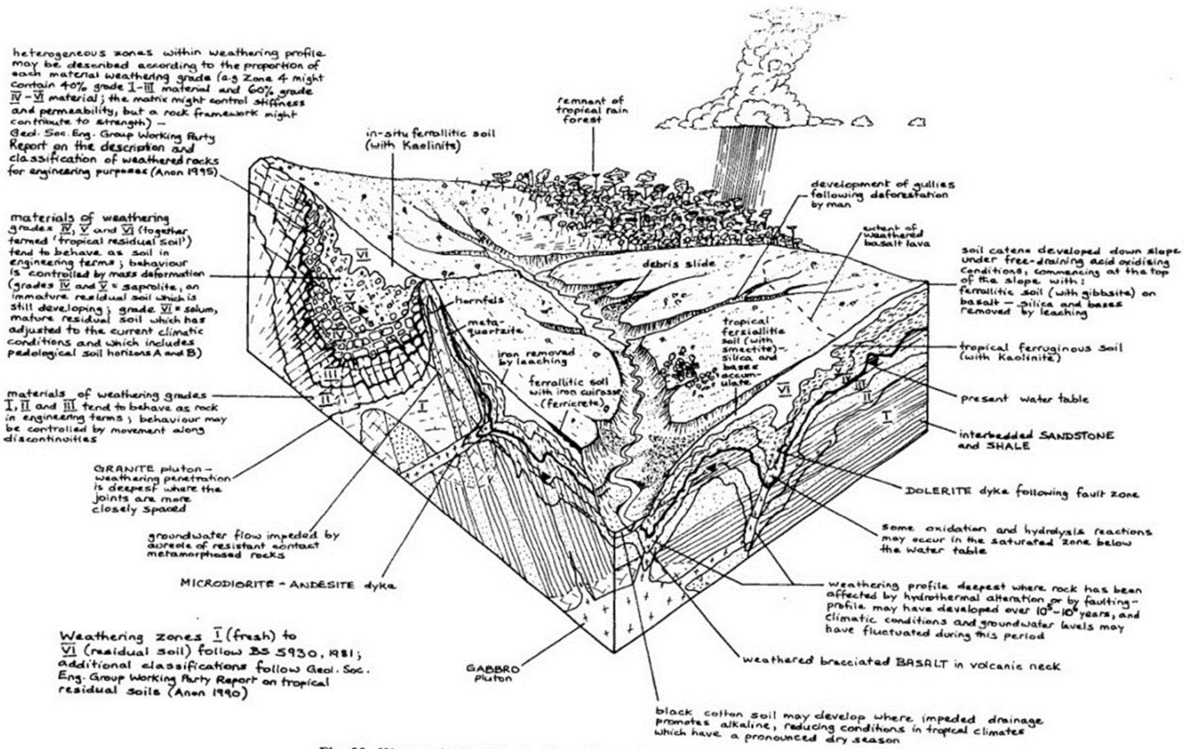

Fig. 33. Wet tropical weathering (superimposed on geology shown in Fig. 19).

Figure 5 Example EGM for a tropically weathered rockmass with complex overburden topography.

Often tectonic fault patterns, together with previous geological history of deformation events control current topography and also the rock and soil conditions that need to be built into the EGM. Thus, only with properly matching the constructed EGM with the correct geological sequencing will reliability of the conceptual framework be guaranteed. Comprehensive understanding of fault frameworks is needed for developing conceptual models, eg, https://www.seismicatlas.org/search?f=1307,1119,1031,1059&s=.

Ensuring conceptual reliability of an EGM for a rock site, depends on achieving solid understanding of controlling geologic history (best developed using palinspastic methods of model construction, such as shown in **Figure 6**).

Utilizing these sorts of verification approaches helps in correcting and averting cases of incorrect, unreliable fault block modelling, commonplace in unverified models, where often examples can be found where a modeller has created wireframe solids of younger faults being cut by older faults. Similar examples of incorrect unreliable modelling that can be averted by utilizing these types of staged historical reconstruction methods are models treating overturned sequences as right way up when reality suggests a thrusted nappe or overfold. These may seem extreme cases, but in fact are commonplace reliability problems that can affect tunnelling interpretations, especially in the Alpine, Andin and Himalayan areas.

All too common reliability problems in soils EGMs are stratigraphic soil sequences that have been interpreted and correlated between boreholes as flat lying when the true environment is in fact more complex due to deep drainages or fan deposits, with quite steep bedding dips. Cross-bedded sandstones can often create the reverse problem of too steep strata interpretation. Models of interdigitated glacial deposits are particularly prone to reliability errors unless the time history of glaciation processes that have been active in the site area are first interpreted and understood. Modelling subdrainage systems in Karst terrain is another arena where thorough understanding of the groundwater flow regime is critical to building a reliable overall EGM. Reliably modelling the sequence of deposits in any subsea deposit system also requires considerable attention to detail in understanding depositional time history and processes.

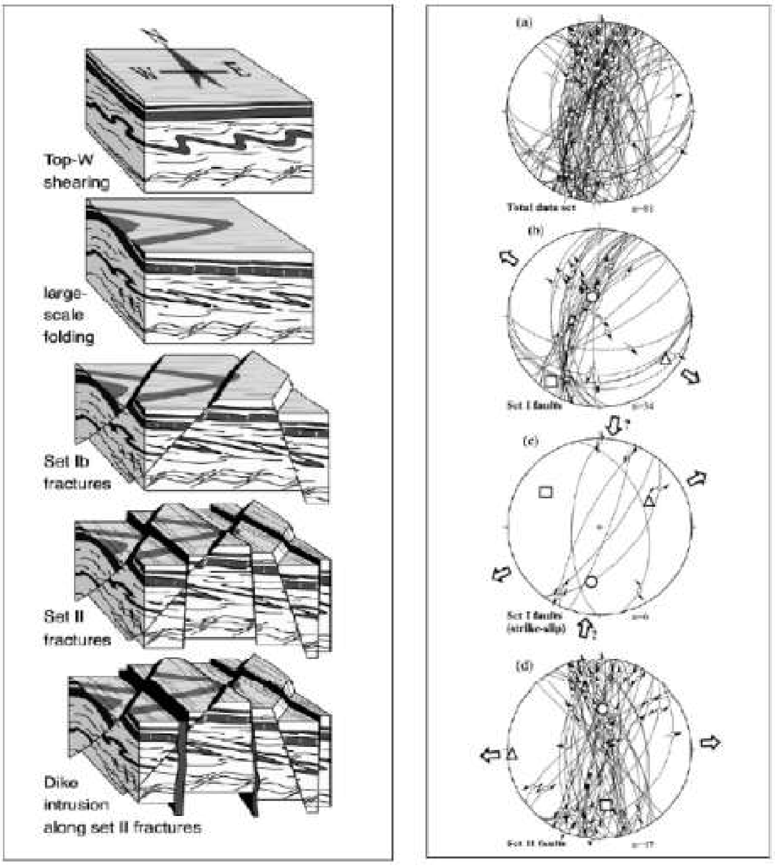

Figure 6. Block model reconstruction of geological history and associated paleo-stress inversion results, after Larson (2003).

As will therefore be evident from the above discussion, quantitatively assessing reliability of a conceptual model is not at all straightforward. Some aspects of assessing degree of complexity (and hence helping define how much data might be needed to verify a specific conceptual EGM in early stages of development) can be achieved by using the approach outlined in Keaton, 2015, Keaton et al, 2019, or as discussed in section 3.1.3, essentially by examining the reciprocal interaction between component parameters in the R-Index definition as proposed by Dematteis and Soldo (2015). These more quantitative methods cannot however realistically assist in reducing reliability errors stemming from inaccuracies in conceptual understanding. Only thorough checking of veracity of the model concept can help validate the model and thus help increase its reliability as a predictive tool.

To aid this process, it is recommended that the EGM modeller self-check his/her own work at sequential steps throughout development and refinement of the model, so that the reliability of the conceptual model that constitutes the basic framework of the EGM is as best as possible benchmarked against appropriate conceptual analogues of the same geological characteristics as the site area being modelled. This demands that the EGM and its base data have been coalesced sufficiently that the model will be deemed reliable enough by expert panel peer review to allow the model to be released for use by others in the project team for engineering design purposes. It must be appreciate by project design teams that even the most intense peer review cannot adequately delve into all details of a typical modern 3D electronic EGM model, yet it is because of errors in these details and mismatches to the assumed conceptual geological model where construction and operations problems arise. The weight of responsibility for adequate conceptual model reliability has thus to rest on the shoulders of the modeller in self-checking his or her own model construction.

The flow chart included as **Figure 7** below, along with the much more detailed checklist and matrix diagrams included in Appendix 1 outlines a process that should allow a modeller to make all the necessary self-checks of the built conceptual model. If conducted in a step-wise manner in sufficient detail and at appropriate stages along the EGM development path, following though this checklist process should allow the conceptual framework basis of the constructed EGM to be validated sufficiently to ensure its reliability for its intended purpose, such that it won't be found deficient when subjected to expert panel peer review.

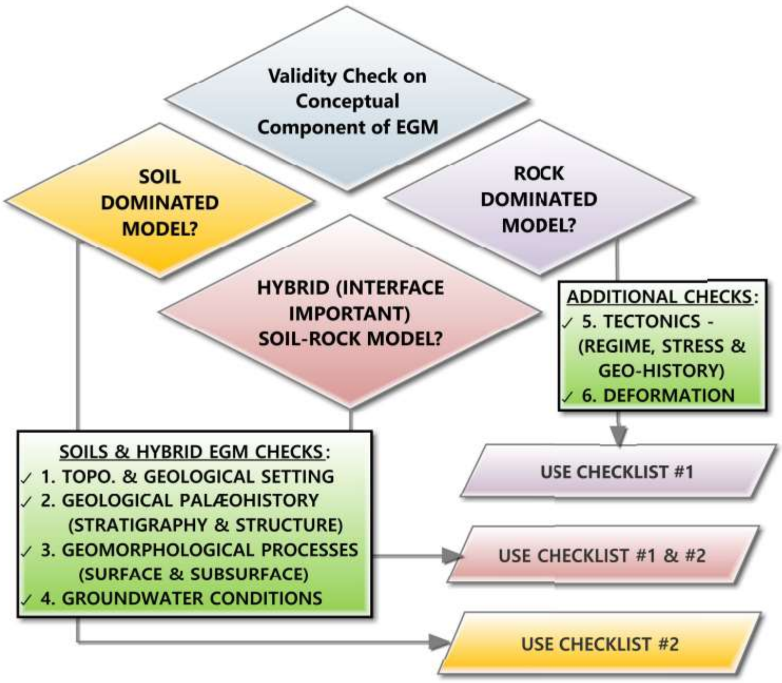

Figure 7. Suggested approach for verification of EGM conceptual framework; refer checklists #1 and #2 at annexures A and B (from Dematteis et al, 2023).

The self-check steps proposed in the checklists included as Annex A for predominantly a rock site and as Annex B for a soil-dominated site, are based on the compilation of checklists of existence, complexity and coherence for each of the features included within the model, which once completed allows validation of the reliability of the conceptual component of the EGM.

The results of undertaking this checklist verification should be written up as part of the formal documentation accompanying presentation of the EGM. The documentation should identify gaps and uncertainties that may remain and identify whether or not the base data have been coalesced sufficiently that the conceptual model can be deemed reliable enough to withstand independent expert panel peer review. Only once both a self-check and an independent review have been conducted should the geological conceptual model be released for use by others in the project team for engineering design purposes, including 2D geological profiles and any 3D geological modelling, when required.

*3.1.3 **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 & 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, Barnett, 2022, see also Appendix 1). This method evaluates the quality of the geotechnical investigation data and the geological complexity of the site to qualify the reliability of the model.

In Dematteis & Soldo (2015) detailed explanations are provided 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 photo interpretation and remote sensing,
    - 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, which allow to calculate 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 1**.

Table 1. 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 & 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 lead to the improvement of the rating. This is to support the decision on the most suitable type of geotechnical investigation to improve the reliability of the model.

3.1.4 *Estimating Ground Model Reliability for Linear Infrastructure Projects*

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, see **Figure 8**.

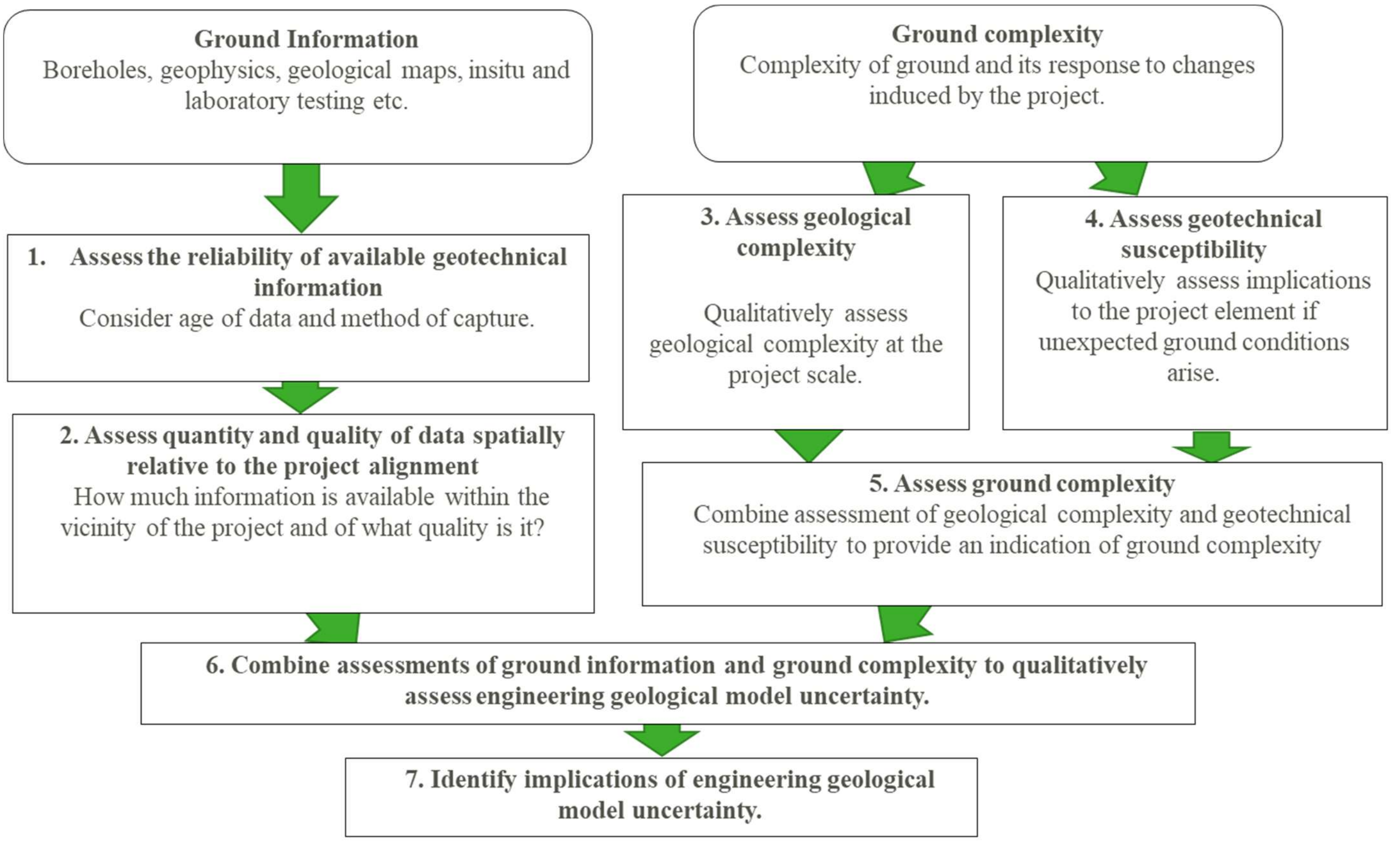

Figure 8 An example of documenting uncertainty in the development of the observational model (from Paul 2018).

3.1.5 *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 & finally Verified" per **Table 2**.

Table 2 *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 e.g. foundation/tunnel and direct observation of in situ conditions. • The EGM has the highest level of reliability.

3.2 *Quantitative approaches*

Quantitative assessments are restricted to evaluating the Observational Model components of uncertainty i.e., 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 (Fenton and Griffiths, 2007))
- Geostatistical methods (both stationary and non-stationary, such as Kriging methods),
- Stochastic simulations.

Detailed overview of these techniques is not within the scope of this guideline. A brief description of some example approaches is provided here and in Appendix 2.

The uncertainty associated with the estimated distribution of measured parameters (Observational EGM uncertainty) propagates towards other useful hydromechanical variables when equations are used. This is called transformation uncertainty. The following methods are also able to quantify and managed this type of uncertainty.

3.2.1 *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 the Montecarlo

Simulation the users can calculate the spatial standard deviation related to the estimated values of the parameters over the whole interested domain.

Vanmarcke (1984) postulated that spatial variation of soil hydro-physical-mechanical variables (called random variables) can be characterised by other than only one value or a mean trend measured through continuous or discontinuous readings. The spatial waving values of a continuous profile of measures m can be divided into a mean trend t and a fluctuation or residual profile values ε according to the following relation:

$$m(z) = t(z) + \varepsilon(z)$$

t(z) is commonly represented by an interpolation function selected through the mean square root (LSM) method. When its determination coefficient R2 is quite high (higher than 0.6) the de-trended measures, named fluctuations, will be randomly distributed about the zero value and their summation alongside the three space dimensions will be approximately zero. They can be defined as random field. A random field is a range of random numbers whose indices are identified with a continuous set of points in the space. A random field is spatially correlated meaning that adjacent values do not differ as much as values that are further apart. Such a spatial dependence is measured by the scale of fluctuation, defined as follows:

$$\delta = 2\int_0^\infty \rho(z)dz$$

where ρ(z) is the autocorrelation function for a distance z. The common models for the autocorrelation function are listed in Table. 1.This latter function represents the shape of spatial dependence of measures falling in a spatial interval δ. The knowledge of δ allows to reduce the amount of the variance σ^2 to the averaged spatial variance $\sigma^2_{averaged}$ through the variance reduction function Γ^2:

$$\sigma^2_{averaged} = \Gamma^2 \cdot \sigma^2$$

In its simplest shape, it can be assumed (Vanmarcke, 1984) as:

$$\Gamma^2 = \frac{\delta}{L}\left(1 - exp\left(\frac{L}{\delta}\right)\right) if\ \frac{L}{\delta} > 1$$

where L is the spatial interval of interest.

Table 1. Autocorrelation function models related to the Scale of fluctuation shape.

Function name	Autocorrelation function model	Scale of fluctuation
Single exponential or Markov	$\rho(\Delta) = \exp(-\lambda\|\Delta\|)$	$\delta = 2/\lambda$
Cosine exponential	$\rho(\Delta) = \exp(-\lambda\|\Delta\|)\cos(\lambda\cdot\Delta)$	$\delta = 1/\lambda$
Second-order Markov	$\rho(\Delta) = (1+\lambda\|\Delta\|)\exp(-\lambda\|\Delta\|)$	$\delta = 4/\lambda$
Squared exponential or Gaussian	$\rho(\Delta) = \exp[-(\lambda\cdot\Delta)^2]$	$\delta = \sqrt{\pi}/\lambda$
Triangular	$\rho(\Delta) = 1 - \frac{\|\Delta\|}{\delta}$	–
Spherical	$\rho(\Delta) = 1 - 1.5\cdot\frac{\|\Delta\|}{\delta} + 0.5\cdot\left[\frac{\|\Delta\|}{\delta}\right]^3$	–

These functions are able to reconstruct the variability structure of random fields in space (Vessia and Russo, 2018). Then, to allow to use the random fields to describe the engineering geological model the simulation of random fields must be used. The first and most used method to do that is the Local Average Subdivision (LAS) by Fenton and Vanmarcke (1990).

Random field simulation is also used combined with the finite element method RFEM in order to propagate the EGM variability to geotechnical and structural project. Some applications can be read in Fenton and Griffith (2008).

*3.2.2 **Kriging Methods***

Kriging methods are a set of univariate and multivariate techniques pertaining to Geostatistics, which allow mapping the spatial distribution of quantitative georeferenced data, such as mechanical and hydraulic properties of soils, rocks, as well as contained fluids. These methods are based on the Regionalized Variable Theory (Matheron, 1973) that considers quantitative attributes of a certain domain (e.g., 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 they are more separated.

These geostatistical techniques provide a quantification of the uncertainty associated to the estimates in terms of Kriging variance, which in turn can provide a standard deviation value (i.e., with the same unit) or required confidence interval limits.

In simple words, values related to close measurements are likely to be more similar than they are more separated (quantified through the spatial autocorrelation). Such an approach resembles the random field theory provided that the regionalised variables can be seen as random variables and the semivariogram function is half the inverse of the autocorrelation function. Accordingly, the variogram models are similar to the autocorrelation ones although, in kriging methods the variograms can be nested, that is the final fitting model variogram can be composed of more than one simple variogram function. Hence, the fundamental assumption of this theory is that intrinsic spatial variation of a certain property can be considered as the sum of three components:

- a deterministic one, represented by a constant mean value or a trend;
- a spatially correlated random one;
- a residual non-correlated one, or white noise.

Under some Stationarity conditions, the semi-variogram function, or simply variogram can be defined and used to estimate subsoil properties throughout the whole investigated area, providing a continuous physically-based interpolation of measurements. A combination of variograms and cross-variograms named Linear Model of Co-regionalization-LMC, is used in multivariate approach when the dependence of spatial variability of more than 2 variables are taken into account. For further details about Geostatistics and Kriging methods, consider reading Gooveaerts (1997), Wackernagel (2003), Webster & Oliver (2007), and Chilès & Delfiner (2012). Besides the outstanding interpolation capabilities of Kriging methods, which are not the focus of this chapter, these geostatistical techniques provide a quantification of the uncertainty associated to the estimates in terms of Kriging variance, which in turn can provide a standard deviation value (i.e., with the same unit) or required confidence interval limits.

However, these indicators of uncertainty have physical meaning only when the statistical distribution of the studied variable is as Gaussian as possible, or at least symmetrical. Thus, sometimes it is appropriate to transform the observations into a normal (or standardized) one and work with them.

Of course, this transformation needs to be reversible, as uncertainty quantification is useful only if fully understandable and easily communicable (e.g., with the same unit of the variable, or as a percentage). To this purpose, there are specific algorithms able to perform an inversion, such as the Lognormal transformation, Normal Score transformation, the Box-Cox transformation, and Gaussian Anamorphosis.

Once calculated, the confidence interval limits, for instance 95 or 99%, of the standardized version of a subsoil property, they can be back-transformed so that two “boundary” values around the estimates can be obtained and used as measures of uncertainty.

Below, a selection of the Kriging methods, extract by the ASTM D5923-18 and its upcoming update:

1) Ordinary Kriging (univariate)

2) Simple Kriging (univariate)

3) Universal Kriging (multivariate)

4) Kriging with External Drift (multivariate)

5) Indicator (Co-)Kriging (univariate/multivariate)

6) Co-Kriging (multivariate)

7) (Multi-)Collocated Co-Kriging (multivariate)

Since in multivariate methods it is common to use data whose measurement devices provide values that refers of different "representative volumes", or "support", a Block Kriging approach is warmly suggested.

3.2.3 ***Stochastic Simulation methods***

Stochastic Simulation methods allow quantifying the uncertainty by providing a number of realizations, obtained using the spatial variability functions defined through the experimental measurements (i.e., 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. Further information about this method can eb found in Appendix 2.

Stochastic simulation methods take advantage of the same basic principles utilized by Random Field and Kriging approaches, which can be deepened through a literature review (Gooveaerts, 1997; Wackernagel, 2003; Webster & Oliver, 2007; Chilès & Delfiner, 2012).

Unlike Kriging methods, which have been developed to estimate a spatial distribution of variables, stochastic simulation techniques are devoted to assessing the spatial uncertainty. Another paramount difference is the capability of Stochastic Simulation methods to preserve the spatial variability, which is instead smoothed in Kriging approaches. For such a property, Stochastic Simulation is used also to obtain optimized maps of estimates.

Stochastic Simulation methods allow quantifying the uncertainty by providing a number of realizations, which are obtained using the spatial variability functions defined through the experimental measurements (i.e., variogram, or LMC). The 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.

It is worth pointing out that there are two main simulation approaches: the Conditional and the Non-conditional one. In the first case, the values (measurement) of the analyzed variable(s) are honoured; in the second case, they are not. For the sake of reliability of the EGOM, the Conditional approach is always preferable.

A selection of applicable Stochastic Simulation methods from the ASTM D5924-18 standard guide (and its upcoming update) are listed here:

1) Sequential Gaussian (Co-)Simulation (univariate/multivariate)

2) Sequential Indicator (Co-)Simulation (univariate/multivariate)

3) Turning Bands Simulation (univariate/multivariate)

4) Annealing

Since in multivariate methods it is common to use data whose measurement devices provide values referring to different "representative volumes", or "support", a Block approach is warmly suggested.

Furthermore, when the spatial interpolation of raw measurements is to be used to calculate derived hydromechanical properties by means of a specific equation, a thorough uncertainty propagation assessment must be undertaken. To this end the stochastic simulation method can be adopted.

4 Incorporation of data uncertainty in design parameters

When the parameters of the EGM become an input data for the design, the knowledge of parameter's uncertainty takes on all its importance. In design practice, two methods are used to manage EGM's parameter uncertainty: Safety Factors and Reliability-Based Design (RBD) methods.

The use of the Safety Factor follows a deterministic approach. The safety factor is the ratio between the Resistance or the Response of the Natural System represented by the EGM to the loads applied by the engineering structures or by the human activities stressing the Natural Environment. Such a factor has been calibrated empirically by technical experience. Thus, the values of the safety factors belong to the technical knowledge and legacy of the EGM performance under different structures gained over time. It is not calculated or estimated but empirically.

Reliability-based design (RBD) methods are currently recognized as the preferred approach in technical codes worldwide instead of Safety Factor. Simplified RBD methods such as the Load and Resistance Factor Design (LRFD) with constant partial factors has now been used only for the coded design limit states. These factors have replaced the safety factors and can be calculated according to fixed probability value of failure accepted worldwide. The Eurocodes, that include all the European Nations, implement reference values for the partial safety factors, although each country can customise these values.

In the last years, the International Standard on reliability approaches for structures ISO 2394 (2015) has been issued to "*enable the possibility to regulate, verify, and document the adequate safe performance of structures and also to consider them in a broader sense as part of societal systems. The International Standard provides for approaches at three levels, namely the following:*

- *risk informed;*
- *reliability based;*
- *semi-probabilistic.*

The methodical basis for this edition of ISO 2394 is described in the Probabilistic Model Code (JCSS, 2001) and Risk Assessment in Engineering - Principles, System Representation and Risk Criteria (JCSS, 2008) by the Joint Committee on Structural Safety (JCSS), and EN 1990 (2007)", to which this guideline suggests to refer.

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Annexes

ANNEX A - CHECKLIST #1 - For self-checking a predominately ROCK EGM

ANNEX B - CHECKLIST #2 - For self-checking a predominately SOILS EGM

ANNEX A

CHECKLIST #1 - For self-checking a predominately ROCK EGM (Dematteis et al., 2023)

Step 1 - Verification of the characteristics of the conceptual model and its coherence - Predominately ROCK EGM

EGM FEATURE OR CONDITION	EXISTENCE	COMPLEXITY	COHERENCY (CONSISTENCY?)
	Y / N	Simple / Complex	Is this feature or condition consistent with the available data and with other features of the model? (Y / N)
Lithostratigraphic complexity of Formations			
unconformities/disconformities			
cross-cutting changes / complications (dykes, sills etc)			
transgressive changes (consistency/non-stationarity?)			
interdigitated units (extent/definition)			
mixed volcaniclastics and layered volcanics			
weathering profile (depth, anomalies)			
solutioning (minor/major; structural or matrix)			
rockmass & rock material properties consistent with defined lithostratigraphy			
…			
Tectonics (current & palæo regimes)			
deformation history:			
defined sequence of **ductile deformation phases** ((folds, shear zones and kinematics)			
defined sequence of **brittle deformation phases** (faults, damage zones, joints, veins & kinematics, etc.)			
structural pattern & fabric:			
consistent structural patterns (at all scales faults to joints) conforming to deformation history			
match between faults shear sense & site stress state			
sufficiently defined continuity of structures representative & relevant to model user objectives			
structure strength properties consistent with defined fault systems (incl. veins and joints)			
structure spacing & frequency representative at relevant model scale (incl. veins and joints)			
overprint issues / complexities			
metamorphism - contact / pervasive (regional)			
alteration influence (hydrothermal etc)			
saprolite development			
…			
Geomorphology			
shallow slides (debris flows, rockfalls, etc.)			
deep gravitational slope deformation			
evolutionary trend of rivers, in erosion or deposition			
…			
Hydrogeology			
shallow acquifer, free surface groundwater			
deep aquifer, artesian waters, pressurized waters			
geothermal flow systems			
karst systems			
perched systems / compartmentalized			
…			
Man-Made Complexities			
Previous Mining			
Previous Infrastructure			
Ongoing Activities/Disturbance			
…			

Step 2 - Ovedall Reliability Check of conceptual EGM

Are there any features or conditions encountered in the observational model that are not anticipated in the conceptual model ?

YES → Review conceptual model & Checklist. Seek Independent check if needed. Modify EGM as necessary. Consider need for additional investigations.

NO ↓

Are there any features or conditions anticipated in the conceptual model that have not so far been encountered?

YES → List possible missing features, consider further targeted investigations, and retain features as possible conditions on Project Risk Register.

NO →

Adequate Self Check Achieved. Proceed to Final Verification of EGM through Independent Peer Review

ANNEX B

CHECKLIST #2 - For self-checking a predominately SOILS EGM (Dematteis et al., 2023)

Step 1 - Verification of the characteristics of the conceptual model and its coherence - Predominately SOIL EGM

EGM FEATURE OR CONDITION	EXISTENCE	COMPLEXITY	COHERENCY (CONSISTENCY?)
	Y / N	Simple / Complex	Is this feature or condition consistent with the available data and with other features of the model? (Y / N)
Lithostratigraphic complexity of Formation Soils			
sensitive clays or metastable silts			
lateral heterogeneity (e.g. gravel/sand/clay, channels of gravel and sand in more fine materials, etc..)			
interdigitated deposits (fans, braided channels)			
erosional unconformities or disconformities			
weathering complications - duricrusts			
frozen zones / ice lensing			
anomalous zones / depressions			
…			
Soil/Bedrock Interface			
buried valleys			
glacial scour channels			
karst solutioning			
gravel infills			
weathered rockmass			
saprolitic zone			
sheeting joints / dislodged blocks			
sinkholes/settlement issues			
…			
Geomorphology			
shallow landslides (debris flows, mudflows etc.)			
rotational slide zones / deep seated movements			
evolutionary trend of rivers - erosional or depositional			
…			
Hydrogeology			
shallow acquifer, free surface groundwater			
deep aquifer, artesian waters, pressurized waters			
perched water tables			
contaminanted flow systems			
…			
Man-Made Complexities			
Previous Excavations			
Fill Deposits (clean / contaminated)			
Previous Infrastructure			
Ongoing Activities/Disturbance			
…			

Step 2 - Ovedall Reliability Check of conceptual EGM

Are there any features or conditions encountered in the observational model that are not anticipated in the conceptual model ?

YES → Review conceptual model & Checklist. Seek Independent check if needed. Modify EGM as necessary. Consider need for additional investigations.

NO ↓

Are there any features or conditions anticipated in the conceptual model that have not so far been encountered?

YES → List possible missing features, consider further targeted investigations, and retain features as possible conditions on Project Risk Register.

NO ↓

Adequate Self Check Achieved. Proceed to Final Verification of EGM through Independent Peer Review