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

Written by Antonio Dematteis and Giovanna Vessia on June 7, 2021

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1. Commission chairpersons and members

Chair: Antonio Dematteis, email: antonio.dematteis@lombardi.group
Co-chair: Giovanna Vessia, email: g.vessia@unich.it
Member: Wayne Barnett, email: wbarnett@srk.com
Member: Trevor Carter, email: tcarter@tgcgeosolutions.com
Member: Diego Di Curzio, email: tcarter@tgcgeosolutions.com
Member: Brian Irsch, email: birsch@schnabel-eng.com
Member: Daniele Pedretti, email: daniele.pedretti@unimi.it

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 workshop to be held in Athens on October 8, 2021 (see section 5).

2. Relaunch of the Commission 28

On 2020 a relaunch program has been implemented and sent to IAEG president and general secretary to reactivate the C28.

The C28 was established on 2009 by the Council meeting, on the proposal of Antonio Dematteis, who was at that time the chair of an IAEG national working group in Italy, working on a Guideline on the Reliability Assessment of the Geological Model.

On 2012 the Guideline on the Reliability Assessment of the Geological Model was published by the Italian chapter of IAEG on his website. The Guideline was also translated into English by the Italian chapter, in order to be used within the C28 with the aim of developing it with international standards.

On 2014 the C28 organized the workshop "Facing with Geological and Geotechnical Uncertainty" during the XII International IAEG Congress in Turin.

Since then, the C28 has not produced further initiatives or documents, mainly because has not managed to develop an adequate international network.

However, the topic treated by the C28 is still of great importance and interest in the engineering geology applied to the market of large civil works. The reliability assessment of geological and geotechnical uncertainties is increasingly required to improve the quality and safety in design, contractual management, the risk sharing management and the financial management during planning, construction, and maintenance phases in all major civil works projects.

A new condition is being created to relaunch the C28, which meets a real need for further study and development of this specific field of the engineering geology. As a matter of fact, quantitative information to build geo-engineering subsoil models come from several new devices and technologies like satellite probes, multiple types of aerial data acquisition systems, indirect geophysical investigations, underground coring, logging and testing probes and point diffuse monitoring networks. They all contribute to enrich geo-datasets of tens of parameters that are stored in large databases commonly managed through GIS-based platforms and software interfaces to numerical 3D terrain models. Nonetheless, the abundance of data taken at different location and time provides a new challenge for scientists and professionals in geo-engineering that is integrating diverse spatial and temporal datasets to describe the present and changing conditions of the Earth at different reliability levels. Hence, the data fusion perspective put geologists and geo-engineers in front of a new quantitative perspective that cannot avoid the geological judgement but needs an additional sensibility and awareness to information technologies, machine learning, geostatistical and artificial intelligence methodologies.

To this end the C28 will work to spread out this renewed approach to geo-engineering modelling towards the civil engineering designing by means of Conferences, Reports, and continuous learning activities such as summer and winter schools, workshops, webinars, etc even joint to C25 "Use of engineering geological models". The cooperation with the ISSGME society especially with TC304 (Engineering Practice of Risk Assessment & Management) and TC309 (Machine Learning) will be another crucial point of the new C28 chair and its members' activity.

3. Minute of the C28 email Meeting held from 14 to 18 Decembre 2021

Agenda of the meeting

See the Appendix A.

Past and ongoing members activities (conferences, short courses, meetings and keynotes, publications, designs and best practices)

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Future activities (conferences, short courses, meetings and keynotes)

Conferences

3rd European Regional Conference of IAEG – 7-10 October 2021, Athens on 8th IAEG Commissions Meeting. C28 will have a meeting alone and another meeting joined to C25. Please, C28 members are all invited to come and submit an abstract at the website www.euroengeo2020.org.

Guidelines to be issued

Joined to C25, the publication "Guidelines for the Development and Application of Engineering Geological Models on Projects". C28 will contribute with but not limited to Chapter 7. Whoever has already material to be shared can send it yet. There is not a fix deadline, but the end of the email meeting could be a first step.

Comments

(**Trevor about the Reliability of Numerical Modelling**) Although the software available today is worlds better than it was even a decade ago, and most models look very impressive when completely built, the credibility of many computer-generated EGMs falls far short of the mark when interrogated in the detail needed to build engineering projects in an actual rock mass. Adequate calibration and verification is often lacking – and its discouraging that this seems to be almost in inverse proportion to the impressiveness of the finished models.

I published the below diagram in a recent Open Pit Slope Stability conference to try to get folks to focus more towards demonstrating reliability in compiled EGMs – and might suggest that a chapter in this TOC be devoted entirely to "RELIABILITY" – which, to my mind, is different from Verification and Calibration, which is well covered in the current TOC.

TABLE 1: Suggested Scale for Ranking Reliability/Confidence and Uncertainty in Structural Feature and Rock Mass Characterization Domaining Definition

CIM NI-43.101 Definition Terminology			Suggested Structural Fabric Definition Terminology		
CONFIDENCE LEVEL	Mineral Resource (Geological Concept)	Mineral Reserve (Economic Asset)	Suggested Feature Shading	CONFIDENCE LEVEL	Suggested Structural Definition Equivalence
			2%	Postulated	Suggested from limited geologic fabric evaluation, eg from Photo-Lineament position only
Inferred	Estimated from limited geologic evidence and sampling; sufficient to imply but not verify existance		5%	Inferred	Estimated from limited geologic evidence, maybe drill intersects and mapping; sufficient to imply but not verify existance
			10%	Possible	Estimated with impoved confidence of Structural Mechanism and Fabric based on drill intersects and mapping; sufficient to verify existance, but not geometry
Indicated	Estimated, but with sufficient confidence to allow Pre-feasibility economic estimation		25%	Indicated	Estimated, but with sufficient confidence to identify connections from point to point along structure, sufficient to generate a reasonably reliable fault wireframe solid
		Probable	40%	Probable	Adequately Defined, sufficient to establish geometry, process zone dimensions, curvature and shear sense; sufficient to construct reliable wireframe solid
Measured	Defined with sufficient precision to support detailed mine planning		60%	Measured	Sufficiently defined by multiple observation points to delineate Slip Mechanism; field measurements of breccia and gouge widths; multiple intersections in DH's and outcrop
		Proven	85%	Proven	Fully defined from multiple intersections at outcrop and in drillholes to delilneate full fault characteristics, with sufficient precision to define offset and full shear sense

(**Dematteis about the Rules of GBR**) Another topic related to point 1 is the professional experiences on the application of the Geological Baseline Report (GBR) in tunnel projects. I am currently working on a hydroelectric project in Australia, which is called Snowy 2.0 (https://www.snowyhydro.com.au/snowy-20/about/). The contract is an EPC with a GBR and a risk sharing criterion for geohazards regulated in the GBR. The application of the GBR certainly has very positive aspects for the cost management of projects since it defines a shared baseline between the owner and the contractor. On the other hand, it could be a negative element when it presents a limit to the dynamic evolution of the geological model during the development of the project and the excavation. The change in the geological Baseline (GBR) is a contractual issue, that can inhibit technical-geological updating of the current geological model. The parties never want to change the GBR to avoid renegotiations. However, new geotechnical investigations may improve the reliability of the geological model and sometimes also require modifications to the model. This topic seems interesting to me and I think it deserves further discussion.

(Barnett about the model development workflow) The most relevant is that (contribution has been attached):

1) 3-D geological model interpretation starts at the rock face during data collection. This is an important part of the model development process and does not seem to be addressed.

2)In most practical scenario developing or operating projects in the world, the model development workflow should be represented as a cyclical workflow. Each cycle starting with new data and improved interpretation. The chapter headings do not suggest that this has been acknowledged.

(Pedretti) Bianchi and Pedretti (2017,2018) developed an approach called "geological entropy". In short, geological entropy is based on Shannon's entropy and allows measuring the spatial order of hydrofacies in porous media, mainly through the spatial variation of the hydraulic conductivity (K) as a consequence of the spatial variation of the geological bodies. Geological entropy can be applied to any kind of heterogenous media. In hydrogeological applications, it can measure the spatial order of unconsolidated or fractured aquifers (Pedretti and Bianchi 2018, Pedretti 2020), under saturated or unsaturated conditions.

Metrics derived from the geological entropy concepts include the entrogram scales and the relative entropy at the scale of the single grid cell (on which the variation of K is interpolated, e.g. using TPROGS, variogram-based simulations or any other method, including deterministic ones). In Bianchi and Pedretti (2017, 2018), these metrics were successfully adopted to demonstrate that the scale of solute transport moments (e.g. the temporal moments of the breakthrough curves during tracer tests) were very well correlated (R2>.9) to empirical functions describing the change in spatial order of the porous media in which the solutes moved.

A general conclusion of Bianchi and Pedretti (2017,2018) model analyses was the following:

- The more "ordered" a system is, the more prone it is to develop preferential flow and channeled transport.
- The more "disordered" (or chaotic), the more well-mixed the system is, leading to more homogenized solute patterns.

Geological entropy metrics can support risk indicators of solute contamination under uncertainty. If a system is prone to preferential flow and channelled transport, it may be also characterized by a high heterogeneity and uncertainty to determine the spatial arrangement of hydrofacies. In typical applications the amount of (hydro)geological data is usually limited and also sparsely distributed in space (e.g. pumping tests performed in existing boreholes) and time (e.g. limited historical time series). As such, a "epistemic" uncertainty in highly heterogeneous systems virtually always exist.

It is particularly difficult to identify well-connected coarse-grained materials or fractured in aquifers (Pedretti et al 2013, Molinari et al 2015), which are usually where solute tends to funnel and migrate. As such, metrics suggesting a "spatially ordered" system should also warn the decision makers about the difficulties to deal with solute contamination in aquifers, particularly if deterministic models are adopted to support the decisions.

(Vessia about the contribution to C25 Guidelines) Working on random field theory and the way to describe the spatial variability of soils, a table of possible scales of fluctuations have been collected by Dr. Di Curzio and I to be implemented (with the contribution of other colleagues) in the updated version of Eurocode 7. The table is here attached (TabA file). I think, anyway, that using the geostatistical tools - based on the random field theory - it is useful for estimate the uncertainties related to 3d geological models.

Thus, related to the point 2 of the Agenda, I will summarize theoretical bases of Geostatistics and some applications for contributing to Cap. 7.1 and 7.2.

(Di Curzio about the contribution toC25 Guidelines) As recently advanced geostatistical approaches are my main interest from a methodological point of view, I will collaborate with Giovanna for sections 7.1 and 7.2.

A Special Issue On Boeg

A special issue on Bulletin of Engineering Geology and the Environment (BOEG) could be discussed and organized after the Conference in Athens, to shed light on new approaches to the "Reliability quantification of the geological model in large civil engineering projects".

4. Collaboration with C25

IAEG-C25: Use of engineering geological models. https://www.iaeg.info/commission-25-use-of-engineering-geological-models/.

At the end of 2020, a collaboration with the C25 began, in the context of the drafting of the "**Guidelines for the Development and Application of Engineering Geological Models on Projects**".

In January 2021, C28 members sent to Fred Baynes the C28' contribution to the Guidelines. Currently this contribution is being analysed and integrated into the guideline by Fred and Steve Parry. A revision of the document by the members of the C28 is planned, which will take place within the times established by the chairs of the C25.

The contributions sent to C25 are attached in Appendix B.

5. Future activities - C28 workshop in Athens, oct. 2021

C28 workshop Athens2021

C28 has planned a workshop on October 8 at the 3rd European Regional Conference of IAEG – 7-10 October 2021, Athens. The DISCUSSION TOPIC is the one that has been selected by the commission members after the email-meeting mentioned in section 3, that will be the topic for the year 2021 and 2022 as well.

The topic is: **3D geological modelling development: methods to assess its reliability**.

At the conference in Athens, C28 members will discuss their past experiences on this topic (or related one) to introduce the critical points to be discussed and developed.

Concerning 2021 activity, C28 members are planning to work in small groups (even involving those members of C25 who would like to) to try to use some approaches that can give an idea of the reliability of 3D geological models on case studies to be chosen. Then, the outcomes of this work (it should take almost a year or 6 months) will be proposed to a larger audience by a Special Issue on BOEG (or elsewhere) and then will be also contacted code offices (i.e., ISO, ASHTOO, etc) to be transformed in guidelines for infrastructure and structure designing.

MLRA 2021

TC304/TC309 Joint International Symposium – MLRA2021 - Machine Learning & Risk Assessment in Geoengineering will be held in Wroclaw from 25 to 28 October 2021 (http://www.MLRA2021.pwr.edu.pl). C28 chairperson Giovanna Vessia is involved as a conference chair of the MIRLA 2021 and will report the results to the C28 workshop.

6. Commission meetings and publications

- Guideline on the reliability assessment of the geological model. The Italian group of IAEG, September 2007, http://www.iaeg.it/comm_opere_sott.htm.
- On 2012 the Guideline on the Reliability Assessment of the Geological Model was translated into English.
- On 2014 the C28 organized the workshop "Facing with Geological and Geotechnical Uncertainty" during the XII International IAEG Congress in Turin.

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

☐ Excellent ☒ Good ☐ Fair ☐ Poor

8. Appendices

A. Agenda of the C28 email Meeting held from 14 to 18 December 2021.

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

Appendix A

Agenda of the C28 email Meeting held from 14 to 18 December 2021.

Agenda for 1st IAEG C28 Meeting
(Email meeting)

Date: Dec 14-18, 2020
Time: Meeting starts at 8.00 a.m on Dec. 14th and closes at 07:00 p.m. (GMT+1, Italy), Dec 18, 2020.

Please email updates on each item to Giovanna Vessia (iaeg.c28@gmail.com) for compilation

1. **Past Activities (conferences, short courses, meetings and keynotes, publications, designs and best practices)**

   - The C28 members could send info about the most relevant activities developed in the year 2020 or earlier concerning the common topic and objectives of the C28. The bibliography and designing documents (if publishable) and the pdf files from the members of their past studies and consulting services could be added to the C28 web page in order to let the readers acquaintance to the topics investigated by the C28.

2. **Future activities (conferences, short courses, meetings and keynotes)**

   - CONFERENCES
     - 3rd European Regional Conference of IAEG – 8-12 April 2021, Athens (Chairs: Vassilis P. Marinos, Constantinos Loupasakis & Charalampos Saroglou)

       On 8th IAEG Commissions Meeting. C28 will have a meeting alone and another meeting joined to C25. Please, c28 members are all invited to come and submit an abstract at the website www.euroengeo2020.org

   - GUIDELINES TO BE ISSUED
     Joined to C25, the publication "Guidelines for the Development and Application of Engineering Geological Models on Projects". C28 will contribute with but not limited to Chapter 7. Whoever has already material to be shared can send it yet. There is not a fix deadline, but the end of the email meeting could be a first step.

   - A SPECIAL ISSUE ON BOEG
     A special issue on Bulletin Of Engineering Geology and the Environment (BOEG) could be discussed and organized after the Conference in Athens, to shed light on new approaches to the "Reliability quantification of the geological model in large civil engineering projects".

3. **Other business**

   - To find out possible members interested in the topics of C28 and available to share a "short" but "fruitful" time to discuss topics about strategies and methods to quantify and eventually reduce the uncertainty in geological modelling for engineering designing.

Appendix B

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

Daniele Petretti

1.1 An aspect of Managing EGM Uncertainty

Components	Contributors
• Please summarise your thoughts on the topic • Keep it brief and to the point • No learned discussions • Just simple advice as to good practice	Fred Baynes

1.2 Another aspect of Managing EGM Uncertainty

Components	Contributors

THE FOLLOWING TABLE COULD BE INTEGRATED AS EXAMPLES OF SECTION 7.2 (K TURNER / J DONG).

In the document I was given, towards the end of the table titled 7.2 "Identifying and Documenting Uncertainty Components", K Turner indicated the following component: "Traditional geostatistical procedures are often supplemented by the confidence index, quantification of transition probabilities of categorical variables, metrics based on information entropy, or multiple point statistical methods." Moreover, the text states that "Information entropy has been used to quantify uncertainty of geological models (Wellmann and Regenauer-Lieb 2012; Bianchi et al. 2015)."

I totally agree with that statement. Actually, that Bianchi (Marco) is a close colleague of mine. We have been extensively working on the application of information theory on solute transport in heterogenous media. Two of our main contributions are found here: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016WR020195; https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018WR022827.

In this sense, I hope that what follows can complement the chapter.

EXAMPLE	Contributor
Bianchi and Pedretti (2017,2018) developed an approach called "geological entropy". In short, geological entropy is based on Shannon's entropy and allows measuring the spatial order of hydrofacies in porous media, mainly through the spatial variation of the hydraulic conductivity (K) as a consequence of the spatial variation of the geological bodies. Geological entropy can be applied to any kind of heterogenous media. In hydrogeological	Daniele Pedretti

EXAMPLE	Contributor
applications, it can measure the spatial order of unconsolidated or fractured aquifers (Pedretti and Bianchi 2018, Pedretti 2020), under saturated or unsaturated conditions. Metrics derived from the geological entropy concepts include the entrogram scales and the relative entropy at the scale of the single grid cell (on which the variation of K is interpolated, e.g. using TPROGS, variogram-based simulations or any other method, including deterministic ones). In Bianchi and Pedretti (2017,2018), these metrics were successfully adopted to demonstrate that the scale of solute transport moments (e.g. the temporal moments of the breakthrough curves during tracer tests) were very well correlated (R^2>.9) to empirical functions describing the change in spatial order of the porous media in which the solutes moved. A general conclusion of Bianchi and Pedretti (2017,2018) model analyses was the following: • *The more "ordered" a system is, the more prone it is to develop preferential flow and channelled transport.* • *The more "disordered" (or chaotic), the more well-mixed the system is, leading to more homogenized solute patterns.* Geological entropy metrics can support risk indicators of solute contamination under uncertainty. If a system is prone to preferential flow and channelled transport, it may be also characterized by a high heterogeneity and uncertainty to determine the spatial arrangement of hydrofacies. In typical applications the amount of (hydro)geological data is usually limited and also sparsely distributed in space (e.g. pumping tests performed in existing boreholes) and time (e.g. limited historical time series). As such, a "epistemic" uncertainty in highly heterogeneous systems virtually always exist. It is particularly difficult to identify well-connected coarse-grained materials or fractured in aquifers (Pedretti et al 2013, Molinari et al 2015), which are usually where solute tends to funnel and migrate. As such, metrics suggesting a "spatially ordered" system should also warn the decision makers about the difficulties to deal with solute contamination in aquifers, particularly if deterministic models are adopted to support the decisions. References: Bianchi M, Pedretti D. 2017. Geological entropy and solute transport in heterogeneous porous media. Water Resources Research, 53(6): 4691–4708. https://doi.org/10.1002/2016WR020195. Bianchi M, Pedretti D. 2018. An Entrogram-Based Approach to Describe Spatial Heterogeneity With Applications to Solute Transport in Porous Media. Water Resources Research, 54(7): 4432–4448. https://doi.org/10.1029/2018WR022827. Molinari A, Pedretti D, Fallico C. 2015. Analysis of convergent flow tracer tests in a heterogeneous sandy box with connected gravel channels. Water Resources Research, 51(7): 5640–5657. https://doi.org/10.1002/2014WR016216. Pedretti D, Bianchi M. 2018. Reproducing tailing in breakthrough curves: Are statistical models equally representative and predictive? Advances in Water Resources, 113: 236–248. https://doi.org/10.1016/j.advwatres.2018.01.023. Pedretti D, Bianchi M. 2019. Preliminary results from the use of entrograms to describe transport in fractured media. Acque Sotterranee - Italian Journal of Groundwater. https://doi.org/10.7343/as-2019-421. Pedretti D, Marco Masetti, Giovanni P. Beretta, Mariangela Vitiello. 2013. A Revised Conceptual Model to Reproduce the Distribution of Chlorinated Solvents in the Rho Aquifer (Italy). Groundwater Monitoring & Remediation, 33(3): 69–77. https://doi.org/10.1111/gwmr.12017.	

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Antonio Dematteis

Another topic related to point 1 is the professional experiences on the application of the Geological Baseline Report (GBR) in tunnel projects. I am currently working on a hydroelectric project in Australia, which is called Snowy 2.0 (https://www.snowyhydro.com.au/snowy-20/about/). The contract is an EPC with a GBR and a risk sharing criterion for geohazards regulated in the GBR. The application of the GBR certainly has very positive aspects for the cost management of projects, since it defines a shared baseline between the owner and the contractor. On the other hand it could be a negative element when it presents a limit to the dynamic evolution of the geological model during the development of the project and the excavation. The change in the geological Baseline (GBR) is a contractual issue, that can inhibit technical-geological updating of the current geological model. The parties never want to change the GBR to avoid renegotiations. However, new geotechnical investigations may improve the reliability of the geological model and sometimes also require modifications to the model. This topic seems interesting to me and I think it deserves further discussion.

Trevor Carter

I fully support this initiative, and can contribute to many of the sections of the outline TOC, most pertinently to §2; 4, parts of 6, specifically §6.2, parts of 7, but most significantly probably to 8 10 and 12, as most of my time and effort as a reviewer (not a builder, these days), seems to be focussed to getting EGMs to be reflective of reality – which I'm sorry to say, many are not.

Although the software available today is worlds better than it was even a decade ago, and most models look very impressive when completely built, the credibility of many computer generated EGMs falls far short of the mark when interrogated in the detail needed to build engineering projects in an actual rockmass. Adequate calibration and verification is often lacking – and its discouraging that this seems to be almost in inverse proportion to the impressiveness of the finished models.

I published the below diagram in a recent Open Pit Slope Stability conference to try to get folks to focus more towards demonstrating reliability in compiled EGMs – and might suggest that a chapter in this TOC be devoted entirely to "RELIABILITY" – which, to my mind, is different from Verification and Calibration, which is well covered in the current TOC.

TABLE 1: Suggested Scale for Ranking Reliability/Confidence and Uncertainty in Structural Feature and Rock Mass Characterization Domaining Definition

CIM NI-43.101 Definition Terminology			Suggested Structural Fabric Definition Terminology		
CONFIDENCE LEVEL	Mineral Resource (Geological Concept)	Mineral Reserve (Economic Asset)	Suggested Feature Shading	CONFIDENCE LEVEL	Suggested Structural Definition Equivalence
			2%	Postulated	Suggested from limited geologic fabric evaluation, eg from Photo-Lineament position only
Inferred	Estimated from limited geologic evidence and sampling; sufficient to imply but not verify existance		5%	Inferred	Estimated from limited geologic evidence, maybe drill intersects and mapping; sufficient to imply but not verify existance
			10%	Possible	Estimated with impoved confidence of Structural Mechanism and Fabric based on drill intersects and mapping; sufficient to verify existance, but not geometry
Indicated	Estimated, but with sufficient confidence to allow Pre-feasibility economic estimation		25%	Indicated	Estimated, but with sufficient confidence to identify connections from point to point along structure, sufficient to generate a reasonably reliable fault wireframe solid
		Probable	40%	Probable	Adequately Defined, sufficient to establish geometry, process zone dimensions, curvature and shear sense; sufficient to construct reliable wireframe solid
Measured	Defined with sufficient precision to support detailed mine planning		60%	Measured	Sufficiently defined by multiple observation points to delineate Slip Mechanism; field measurements of breccia and gouge widths; multiple intersections in DH's and outcrop
		Proven	85%	Proven	Fully defined from multiple intersections at outcrop and in drillholes to delilneate full fault characteristics, with sufficient precision to define offset and full shear sense

Carter, T. G. (2018). "Suggested Standards for Improving Structural Geological Definition for Open Pit Slope Design" Proc. Slope Stability 2018 - International Symposium on Slope Stability in Open Pit Mining & Civil Engineering, XIV Congreso, Mineria-2018 (IERM), Sevilla, Paper #102, 26pp (published by Australian Centre for Geomechanics).

Giovanna VESSIA and Diego DI CURZIO

Managing EGM Uncertainty

Uncertainties in soil and rock modeling stem from the natural spatial variability of natural materials and the impossibility of measuring their properties at every point. The first uncertainty is called *Inherent (natural) variability* and the second *epistemic uncertainty*. In addition, other uncertainties affecting measured properties/parameters are due to the *testing devices* and the *transformation models* between the measured properties and the design variables. The uncertainties related to testing devices are systematic and cannot be removed, as well as the inherent variability and the transformation uncertainty. This latter, however, depends on the transformation model and variables and can be quantified by propagating the original uncertainty affecting the measured variables. Only the epistemic uncertainty can be reduced by increasing the point of measures. In order to account for the spatial variability structure of soils and rocks' properties, Geostatistical tools can be adopted. Geostatistics consists of a large family of spatial estimation techniques based on the regionalized variable theory (Matheron, 1973).
Three methods out of the large family of Geostatistical methods used in presence of random fields are herein briefly described:

1) the Ordinary Kriging (OK), a stationary univariate technique.
2) the Multi-Collocated Co-Kriging (MCCK), a stationary multivariate method
3) the Intrinsic Random Function of k order (IRF-k), a non-stationary univariate

All of the preceding methods allow reconstructing the spatial variability structure of original and derived variables (random fields), independently from their distributions. Additionally, the second method enables to build 3D data models by using datasets measured at different points in the space. This latter is a helpful numerical method to fuse different data sources. Some applications can be found in Vessia et. al (2020a,b)

1. Ordinary Kriging

The Ordinary Kriging (OK) requires the assumption of stationarity, i.e. the covariance between any two locations depends only on the distance between observations but not on their geographic locations. The semi-variance (γ) at a given distance h – named lag – is estimated as the average of the squared differences between all observations (Z) separated by the same lag:

$$\gamma(\mathbf{h}) = \frac{1}{2N(\mathbf{h})}\sum_{i=1}^{N(\mathbf{h})}[z(\mathbf{x}_i) - z(\mathbf{x}_i + \mathbf{h})]^2 \quad (1)$$

where N(**h**) is the number of pairs of observations spaced h. The semi-variance γ plotted versus distance h is called semi-variogram. Based on the semi-variogram model, Ordinary Kriging can be performed. The semi-variogram model is fundamental to choose the weights λ_i for interpolation and for evaluating the uncertainties of the estimates. Kriging estimator $Z^*(\mathbf{x}_0)$ of $Z(\mathbf{x}_0)$ at an unsampled point x_0 is given by a linear combination of the observations at the points $\mathbf{x}_i$:

$$Z^*(\mathbf{x}_0) = \sum_{i=1}^{N}\lambda_i \cdot Z(\mathbf{x}_i) \quad (2)$$

where λ_i are weights that are chosen in such a way that the estimator is unbiased:

$$E[Z^*(\mathbf{x}_0) - Z(\mathbf{x}_0)] = 0 \quad (3)$$

and the estimation variance is minimized. Using a Lagrangian multiplier μ, the minimization of the estimation variance under the constraint of unbiasedness yields a set of N+1 linear equations:

$$\begin{cases} \sum_{j=1}^{N} \lambda_i \cdot \gamma(\mathbf{x}_i, \mathbf{x}_j) + \mu = \gamma(\mathbf{x}_i, \mathbf{x}_0) & i = 1, \ldots, N \\ \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots & \\ \sum_{j=1}^{N} \lambda_i & \end{cases}$$

(4)

From which the λ_i and μ can be calculated. The estimation variance is then given by Eq. (5) and represents a measure of uncertainty in the prediction of x_0:

$$\sigma^2(\mathbf{x}_0) = \mu + \sum_{i=1}^{N} \lambda_i \cdot \gamma(\mathbf{x}_i, \mathbf{x}_0) \tag{5}$$

where $\gamma(\mathbf{x}_i,\mathbf{x}_j)$ and $\gamma(\mathbf{x}_i,\mathbf{x}_0)$ are the semi-variances between the observed locations x_i and x_j and between the observed location x_i and the interpolated location x_0, respectively. Advantages of using Ordinary Kriging have been pointed out by Castrignanò (2011): (1) the estimated value is the most precise among the linear interpolators; (2) OK also calculates estimation variance; (3) estimation variance depends only on the semi-variogram model and on the configuration of the data locations with respect to the interpolated point; (4) OK is an exact interpolator because the estimated values are identical to the observed values at the sample locations. However, OK is an optimal and unbiased estimator only if the variogram model correctly interprets the spatial variability structure of data.

2. Multi-Collocated Co-Kriging

This stationary multivariate geostatistical tool is based on the Linear Model of Coregionalization (LMC), developed by Journel and Huijbregts (1978), that considers the studied variables as a result of the same independent physical processes. The LMC consists of direct variograms and cross-variograms (Wackernagel, 2003). The direct variogram is the spatial dependency function of the variance of a given random function Z, related to a separation vector, named lag ($\mathbf{h}$), while the cross-variogram ($\gamma_{z_i,z_j}(\mathbf{h})$) is the measurement of the joint variability of two variables $z_i(\mathbf{x}_\alpha)$ e $z_j(\mathbf{x}_\alpha)$ (Webster and Oliver, 2007; Castrignanò, 2011; Chilès and Delfiner, 2012). The LMC is defined as follows:

$$\gamma_{z_i,z_j}(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{\alpha=1}^{N(\mathbf{h})} \{[z_i(\mathbf{x}_\alpha) - z_i(\mathbf{x}_\alpha + \mathbf{h})][z_j(\mathbf{x}_\alpha) - z_j(\mathbf{x}_\alpha + \mathbf{h})]\} \quad \text{with } \alpha = 1, \ldots, N(\mathbf{h})$$

(6)

where x_α is the location of the sampling point. The LMC is adapted to the $n(n+1)/2$ experimental direct variograms and cross-variograms of the considered variables by a linear combination of N_S basic variogram functions $g^u(\mathbf{h})$:

$$\gamma_{ij}(\mathbf{h}) = \sum_{u=1}^{N_S} b_{ij}^u \, g^u(\mathbf{h}) \quad \text{with } i, j = 1, \ldots, n$$

(7)

where $\gamma_{ij}(\mathbf{h})$ are the variogram models, u is the spatial scale and b_{ij}^u are the partial sill of the spatial structure $g^u(\mathbf{h})$. Using the matrix notation, the previous equation can be written as:

$$\mathbf{\Gamma}(\mathbf{h}) = \sum_{u=1}^{N_S} \mathbf{B}^u \, g^u(\mathbf{h})$$

(8)

where $\mathbf{\Gamma}(\mathbf{h})$ is a matrix, whose diagonal elements are the direct variograms, while the non-diagonal elements are the cross-variograms, and $\mathbf{B}^u$ is the Coregionalization Matrix, that is a symmetric matrix of the LMC coefficients b_{ij}^u.

In Multi-Collocated geostatistics, the LMC is modeled also considering secondary auxiliary exhaustive variables in the whole domain, reducing the computation time and improving considerably the primary variable estimation and their spatial relationship assessments, especially when the primary variable sample size is small (Andrade and Stigter, 2013; Castrignanò et al., 2012, 2015; Di Curzio et al.,2019). The Multi-Collocated Co-Kriging (MCCK) uses the linear estimator ($z^*_{i_0}(\mathbf{x}_0)$), described by the following equation:

$$z^*_{i_0}(\mathbf{x}_0) = \sum_{i=1}^{n}\sum_{\alpha=1}^{n_i}\lambda_\alpha^i\, z_i(\mathbf{x}_\alpha) \quad \text{with } i = 1, \dots, n \tag{9}$$

where $\mathbf{x}_0$ is the position where primary variables are estimated, and $z_i(\mathbf{x}_\alpha)$ are the measured values in the neighborhood.

The MCCK system of equations is obtained by imposing the optimal unbiased estimation condition. It consists of $\sum_{i=1}^{n} n_i + n$ linear equations and $\sum_{i=1}^{n} n_i + n$ variables, represented by the weights λ_β^j and n Lagrangian coefficients μ_i:

$$\begin{cases} \sum_{j=1}^{n}\sum_{\beta=1}^{n_j}\lambda_\beta^j \gamma_{ij}(\mathbf{x}_\alpha, \mathbf{x}_\beta) + \mu_i = \gamma_{ii_0}(\mathbf{x}_\alpha, \mathbf{x}_0) \quad \text{with } i = 1, \dots, n \text{ and } \alpha = 1, \dots, n_i \\ \sum_{\beta=1}^{n_i}\lambda_\beta^i = \delta_{ii_0} \quad \text{with } i = 1, \dots, n \end{cases} \tag{10}$$

where δ_{ii_0} is the Kronecker delta that is: 1 in case of primary variable or 0 in case of auxiliary variables. The uncertainty of the estimation is assessed using the variance ($\sigma^2(\mathbf{x}_0)$):

$$\sigma^2(\mathbf{x}_0) = 2\sum_{i=1}^{n}\sum_{\alpha=1}^{n_i}\lambda_\alpha^i\,\gamma_{ii_0}(\mathbf{x}_\alpha, \mathbf{x}_0) - \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{\alpha=1}^{n_i}\sum_{\beta=1}^{n_j}\lambda_\alpha^i\,\lambda_\beta^j\gamma_{ij}(\mathbf{x}_\alpha, \mathbf{x}_\beta) - \gamma_{i_0 i_0}(\mathbf{x}_0, \mathbf{x}_0) \tag{11}$$

3. Intrinsic Random Function (IRF-k) theory

Variables describing natural phenomena often show trends or drifts along with particular directions (i.e. soil strength attributes along with depth), which violates the spatial stationarity condition, required by the application of ordinary kriging. Whenever the studied variables show the aforementioned systematic variations, stationary methods cannot be used, and the drift must be estimated contemporarily with the stochastic residuals by means of more complex numerical methods. When data show a weak tendency, the observations can be written as:

$$Z(\mathbf{x}) = m(\mathbf{x}) + r(\mathbf{x}) \tag{12}$$

where m(x) is the physical trend or drift, which is a deterministic component, whereas r(**x**) is the random residual. The variable Z(**x**) is not stationary and universal kriging should be employed to carry out interpolation (Matheron 1973). Matheron proposed a method based on Intrinsic Random Functions of k-order (IRF-k), which is a Kriging variant that identifies the trend and reconstructs the spatial random structure by means of generalized spatial increments of higher order k which filter out the trend to get the stationarity again (Chilés and Delfiner, 2012). In IRF-k theory (Cressie, 2015; Buttafuoco and Castrignanò 2005), the trend function m(**x**) in Eq. (12) is expressed through a polynomial function:

$$m(\mathbf{x}) = \sum_{l=0}^{K} a_l f^l(\mathbf{x}) \tag{13}$$

where $f^l(\mathbf{x})$ are monomials, K+1 is their number and a_l their coefficients. The stochastic component of variation was assessed and modeled by increments of a higher order, since increments of the first order, Z(**h**+**x**)-Z(**x**), are able to filter a constant (the local mean) that is a polynomial of 0 order. Taken m(x) as a polynomial of k-1 order in the coordinates **x**, an increment of k order is able to filter the whole drift. This increment can be written as:

$$Z(\lambda) = \sum_{\alpha=1}^{N} \lambda_\alpha Z(\mathbf{x}_\alpha) \tag{14}$$

where λ_α satisfies the following condition:

$$\sum_{\alpha=1}^{N} \lambda_\alpha f^l(\mathbf{x}_\alpha) = 0 \qquad l = 0,1,\dots,k \tag{15}$$

where $\mathbf{x}_\alpha$ are the sampling points. The intrinsic hypothesis requires the variance of the increments of k order to fulfill the second-order stationary condition: this condition implies that their variance depends only on the distance between pairs of points:

$$\mathrm{var}\left[\sum_{\alpha=1}^{N} \lambda_\alpha Z(\mathbf{x}_\alpha)\right] = \sum_{\alpha=1}^{N} \sum_{\beta=1}^{N} \lambda_\alpha \lambda_\beta K(\mathbf{x}_\alpha - \mathbf{x}_\beta) \tag{16}$$

where $K(\mathbf{x}_\alpha\text{-}\mathbf{x}_\beta)$ is called generalized covariance (GC) function of k order. The semi-variogram can be considered as GC of 0 order. A convenient model for the generalized covariance is the polynomial GC model, namely a linear combination of a given set of generic basic structures. All the possible combinations can be reduced in practice to a combination of four elementary models used with terms arranged by increasing regularity (Chilès and Delfiner 1999):

$$K(\mathbf{h}) = C_0\delta(\mathbf{h}) - b_0|\mathbf{h}| + b_s|\mathbf{h}|^2 \log|\mathbf{h}| + b_1|\mathbf{h}|^3 \tag{17}$$

where $\delta(\mathbf{h}) = 0$ for $\mathbf{h} = 0$, else $\delta(\mathbf{h}) = 1$. The coefficients C_0, b_0, b_s, and b_1 in a two-dimensional space R^2, must satisfy the following set of inequalities: $C_0 \geq 0$; $b_0 \geq 0$; $b_1 \geq 0$, $b_s \geq -(3/2)\sqrt{b_0 \cdot b_1}$, for the K(h) to be a valid generalized covariance of IRF-k. Unlike the variogram, the generalized covariance cannot be estimated directly, but it depends on knowing only the order of the polynomial. The coefficients of the drift do not need to be known and, in practice, the order is assumed to be ≤ 2. Summing up, the structural analysis consists of two steps:

1) Searching the order k of the drift,
2) Calculating the generalized covariance $K(\mathbf{h})$ and fitting a parametric model to it according to Eq. (17).

To determine the degree of drift the least-squares errors are ranked in ascending magnitude for each polynomial order of k = 0, 1 or 2. The first rank is assigned to the order producing the smallest error, the second rank to the second one, and so on. These ranks are finally averaged for each target point and the smallest averaged rank corresponds to the optimal degree of the drift. After that, to determine the optimal generalized covariance, knowing the degree of the drift, the first task is to calculate the experimental generalized covariance (Eq. 17) and to fit each combination of the basic covariance models in Eq. (18). Since the conditions on the coefficients are not necessarily met, all possible combinations of only three, two, or one basic structure are tested and the best one is retained. Jackknife test is used to select the optimal generalized covariance; the model that leads to a mean standardized error closest to 1, is finally retained. More details on the approach of fitting can be found in Chiles and Delfiner (1999). The universal kriging system can then be written as:

$$\begin{cases} \sum_{\beta=1}^{N} \lambda_\beta K(\mathbf{x}_\beta - \mathbf{x}_\alpha) - \sum_{l=0}^{K} \mu_l f^l(\mathbf{x}_\alpha) = K(\mathbf{x}_0 - \mathbf{x}_\alpha) \\ \sum_{\alpha=1}^{N} \lambda_\alpha f^l(\mathbf{x}_\alpha) = f^l(\mathbf{x}_0) \end{cases} \qquad \alpha = 1,\dots,N;\ l = 0,\dots K \tag{18}$$

and the intrinsic kriging variance of order k is:

$$\sigma_K^2 = K(0) - \sum_{\alpha=1}^{N} \lambda_\alpha K(\mathbf{x}_0 - \mathbf{x}_\alpha) + \sum_{l=0}^{K} \mu_l f^l(\mathbf{x}_0) \quad (19)$$

where K(0) is the variance, μ_l is the Lagrange multiplier, and the other symbols were previously defined.

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Memo

To: C28 Working Group Initial Contribution

From: Dr Wayne Barnett

Subject: Contributions to "Guidelines for the Development and Application of Engineering Geological Models on Projects"

2 The EGM Development Process

4.1 Overview of Development Process

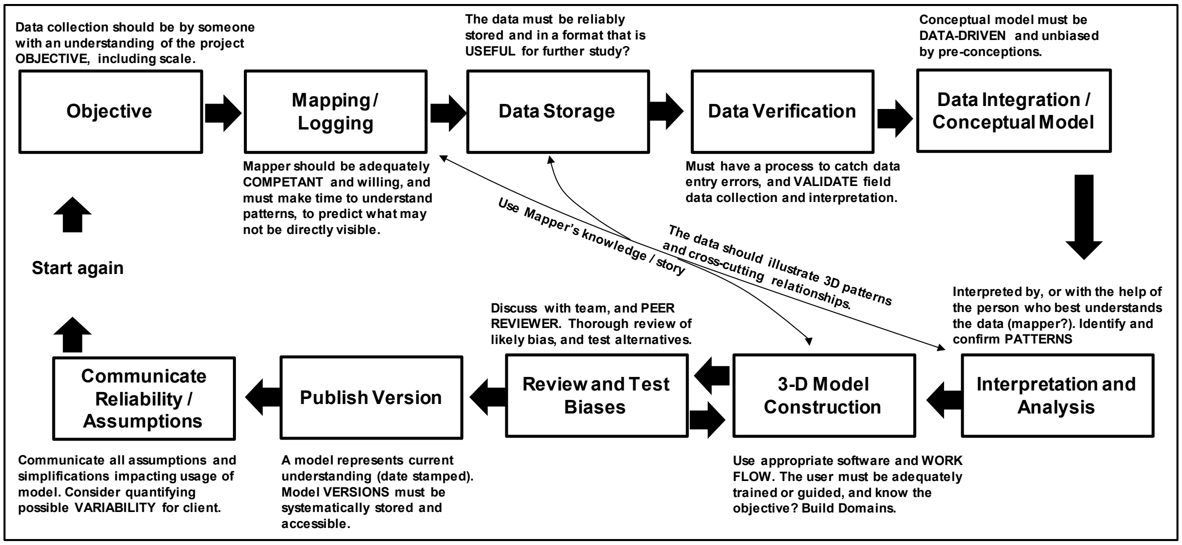
What seems to be missing from the proposed EGM development process is the fact that the data collection is integral in the 3-D model interpretation process. Interpretation starts at the rock face during data collection. Without including this step, the model will be less reliable. Geologist need to interpret what they are measuring and need to decide what else or where else should be measured, based on their data, observations and interpretation. Clearly more experienced persons have an advantage. This does not mean that the field interpretation cannot change.

A geological model is also dependant on the quality and type of mapping. It is essential that the mapping captures geological patterns (structural patterns and contact traces).

I propose the inclusion of a clear model development workflow that includes stages in the following image. This is an ideal workflow for mines but could be applied anywhere. Note that this is a process workflow, but the systems to manage the process should be pre-setup to optimize the workflow.

It is also important to acknowledge that a geological model is an interpretation based on a specific date in time, in which specific data is available to inform the model. In most practical applications of a geological model in industry, the model will be required to be updated based on new data. This means that the model development workflow should be represented as a cyclical workflow.

A workflow diagram is presented below in the first figure.



4.3 Assemble relevant engineering and geological information in a desk study

Again, this Table of Contents workflow is suggestive of a once off model development process. In any engineering process the workflow should iterative, by testing the model with new data, and then updating the model.

4.4 Conceptualize the engineering geological conditions using the desk study

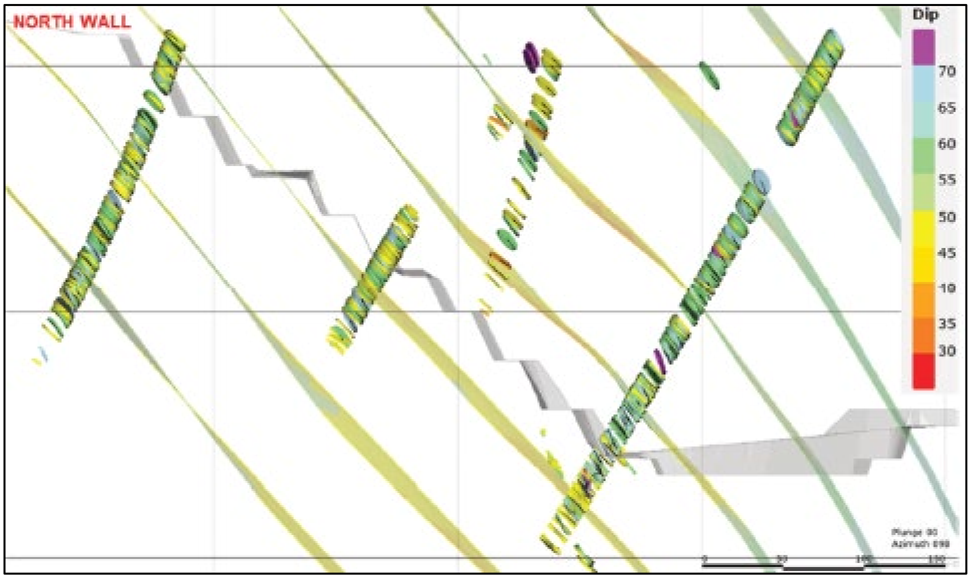
I think sections 4.4. to 4.6 may be a little outdated. With modern 3-D geological modelling tools, the best place to build the Conceptual model is within the 3-D computer modelling environment once all the data is imported. Data provide visual patterns and can be used to develop or improve a Conceptual Model, before model construction begins.

4.7 Creating Zones/Grouping

I presume that this has to do with Domains or Domaining?

Attached is a paper from Trevor and myself that is applicable.

In addition, a concept becoming very important in the mining industry is that of Rock Fabric Models or Domains. These should be applicable to any construction environment into rock mass with a pervasive fracture or foliation pattern. The fractures may be bedding parallel. Attached is another paper on a Fabric model development.



4.8 EGM development related to Project stages

There are several sources from mining industry that should be considered here, including Read and Stacey (2009) and Carter (2018).

4.10 EGM development driven by risk considerations

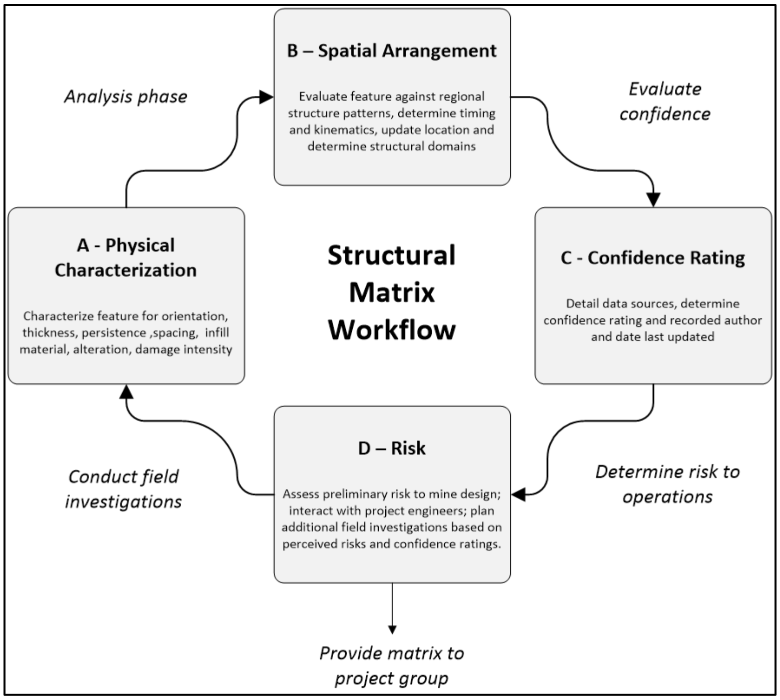
In the mining industry models are typically developed for geotechnical design purposes. The criticality of communication is extremely important. This is why there is communication and peer review emphasized on the workflow chart in section 4.1 above.

The Guideline Table of Contents may be missing an important section…**Handover and Communication of Relevant Model Assumptions**

Perhaps this is meant to be in the section **Documentation of EGMs?**

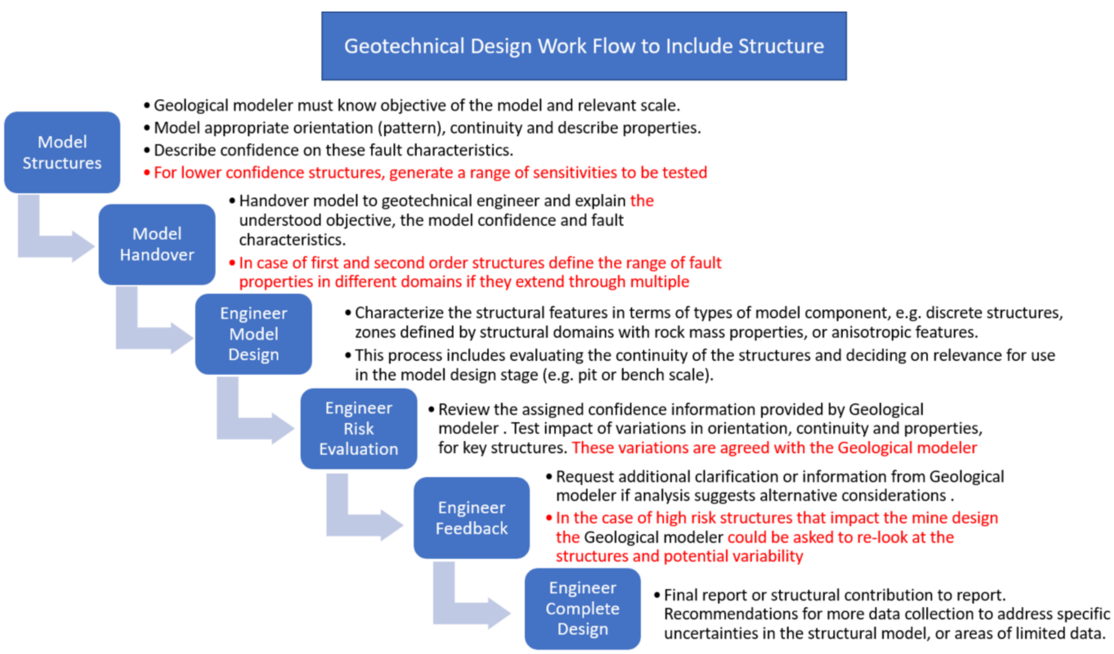
It proposed here that the guidelines should include a Model Handover best practices process.

Included in this is the use of ways to communicate the interpreted properties of the models. In the mining industry we developed a process to summarize the understood properties of each fault in the structural model as way to communicate to the client (e.g. geotechnical engineer). Campbell et al (2014) is an example of this. Essentially all properties are summarized in a table listing each fault wireframe. There are



Overall workflow of structural matrix from Campbell et al (2014).

The following is a draft recommended workflow for consideration of the types of communication that should provided to the geotechnical engineer who needs to use the model. Note that the process becomes a dialogue with the engineer with possible requirements to update or test alternative interpretations of the model, as relevant to the study objectives.



The critical point of the above is that a model cannot be completed until the client has gone through all the processes required to determine its applicability to the project objective.

5 Computer Based Modelling Techniques

I can provide text, or undertake reviews of most of the section in this Chapter. I cannot provide all content at this time. We are in the process of finalizing a Large Open Pit guidelines document for developing structural and geological model for Open Pits.

5.8.4 Virtual Reality Systems

I need to comment on this.

We have developed that worlds first complete Augmented Reality and Virtual Reality geological mapping system and interpretation system.

https://www.srk.com/en/easymine-mapping-software

A paper on the virtual reality system is also attached.

7 Managing EGM Uncertainty

7.1 Aleatory vs Epistemic Uncertainty

Aleatory uncertainty is simple in concept and statistically quantifiable, but such probabilistic uncertainty can apply to a significant range of data used as inputs into models. This includes field data (mapping and drill hole derived) and laboratory measurements, as well as geophysical survey data.

Epistemic uncertainty is embedded in most derived data sources and in the modelling. Examples include:

- Observed and measured data quality is subject to the geological knowledge of the observer who collected the data, who may have misunderstood what was measured because of lack of experience and training.
- Geological interpretation is impacted by biases. These are enhanced by linear geological model building workflows. A fixed choice on the overall conceptual model and any significant interpretational decision points during model construction may force or overly influence subsequent decisions. Bond et al. (2008) summarize several types of bias, and the most relevant include:

- 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).

- Greater uncertainty exists for parts of a geological model interpretation that lack data, or in the extrapolation of a structural feature from data-rich areas to data-poor areas.
- Choice of interpretation software and model construction methodology, and the user’s ability to access all available data for interpretation. For example, explicit and implicit wireframe construction workflows tend to produce different interpretational bias and different geometric and topological structure bias (Cowen, 2017). Different software functionality, complexity and user expertise influences the product.
- Quality of additional inputs, such as geophysical data (including quality of data, of processing, and of interpretation), and resolution and representativeness of the data (such as magnetic susceptibility) to the feature of interest. There may be an addition level of interpretation bias of geophysical data before it is included in a model as “data”.

In conclusion, interpretational uncertainty in a geological model includes subjectivity from the data collection process through to the final 3-D model and cannot be quantified precisely.

7.2 Identifying and Documenting Uncertainty

The identification of model uncertainty can be divided into two categories:

1. Geological Modeler Uncertainty Documentation
2. Peer Review Identified Uncertainty

The process of documentation of uncertainty by the geological modeler is done during and after the model development. This can be done using a Structural or Documentation Matrix (see above) or similar systematic documentation process. Various data density or distance interpolation techniques can be used to help visualize uncertainty. However, model uncertainty is also very much subjective, and depends on the experience of the geologist, particularly when interpolating structures or contacts away from data. This makes it difficult to quantify.

A more comprehensive method of documenting uncertainty is placing points systematically through the model, such that the points contain information from the modelling indicating likely uncertainty in position and/or orientation as determined/estimated by the modeller. Such a process creates spatially distributed uncertainty data that can be used in a variety of ways.

8 Measuring EGM Quality

8.1.2 Verification of Site Models

It is important to also discuss uncertainty with regards to models that are actively maintained in mining environments. This again requires detailed model review by a sufficiently experienced person. It is more successful a process if the review includes field verification of modelled features. This process is typically more difficult in early stage engineering projects with limited data, but in active mines, for example, detailed checks can be undertaken.

An example of such a process is as follows:

A careful comparison is made of the interpreted fault wireframes to the actual rock exposures during a field visit audit. The field visits take consideration of compliance to:

1. Fault pattern, including dip and strike, and typical fault system patterns;

2. Continuity, noting visible trace lengths in exposures, and tendency for segmentation;

3. Properties, such as the waviness, roughness of the plane, and the infill fault rock material; and

4. Timing relationships, specifically for cross-cutting priorities.

Every modelled and observed fault is tabulated and labelled as compliant to observation or not for the two categories of Pattern and Continuity. Observed timing relationships are factored into the assessment of the Continuity compliance. Compliance to observation is then calculated as a percentage of reviewed faults. Not all faults in the mine need to be reviewed during such an audit, but a representative sample should be undertaken until the auditor has a clear understanding of the geological conditions. Examples of actual audit results are shown in Figure below.

The Pattern compliance and Continuity compliance are represented as percent values. Similarly the amount of data support for each modelled feature can grouped by classes from no data support to excellent support – see below.

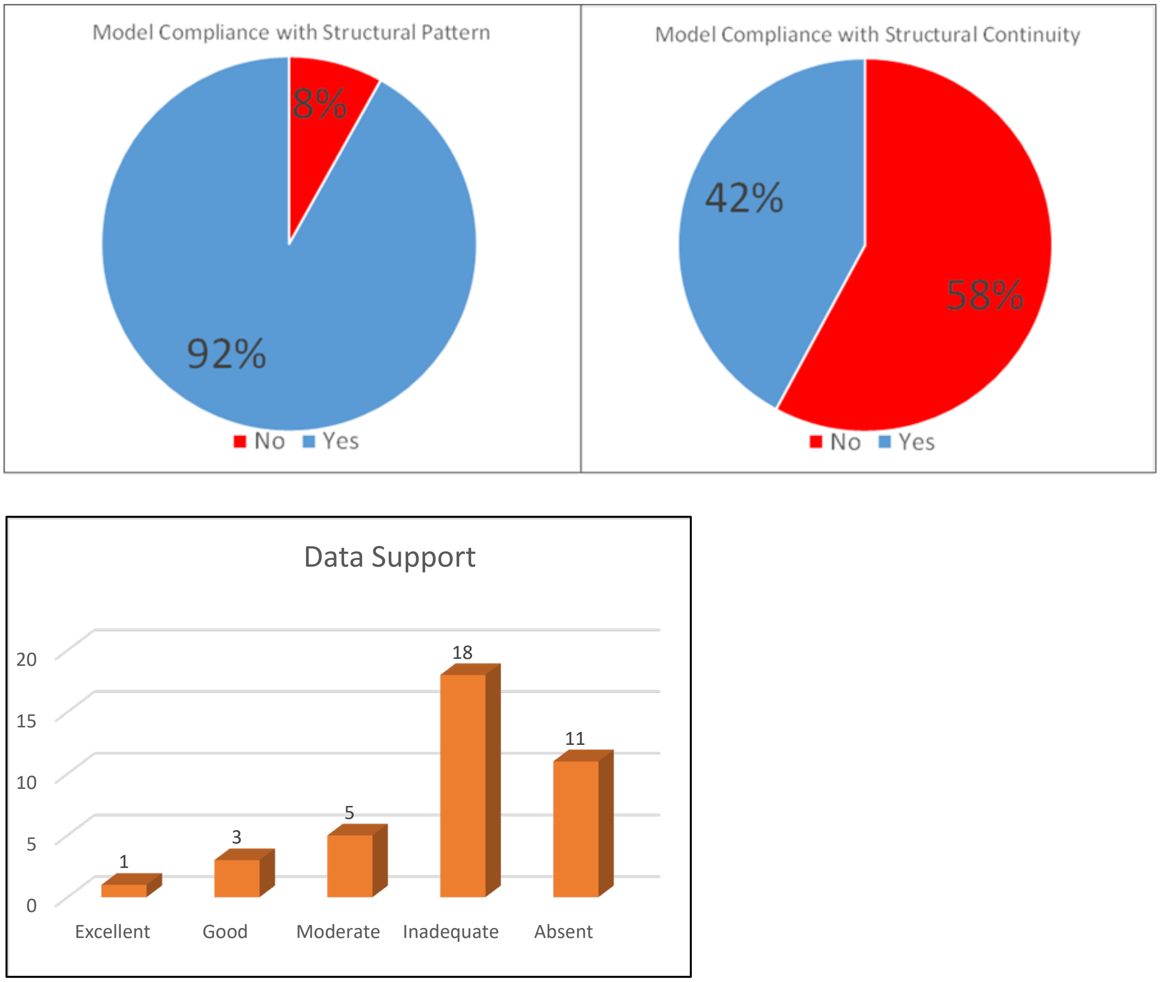


Figure: Example of a structural model review with results displayed graphically

Uncertainty can be subjectively measured through custom designed Reliability rating systems. For open pits I currently consider the following components. Each has a rating that can be shared with C28.

Investigation parameters:

1. Quality of mapping (1-10)
   - % bench mapping
   - Adjustment for the type of mapping (pattern vs point)
2. Quality of logging (1-10)
   - Drillhole Spacing

  - Oriented Core / ATV / OTV
  - Adjustment for relevant geophysical investigations

3. Overall Geological Complexity Rating (1-10)
4. Adjustment for quality of model including experience of modeller, extrapolation criteria, conceptual model application; and the results of a site visit check done as per example figures above.