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Engineering geological models in open pit slope engineering

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Abstract

The key to the successful design and management of slopes in mining is in understanding the geological controls on rock behaviour when it is stressed by surface excavation, pore pressure changes and external forces such as seismic loads. The purpose of this geological approach to rock slope engineering is to enable more accurate and reliable prediction of stability conditions when undertaking slope design at any stage of the mine life cycle, from feasibility studies to mine closure.

There is a trend in recent practice to concentrate the geotechnical model development towards rock mass classification and how this rock mass model can be used in stability analysis. The geological component of the geotechnical model is often neglected or directly lifted from the resource model. As the resource model has an objective to predict mineralisation and grade, it is typically not focused on areas in the deposit of geotechnical importance. These factors can sometimes take attention away from the main features of the geotechnical model that are driving behaviour and failure mechanisms, in particular structure, geological influence on change in rock mass condition, and groundwater. The role of the engineering geological model (EGM) is to ensure all the key geological controls on rock behaviour and performance are adequately identified and evaluated to inform the analysis, design and management of slopes.

The paper describes the conceptual and observational types of EGMs and how they relate to the mine design life cycle. The geology, structure, rock mass and hydrogeology components of the EGM are summarised and described in relation to development of the model, including the engineering geological description, model geometry and visualisation, and geotechnical characterisation of engineering properties and parameters. The importance of conceptualisation is emphasised, and the notion of EGMs as both a knowledge framework and ideology are summarised as the preferred approach to more accurate development of geotechnical models for mine design.

Keywords: *engineering geological models, conceptual models, observational models, regional geology, structure, rock mass, hydrogeology, characterisation, model geometry, visualisation, geotechnical parameters, conceptualisation, knowledge framework*

1 Introduction

An important function of the slope design role for open pit mining is prediction of how the rock will behave when the pit wall is excavated. The difficulty in making slope stability predictions is that we are engineering in naturally occurring materials which are inherently variable and complex in nature. Fortunately, we have a whole branch of science to help us unravel this variability and complexity to ensure our predictions are sufficiently accurate for the project status under investigation. Geology is the science which allows us to understand the natural materials in which pit slopes are excavated and, as such, is the most important contributor to the geotechnical model for engineering design.

In recent years there has been a decline in the quality of the geological input into compilation of the geotechnical model in open pit slope engineering. This affects reliability of the slope stability predictions with implications for mining risks. Examples of declining geological standards are listed as follows:

- Direct application of the resource model as the main geological input into the geotechnical model. The resource model has an objective to predict mineralisation and grade. It is typically not focused on areas in the deposit of geotechnical importance for slope design. Further, the resource model alone does not contain the information required to understand geological controls on rock behaviour and potential failure mechanisms, which are objectives of the geotechnical model.

- There is a trend towards concentrating the geotechnical model development around rock mass classification systems including limiting data collection to the inputs for classification systems such as rock mass rating (RMR) and Q. This approach can take focus away from the main elements of the model that are likely driving rock behaviour and failure mechanisms, in particular structure and groundwater.

Accordingly, there is a need to bring emphasis back to geology when building the geotechnical model. This can be accomplished through the concept of engineering geological models (EGMs).

The purpose of this paper is to explain the idea of EGM and its application to open pit slope engineering. Different types of EGMs are described including how they relate to the mine design life cycle. The geology, structure, rock mass and hydrogeology components of the EGM are summarised and discussed in relation to the fundamentals of the model development which comprise engineering geological description, model geometry and visualisation, and geotechnical characterisation of engineering properties and parameters. The importance of conceptualisation is emphasised, and the notion of EGMs as both a knowledge framework and ideology is introduced as the preferred approach to more accurate development of geotechnical models for mine design.

2 Development of the engineering geological model concept and its reference in existing guidelines for pit slope design

2.1 Brief history of engineering geological models

Discussion in the literature about the use of models in engineering geology can be traced back to the 1970s and earlier (Baynes & Parry 2022) but Professor Peter Fookes more widely promoted the concept of models in the first Glossop Lecture to the Geological Society of London in 1997, which was titled *Geology for Engineers: the Geological Model, Prediction and Performance* (Fookes 1997). This lecture laid the foundation for the concept of 'Total Geology' which is detailed in Fookes et al. (2000), including the founding ideas that 'The geological history of the area determines the geological condition of the site' and 'The power of the model is more in its ability to anticipate conditions than to predict them precisely.' (Fookes 1997)

The challenge of managing the heterogeneity of ground conditions was discussed by Fookes:

> *'I think the multiplicity of the variables even in a seemingly simple geological situation gives potentially a wide range of problems for rock and soil description, sampling and testing, and of identifying reasonable alternative geological possibilities for the whole or parts of the model.'* Fookes (1997)

Fookes also acknowledged that engineering geology needs to be:

> *'…an identity that can offer not only the geological model, but qualification and quantification of subsurface and surface geological and geomorphological processes of all or any facet of geology in engineering circumstances.'* Fookes (1997)

A seminal paper in the evolving concept of EGMs is a keynote lecture by Tim Sullivan at the 11th Congress of the International Association for Engineering Geology and the Environment (IAEG) in 2010 (Sullivan 2010). Sullivan draws on the work by Woodall (1985), McMahon (1985) and Knill (2003) to illustrate the truism that we face significant gaps and uncertainties when building the EGM and as such, we work with limited vision generated by:

- Variability in geology.
- Limited investigation.
- Limited knowledge and experience.

The enormity of the EGM task is well summed up by McMahon:

> *'It has always seemed to me that uncertainty is the very essence of geotechnical engineering. Our materials are natural in origin, often irregular in form and highly variable in their properties. They are usually obscured from sight and can be investigated only to a small extent at great expense.'* McMahon (1985) as quoted in Sullivan (2010)

To counter the handicap of limited vision, Sullivan (2010) describes use of the scientific method, inductive reasoning, education and mentoring as part of the tools necessary for deployment during the EG modelling process. The Sullivan paper is probably the first publication to discuss the EGM building process.

In 2009 the IAEG formed Commission 25 (C25) on the *Use of Engineering Geological Models*. C25 published an interim report in 2014 (Parry et al. 2014) that defined a model as 'an approximation of reality created for the purpose of solving a problem', outlined a methodology for developing engineering geological models, differentiated the conceptual and the observational component of that process, and provided some examples (Baynes & Parry 2022). The C25 interim report was expanded by Baynes et al. (2021) to explain the EGM as a knowledge framework that can be used to understand and communicate everything that is known about the geological and associated engineering information at any stage of a project (Baynes & Parry 2022).

In 2022, C25 published *Guidelines for the Development and Application of Engineering Geological Models on Projects* (*Guidelines*) (Baynes & Parry 2022). The *Guidelines* provide:

> *'…succinct, practical, accessible and authoritative advice on the effective use of Engineering Geological Models in a wide range of applications including civil engineering, mining, geohazard studies, offshore studies, land-use planning and environmental assessments.'* Baynes & Parry (2022)

The *Guidelines* cover the principles and processes used in development of the EGM, assembly and communication of the model, and management of uncertainty in the model. Specifics of EGMs for different types of projects are illustrated, including rock engineering projects (Eggers 2022) and models for the design of excavations in structurally controlled rock masses (MacKean 2022).

This paper utilises the information provided in this history of EGM development and provides guidance on the use of models in open pit slope engineering. This is based on experience in the application of models on mining projects, along with teaching the concept and use of models at universities in Australia, New Zealand and Norway, and also as an active member of C25.

2.2 Reference to engineering geological models in the existing guidelines

The Guideline documents published by the Large Open Pit (LOP) Project represent a significant body of knowledge on open pit slope stability and design. The original document on *Guidelines for Open Pit Slope Stability* was published in 2009 (Read & Stacey 2009) before the work of IAEG C25 was available. Read & Stacey (2009) discuss the geotechnical model as being the fundamental basis for all slope designs and list the main components of the model being the geological model, structural model, rock mass model (material properties), and the hydrogeological model.

As such, the main elements of what comprises a geotechnical model, or EGM, are discussed and the importance of the model to design is stressed. The Read & Stacey (2009) *Guideline* also emphasises the significance of understanding the physical setting of the deposit, stating:

> *'Pit design is too often focused on the characteristics of the ore body and waste rocks in proximity. We must also take heed of the natural processes that occurred before the deposit was developed if we are to develop a reliable model.'* Read & Stacey (2009)

This 'big picture' view is fundamental to the EGM approach. It is one of the keys to help manage the gaps, uncertainty and limited vision in geotechnical engineering. While the *Guideline* mentions the role of geology in the geotechnical model, it doesn't provide advice on how to use engineering geology to better understand the geotechnical model components and how geology can provide a framework for linking all the model elements into one coherent body of knowledge for slope design.

For example, when it comes to explaining how to build the geotechnical model, Read & Stacey (2009) take more of a 'mechanical' rather than a geological approach. The illustrative example provided in the *Guideline* takes different layers of information comprising intact rock strength, fracture frequency and joint condition, and merges these into a composite rock mass rating layer. Rock mass rating is then superimposed with layers showing lithology, alteration and structure to define geotechnical domains (Figure 1).

The limitation of this process is that it does not provide guidance on how to use the information to advance an understanding of the main objective of the model, which is to predict the geological controls on behaviour and potential failure mechanisms. Instead the focus is more aligned with providing an input into a stability analysis. For example, the roles of conceptualisation and characterisation, as applied within a knowledge framework of the engineering geological model of the deposit, are not explained as part of the geotechnical modelling process.

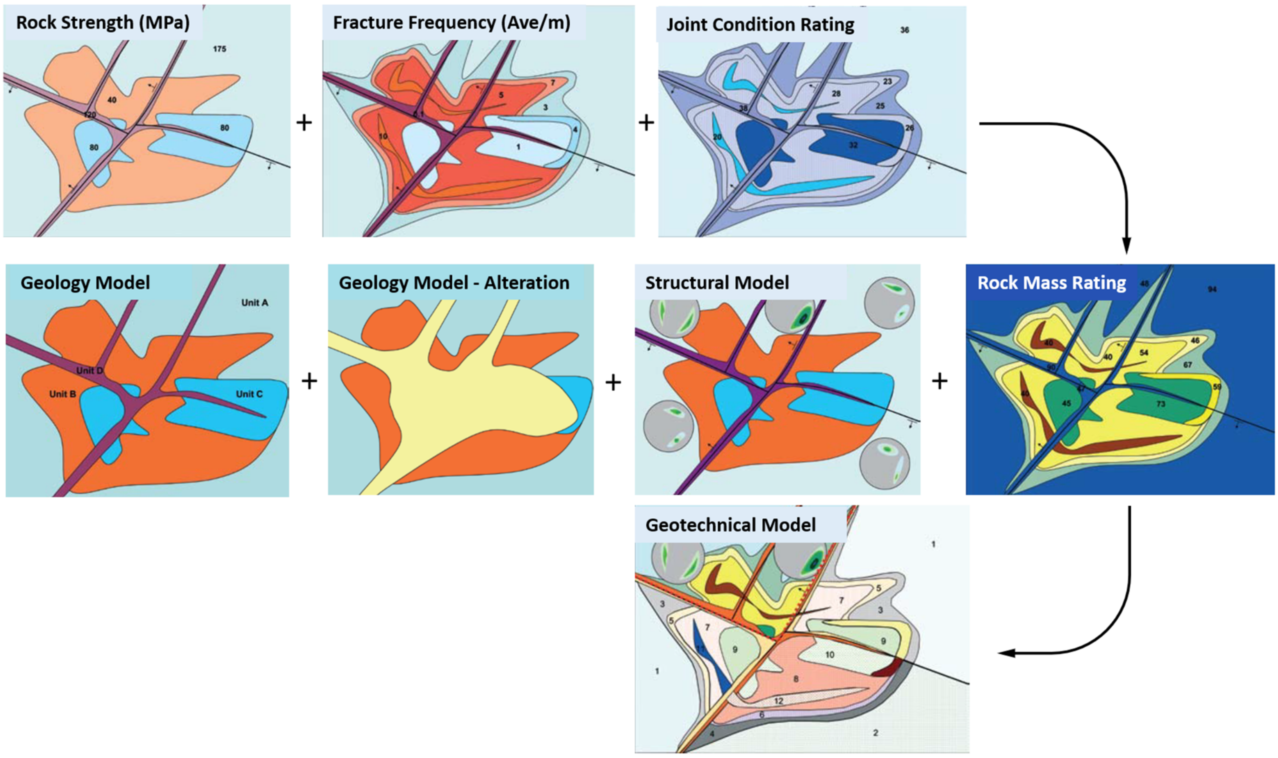

Figure 1 The model-building process described in Read & Stacey (2009) comprises bringing together successive layers of individual datasets into a 3D solid model (based on Figures 7.3 to 7.11 from Read & Stacey 2009)

This paper promotes the engineering geological approach to building the model whereby the emphasis is on understanding the key geological characteristics and processes likely to control slope stability conditions. This approach applies focus on identifying the most critical mechanisms to be tested in the engineering analysis for slope design.

EGMs have a role in all areas of geotechnical engineering for open pit mining, including topics of the other *Guideline* documents comprising slope depressurisation (Beale & Read 2013), waste dumps (Hawley & Cunning 2017), weak rocks (Martin & Stacey 2018) and slope performance management (Sharon & Eberhardt 2020). However, the use of EGMs and geotechnical models is not specifically addressed in any of the additional *Guideline* documents listed here. This is a major gap in the thinking and approach to applying the concept of models in open pit mining.

3 Fundamentals of engineering geological models

3.1 Definitions

The C25 definition of an EGM is as follows:

> *'…a comprehensive knowledge framework that allows for the logical evaluation and interpretation of the geological, geomorphological and hydrogeological conditions that could impact a project and their engineering characteristics.'* Baynes & Parry (2022)

Sullivan (2010) described the EGM as:

> *'…a way of transferring or presenting information that captures the essence of the character of the soil or rock mass, in a simple form that meets the objectives. The model should be quantified where applicable with the degree of variability shown.'* Sullivan (2010)

Overall an EGM can only be an approximation of the actual geology which has been simplified and quantified, with the variability explained in order to answer the specific engineering questions driven by the objectives of the project. The geotechnical model can be considered as an expansion of the EGM, where the application of geotechnical parameters allows quantification of the model in preparation for analysis.

3.2 Key principles

There are four key principles which define the nature of EGMs. These principles contribute to the fundamental difference of the EGM approach to the geotechnical model-building process outlined by Read & Stacey (2009).

1. **Models are objective driven**. For the same geological and geomorphological setting, different types of projects will ask specific engineering questions. For example, the focus of the EGM will be different if the objective is slope design, blasting and excavatability, materials handling and hauling, or slope depressurisation.
2. **The EGM is a knowledge framework** that can contribute to the solution of geotechnical engineering problems and the management of geotechnical risks (Baynes et al. 2021). In other words, it provides the structure that facilitates application of geological solutions to engineering problems using skills, experience and education in the geological issues which are important to the objectives of the project.
3. **The EGM operates as a thought system** within a heuristic environment. Model building involves critical thinking through application of the scientific method and inductive reasoning processes (Sullivan 2010). This type of thought environment allows the development of a network of interconnected ideas and concepts which form the basis for development of the knowledge framework.
4. **Conceptualisation** is a fundamental process in the formulation of an EGM. This is the ability to anticipate conditions, as first noted by Fookes (1997), which provides a powerful tool for formulating the model. As data is collected during feasibility and final design investigations, and as part of pit slope management tasks while mining, the conceptual model provides the context for interpretation of the data when formulating and updating the observational model.

Accordingly, an EGM is not just a collection of datasets and a visualisation of what is in the ground. The maps, sections, logs, sketches, descriptions and 3D models only form part of an EGM if they demonstrate the conceptual basis underlying their generation (Baynes et al. 2021). This is the essence of the EGM approach, which is shown diagrammatically in Figure 2.

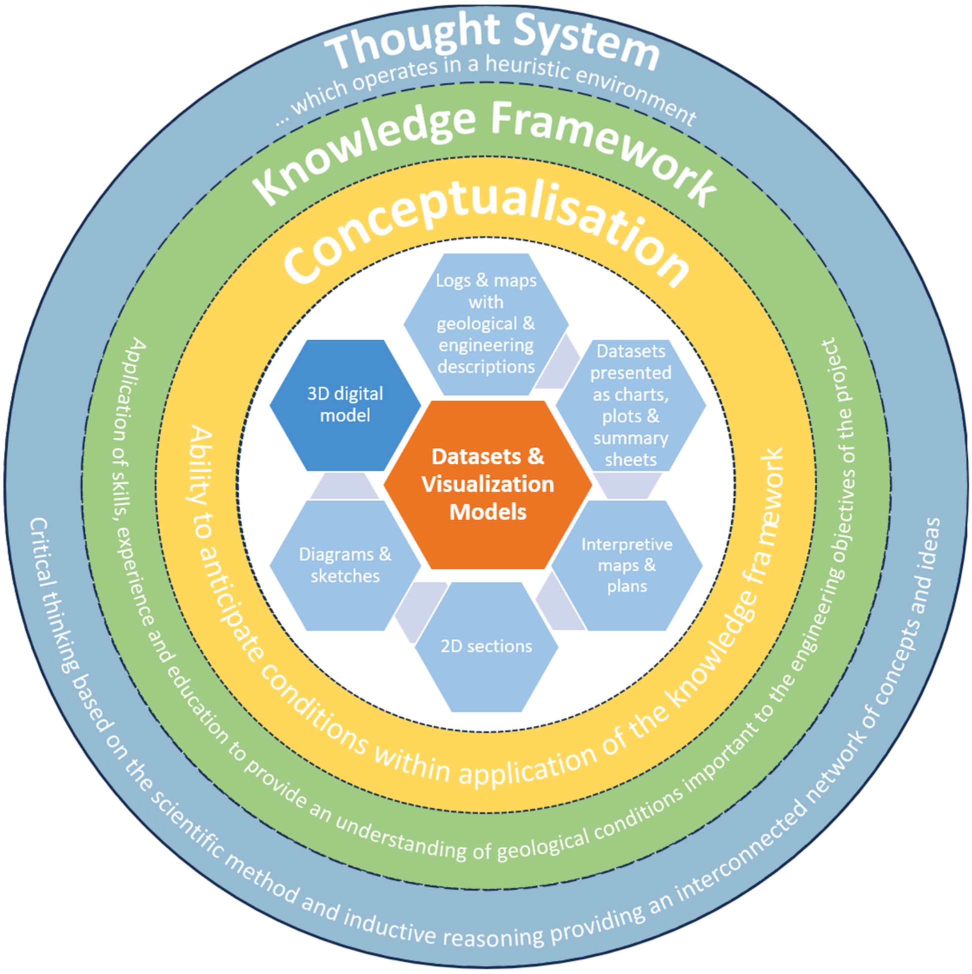

Figure 2 The EGM approach comprises the development of conceptual models using a knowledge framework operating within a heuristic thought system. The outputs of the model are the datasets and model visualisation interpreted through the lens of the conceptual model and knowledge framework

Conceptualisation, the knowledge framework and heuristic thought system are key factors defining the model-building process. Hence an EGM is more than a multilayered presentation of the datasets: it is an interchange between the conceptual and observational models, which is repeated each time the models are updated in subsequent project stages. In a general sense, the EGM approach can be considered as an ideology for development of more accurate and reliable geotechnical models to improve the management of mining risk.

3.3 Types of models and stages of model development

The relationship between different types of models, the project stages in which they are undertaken, the data sources used and the activities carried out to compile each model are summarised in Figure 3. This chart forms a generalised workflow diagram for assembling and interpreting an EGM for rock slope engineering projects.

3.3.1 Conceptualisation

There are two types of EGMs, as shown in Figure 4. Modelling starts with conceptualisation that is first undertaken at the beginning of the project. It normally forms part of scoping, order-of-magnitude or preliminary studies based on a desk study of the literature, geological knowledge and experience of the project area, supported by the concept of Total Geology (Fookes et al. 2000). The early studies are when the engineering objectives are first established and key geotechnical questions that are to be addressed by the model and design are compiled. Overall, conceptualisation allows an assessment of what conditions and variations may be present, and the geological and geomorphological processes that have produced them that could be of engineering significance to the project (Baynes et al. 2021). It is not a model in real space; instead it provides a concept of what might be anticipated.

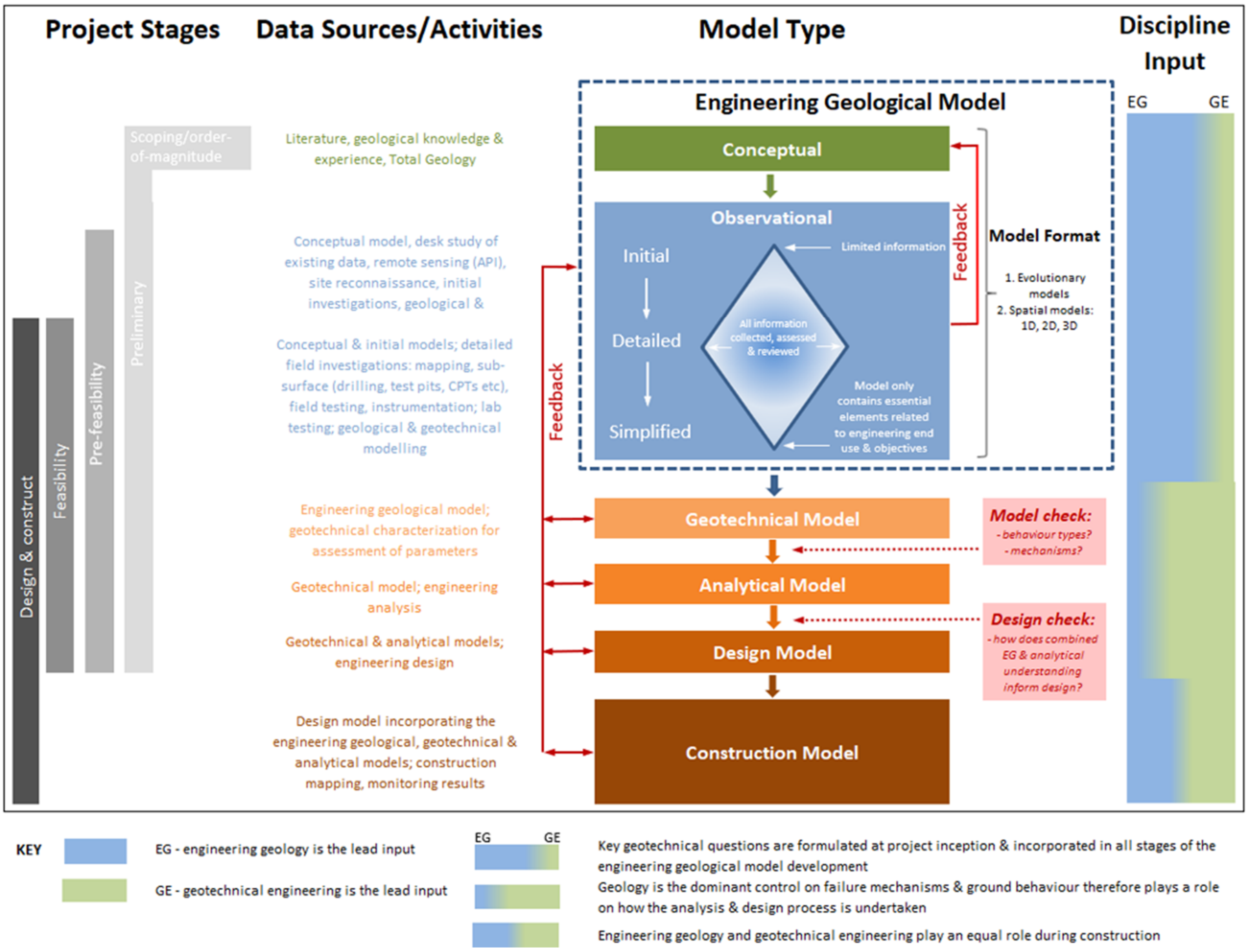

Figure 3 Work process diagram for building the EGM during different project stages, showing model types and development, data sources, activities, and the role of the geologist and engineer working as a team in the modelling process. Adapted from Eggers (2022)

For rock slope engineering projects, conceptualisation is particularly critical to the success of the overall modelling process. Ultimately, this early step allows generation of hypothetical structural and geological models (for example, models of rock alteration in porphyry and epithermal deposits) that are developed at the project scale based on the global and regional-to-district scale tectonic setting. The hypothetical models provide the framework in which future investigation data and ideas are tested and revised. The site-specific data forms the observational model, which is a real representation of the geology constrained in space and time.

As new data is collected during subsequent phases of investigation, the conceptual model is updated (represented by the red feedback loops in Figure 3) to allow more accurate interpretation of the upgraded observational model. It is important that engineering analysis and design only proceed once the observational data is reconciled with the concepts, as summarised in the red box in Figure 5. The reconciliation process is represented in the workflow diagram in Figure 3 as two hold points: a model check that the EGM answers the key questions on ground behaviour types and potential failure mechanisms, and a design check that the combined EGM and analytical understanding are sufficient to inform engineering design. If any residual discrepancies remain after these checks which cannot be resolved by updating the models, a decision can be made whether they are able to be managed going forward as project risks (Baynes & Parry 2022).

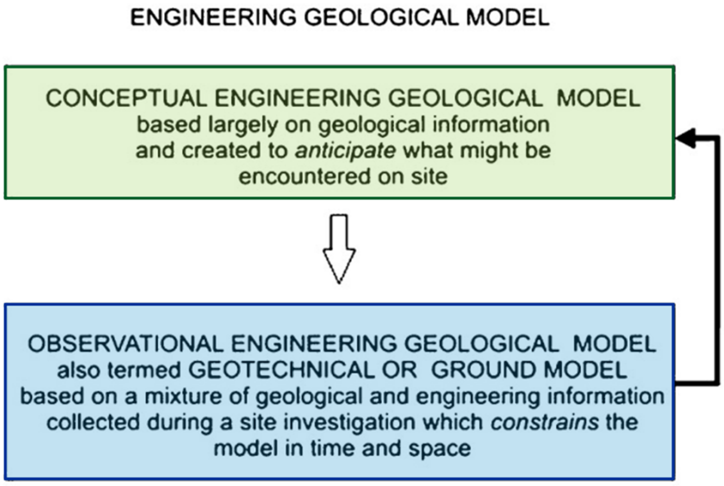

Figure 4 Types of engineering geological models. IAEG C25 (Parry et al. 2014)

3.3.2 Observational model

Development of the observational model can be represented by a diamond shape (Figure 3) that denotes the amount of information that is used or contained in the model at each stage (Sullivan 2010). At the early stages during conceptualisation and initial building of the observation model, data is limited. Once the investigation is complete there is a comprehensive collection of information at the centre of the diamond. This could comprise engineering geological mapping and diamond core drillhole data including geotechnical logging, structural logging of orientated core, borehole imaging (optical and acoustic televiewers), field testing, borehole instrumentation, and so on. The next step in the workflow involves collation, presentation and interpretation of the data to refine the observational model. This is a simplification process to focus the model on the key geotechnical questions to be addressed by the engineering design (Sullivan 2010).

This process may be cycled two or three times as the project goes through pre-feasibility, feasibility and detailed design stages. At each stage the conceptual model is refined and the observational model becomes more detailed to meet higher levels of confidence as the design reaches implementation and operational phases. This is achieved via feedback loops in the model development as the project moves through to construction and operation, as shown in the blue box in Figure 5.

While the geologist is responsible for development of the EGM, the engineer plays a key part in the early stages when helping to formulate the geotechnical questions that the model should address (Figure 3). During analysis and design, the geologist should maintain involvement to ensure that the geological controls on ground behaviour and failure mechanisms are adequately captured in the analysis and design. Pit slope management and implementation of the ground control management plan are shared responsibilities between the geologist and engineer.

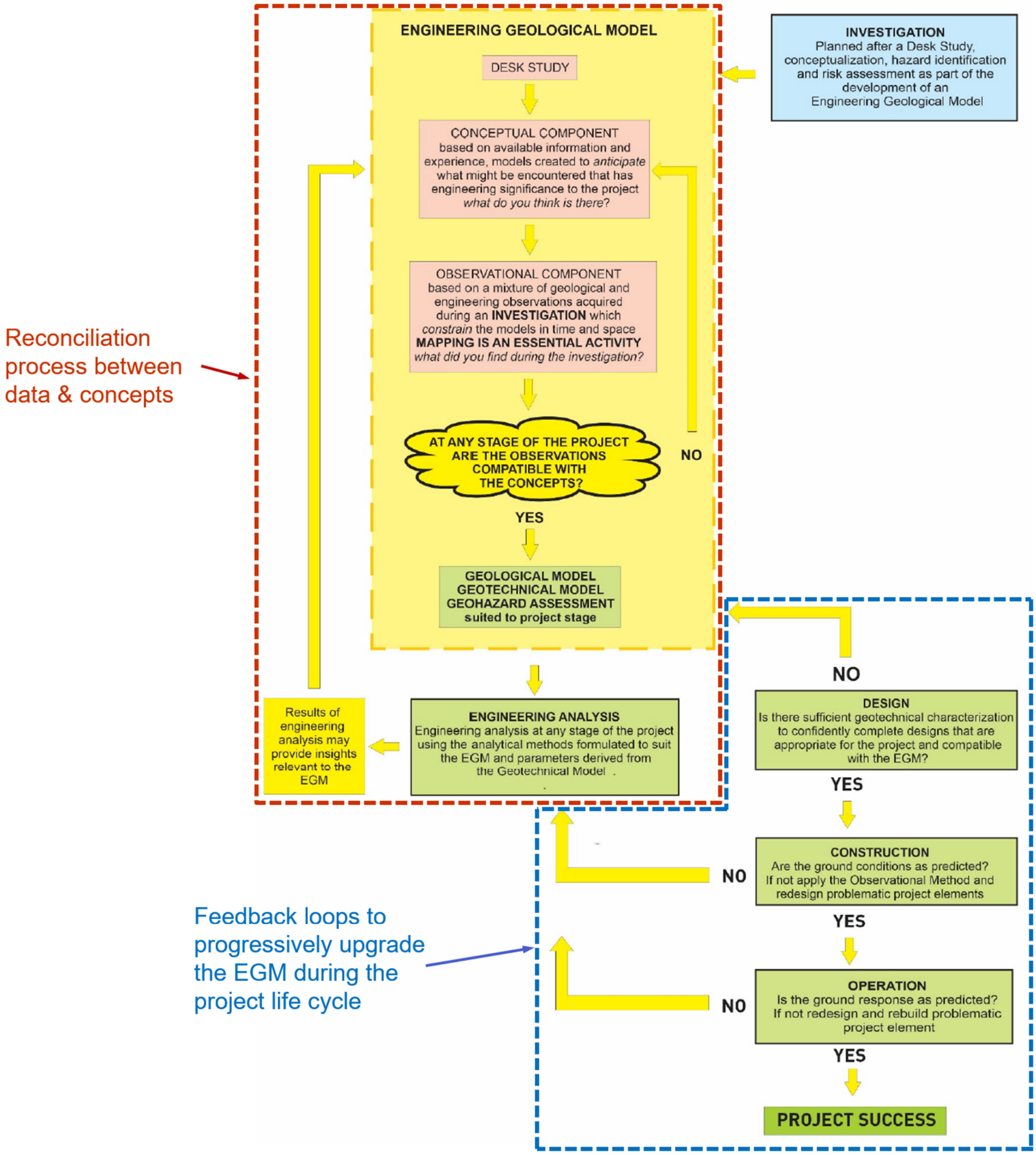

Figure 5 **Reconciliation process between the observational data and model concepts (red box) and feedback loops used to progressively upgrade the EGM during the project life cycle (blue box). Adapted from IAEG C25 (Baynes & Parry 2022)**

4 Engineering geological models for rock slope engineering projects

4.1 Components of the engineering geological model

The main components of an EGM for a rock slope engineering project are summarised in Figure 6. Each of these components are formulated during different stages of the model development as shown in Figure 6, based on the work process diagram presented in Figure 3.

The global tectonic and regional-to-district scale geological setting is established during conceptualisation. It is important that this 'big picture' is established early in the modelling process because it provides a powerful tool to help anticipate the geological conditions expected at the project scale. The strength of this approach is that the 'big picture' understanding helps to find and bridge the gaps and assess the uncertainties that are inevitable due to the limited 'sampling' of the rock mass that can be achieved by an investigation program. Established structural and geological concepts can be used to test the data collected when building the observational model. This is an example of applying the knowledge framework as part of the model-building process.

The main components of the EGM can be labelled as follows: geology, structure, rock mass and hydrogeology. Figure 6 lists the different elements and features to be observed, recorded and interpreted under each component. Key questions that should always be addressed for each dataset collected and incorporated into the model are (Sullivan 2010):

- How accurate is each source of data or information?
- How representative is each source of data or information?

These questions are central to evaluating the confidence level of the model and its reliability, or fit-for-purposeness, for the project stage being investigated.

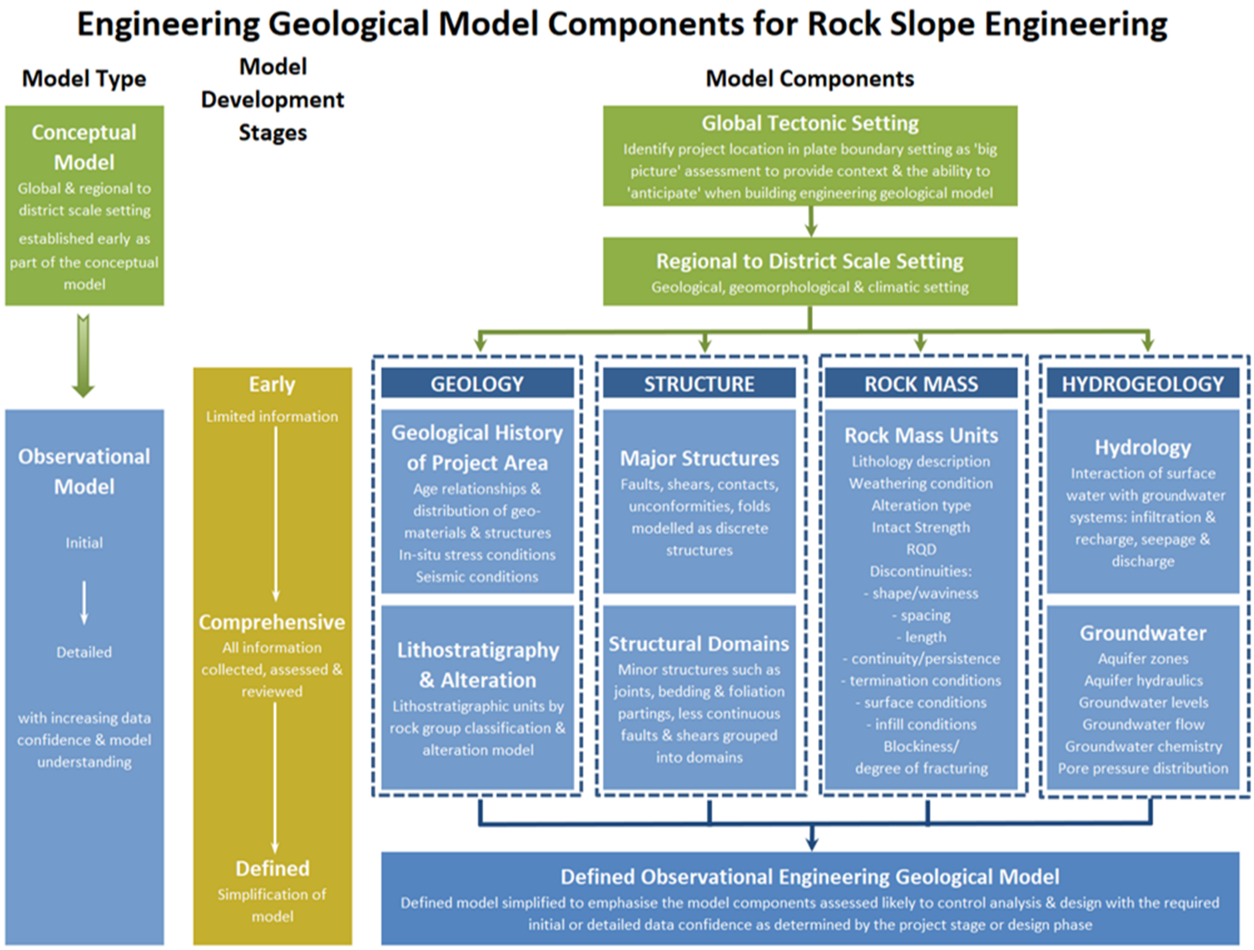

Figure 6 Components of the EGM for a rock slope engineering project. Adapted from Eggers (2022)

The geology component, in particular knowledge of the geological history of the rocks that are being engineered, is essential for the other parts of the model. The geological history helps form a link between the conceptual and observational models, providing an avenue for applying the geological concepts to interpretation of the investigation data. The geology component of the EGM should incorporate:

- Knowledge of the structural geological history that allows interpretation of the possible stress conditions, including palaeostresses from previous tectonic regimes that may still be locked in the rock mass.
- Regional structural associations, for example, pull-apart basin and intrusion-related structures in porphyry copper and epithermal gold deposits for mine design studies.
- Understanding of the geomorphological history of the site and how deposition, erosion and weathering processes may have altered stress conditions, formed unconformities, triggered geohazards and resulted in the generation of superficial materials deposited over rock.
- Depending on the location, the earthquake history of a region may be important for the purposes of establishing earthquake magnitude – return period relationships.

4.2 Description, assessment and presentation of the model components

Each component of the model can be described, assessed and presented using the methods and steps listed in Figure 7.

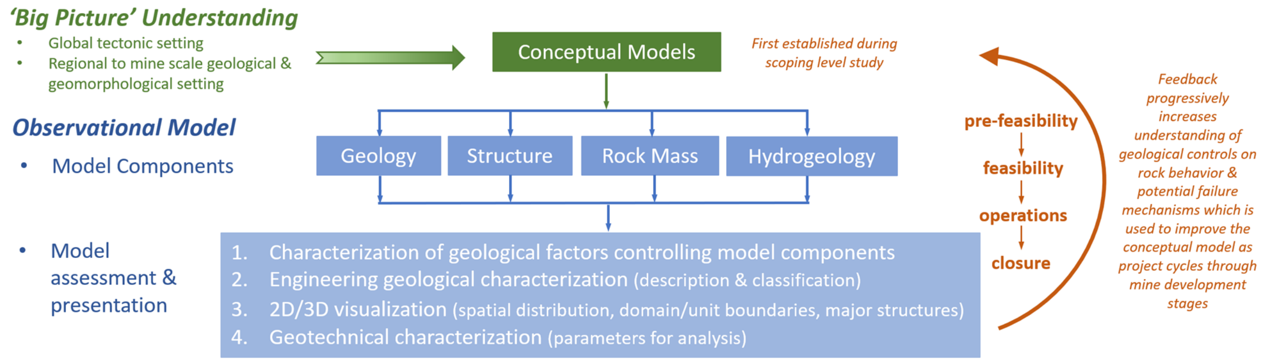

Figure 7 Description and presentation of the EGM. Adapted from Eggers (2022)

The model assessment steps are:

1. **Assessing the geological factors** which control or influence the distribution and change in condition of the model feature: for example, the impact of lithology and weathering on fault condition, differentiation of rock mass units by lithology, degree of weathering or alteration history, fault damage, and so on. Ideas about these factors are based on the hypothetical models formulated during conceptualisation that result from the 'big picture' geological understanding of the project. As the project cycles through the pre-feasibility-feasibility-execution design stages, increasing knowledge of the geological controls gained from the observational modelling are fed back into the conceptual models to better inform the next stage of project development.
2. **Engineering geological characterisation** of structure, rock mass units and hydrogeological units using appropriate engineering description and classification systems. In some instances, project-specific systems can be devised to record and describe elements of the rock mass that are distinctive to the project geology. For example:
   a. Different types of brecciated rock in porphyry copper deposits to capture the key elements of the clast-matrix textures that will control ground behaviour of the rock mass
   b. Different styles of fault damage in major structures that influence shear strength properties.
3. **Visualisation/model geometry** (spatial distribution) comprising boundaries between structural domains, rock mass units and hydrogeological units, and discrete modelling of major structures. The boundaries and major structures can be presented in 1D (for example, borehole logs), 2D (plans and cross-sections) or 3D (wireframes or block models). While visualisation is central to the model

presentation, it does not represent the whole model. Further, well-presented 3D digitally generated models can project a sense of truth which is actually a virtual reality, or a perception of certainty, which may not be correct (Bond 2015). Hence it is important that the degree of uncertainty in the 2D or 3D model visualisation is described in the accompanying documentation.

4. **Geotechnical characterisation** which incorporates quantification of the physical properties such as the strength, stiffness and permeability of intact rock, the structure and the rock mass ready for numerical analysis. This is based on engineering the geological characterisation of intact rock, the structure and the rock mass together with the compilation and evaluation of laboratory test results.

A key task in the model-building process is the assessment of units or domains which may represent areas of similar structure, rock mass or hydrogeological conditions. Decisions on how the units are defined and boundaries demarcated is based on the assessment of geological factors in step 1 as described above. The units selected should also reflect the conditions that are significant to the project (Baynes & Parry 2022). The tasks and methods for evaluation of units or domains (e.g. structural domains, rock mass units, hydrogeological units) involve grouping and division followed by constraining and characterising each unit as explained in Figure 8.

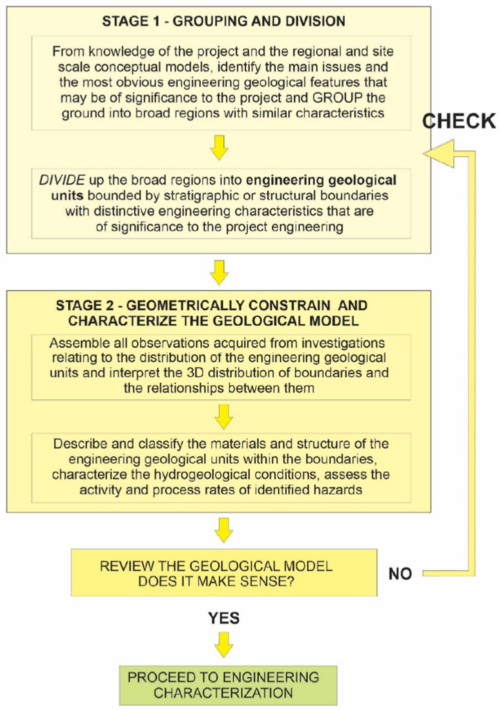

Figure 8 Process for interpretation and assessment of engineering geological units in the EGM. IAEG C25 (Baynes & Parry 2022)

5 Application of engineering geological models methods for rock slope engineering projects

The material that follows provides guidance on and examples of the information contained in some elements of the EGM for rock slope engineering. More information can be found in Eggers (2022) and MacKean (2022).

5.1 Conceptual model

An example of the start of a conceptual model is shown in Figure 9. This is for a porphyry copper-gold deposit located in Southeast Asia. Regionally, the deposit is located in a convergent zone of volcanic and sedimentary fold belts which are intensely folded and faulted. At the deposit scale both low angle thrust faulting and sub-vertical normal faulting occur. A package of volcaniclastic and sedimentary rocks have been hydrothermally altered with porphyry stocks at depth. An upper oxide and supergene zone occurs, forming a cap of enriched mineralisation.

Figure 9 is a compilation of diagrammatic sketches summarising the main elements of the geology that have the potential to influence geotechnical conditions important for slope design. These sketches were formed while reading geological reports and published papers on the deposit during the desk study and represent the first ideas recorded at the very start of the model-building process, during the planning of feasibility studies. As such the sketches are not a model in real space; instead they provide a concept of what might be expected. While the sketches are simplistic in form they act as memory triggers on the geological factors and history to be considered during planning of the feasibility geotechnical investigations and interpretation of the mapping and drilling data collected. This mine is now in operation and the conceptual model is supported by mapping of bench exposures, allowing a more sophisticated understanding of the alteration and structural factors controlling slope design.

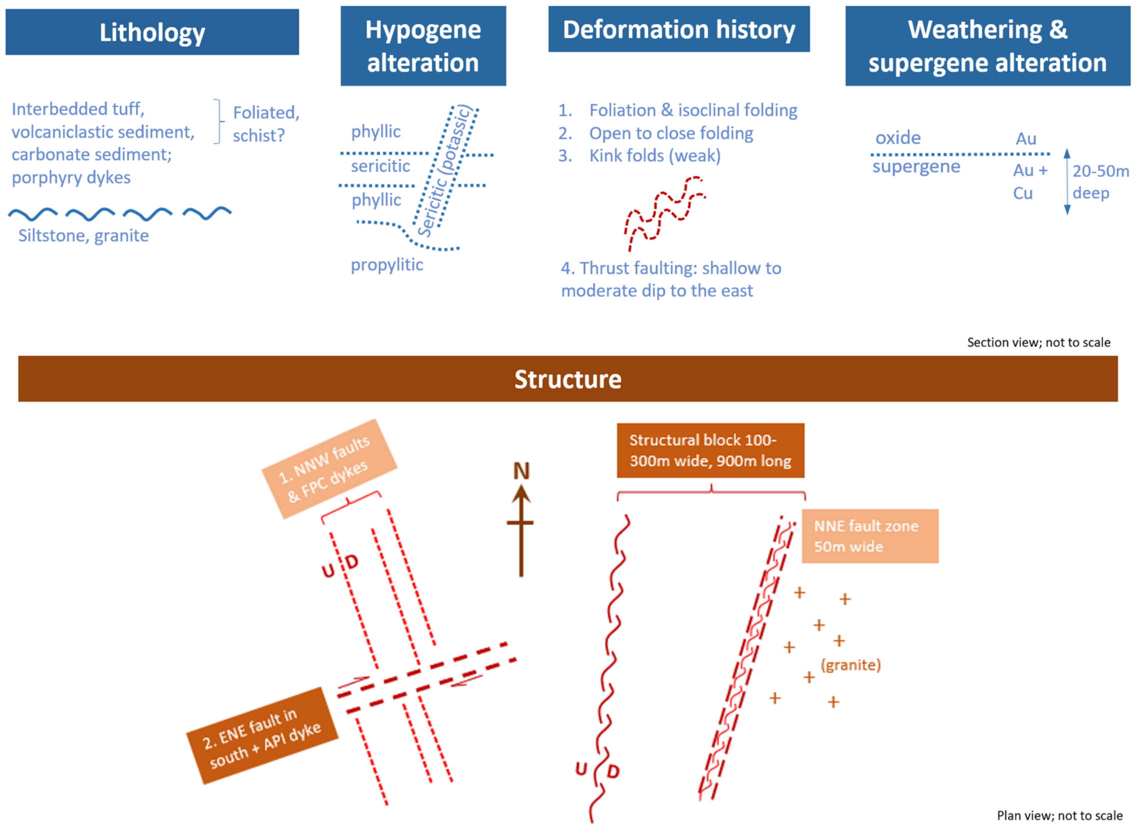

Figure 9 A compilation of diagrammatic sketches as part of the early development of a conceptual model for a porphyry copper-gold deposit in Southeast Asia

5.2 Structure

In hard rock mining, geological structure is likely to be a dominant control on rock behaviour and potential failure mechanisms. As such it is usually the most important component of the EGM.

Structure can normally be divided into two scales:

1. Large structures that have continuity at approximately the same scale as the pit. As such, these normally comprise faults and shears, unconformities and geological contacts which are typically modelled discretely.
2. Medium to small-scale structures, represented in the model as structural domains.

The large structures model will typically include a hierarchy or order of structures that assists with understanding which defects will control stability at different slope scales (bench, inter-ramp or overall slopes). In a structurally complex rock mass, a hierarchy scheme that is more sophisticated than differentiating between 'major' and 'minor' structures may be required to capture all the elements important for structural modelling. An important role of the conceptual model is to provide an understanding of the structural history of the deposit which can be used to recognise the different generation of structures that may be important to stability and design. Large structures in the resource model should be reviewed for geotechnical relevance as faults are sometimes interpreted to account for changes in ore grade but may not form a discontinuity or zone of damage in the rock mass.

For scoping to feasibility studies, the available data are dominantly from boreholes for a majority of projects. Table 1 presents a scheme that assists with interpretation of major structures from borehole logs, core photographs and downhole images. Similar systems can be devised based on mapping data or lineament analysis, typically using mapped or visible length and persistence as one characteristic to help judge the structural hierarchy.

Table 1 Example of a hierarchy of structures based on borehole data (Eggers 2016)

Hierarchy	Description
Primary structures	Clay gouge or pug seam surrounded by a wider clay breccia zone with a higher proportion of matrix supported, chaotic to rotated breccia fabric; this zone may grade into a fragmented to highly fractured zone changing from matrix to clast supported, mosaic to crackle breccia depending on the width and nature of the 'damage' zone
Secondary structures	Lesser development of a clay breccia zone without a significant gouge or pug zone inside fragmented to highly fractured rock
Tertiary structures	Fragmented to highly fractured rock in the immediate footwall and hanging wall of the fault plane without development of gouge or clay breccia materials

Interpretation of the structural model is often based on several data sources in feasibility studies: principally the evaluation of borehole intersections supported by a lineament study and sometimes mapping where there are exposures available. The system presented in Table 2 enables all these data sources to be brought together to classify each structure. The fault classification is used to rate each structure for the level of confidence in terms of accuracy of prediction, as shown in Table 3. The confidence rating, together with the hierarchy evaluation, contribute directly to knowledge of which structures can be relied on for stability analysis and the slope scale at which the structure may impact on the design.

Table 2 Example of a classification of fault data sources (Eggers 2016)

Airphoto/LiDAR lineament	Drillhole intersection	Surface exposure
Y – with	1 – with	Y – with
N – none	0 – without	N – none

Table 3 Example of a fault confidence rating system (Eggers 2016)

Airphoto/LiDAR lineament	Drillhole intersection	Surface exposure
1	Y1y	High
2	Y0y, Y1n, N1y	Medium
3	Y0n, N1n, N0y	Low

In the structural model it is important to clearly differentiate between internal structure that forms a fabric in the rock mass and true defects (discontinuities). The same structure type can form both a fabric in the intact rock and defects that operate at different scales in the rock mass. Examples include bedding in sedimentary rocks and foliation in metamorphic rocks. Project-specific classification schemes can be set up to describe different types of structures. An example is presented in Figure 10, which is a scheme established for a shale- and phyllite-hosted gold deposit in Siberia which has undergone low-grade regional greenschist facies metamorphism.

Internal structure	**Defect (discontinuity) structures**		
Foliation fabric	**Foliation parting**	**Foliation shear**	**Foliation parallel sheared zone or crush seam**
Repetitive layering in the intact rock forming a planar fabric due to the preferred orientation of the constituent mineral grains, which in metamorphic rocks is often platy minerals. Can form an anisotropy in the strength of the intact rock material.	Single separation in the rock mass which is parallel (or near parallel) to foliation, with no signs of shear.	Single separation in the rock mass which is parallel (or near parallel) to foliation where the defect shows evidence of shear displacement such as polished or slickensided surfaces.	Zone of rock fragments (clasts), soil material or a mix of rock fragments in a soil matrix with boundaries which are parallel to foliation; sheared zone is characterised by closely spaced joints, sheared surfaces which divide the mass into lenticular or wedge-shaped clasts; zone can be either clast or matrix supported. Crush is a seam of soil material with variable content of rock fragments with boundaries which are parallel to foliation; seam is often matrix (soil) supported but can be clast (rock fragments) supported.

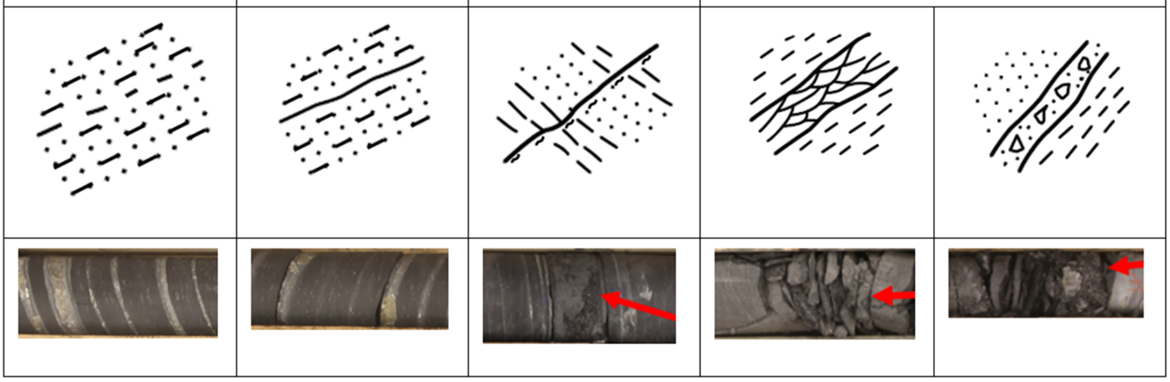

Figure 10 Example of a shale foliation structure classification scheme differentiating between fabric and different types of defects (Eggers 2022)

5.3 Rock mass

5.3.1 Geological controls on rock mass condition

Compilation of the rock mass component of the EGM requires evaluation of the geological controls on change in rock mass condition across the deposit or pit. The conceptual model provides the deposit geological history to help identify different episodes of structural, alteration and weathering processes that have overprinted on the rock mass. Examples of geological controls on the definition of rock mass units include:

- Lithostratigraphy (change in rock type).
- Weathering and supergene alteration.
- Hypogene alteration (particularly in porphyry- and epithermal-style mining projects).
- Breccia types (hydrothermal, magmatic, volcanic breccia etc).
- Tectonic, both fault zone materials and fault damage (fractured) zones in adjacent rock.

It is important to remember that most deposits usually have several different geo-controls on the type and distribution of rock mass units. As the complexity of the geological history increases, the number of geo-controls on rock mass conditions usually rises.

5.3.2 Porphyry copper example 1

An example of a rock mass model for a porphyry copper deposit in Southeast Asia is shown in Table 4. The rock type in this example is the same across the deposit, comprising an andesite on the flanks of an old stratovolcano. The main differentiator in rock mass condition at this deposit is high sulphidation hypogene alteration, late-stage supergene alteration, hydrothermal brecciation and faulting.

When confronted with such complexity, particularly where there are multiple brecciation events, it may not always be possible to completely unravel the geological history responsible for the rock mass conditions within the scope and context of the engineering studies. In these situations, there should be additional focus on engineering geological characterisation to identify and separate rock mass units which are the product of overprinting events of a similar nature.

Table 4 Example of a rock mass model for a porphyry copper deposit in Southeast Asia (Eggers 2016)

Rock mass unit	Rock mass description	Correlation with geological model	
		Alteration/rock type	**Faulting**
WR	'Weathered rock'	Argillic/EW-HW rock	
FR	'Fractured rock' with high to moderate rock quality designation (RQD), no clay and isolated shears	below gypsum surface Late-stage andesite	Outside major fault zones
HF	'Highly fractured rock' with low RQD, occasional shears and breccia zones	Propylitic better quality intermediate argillic	
FG	'Fragmented rock' with very low to zero RQD; some clay matrix development (clast supported) with some shears	Advanced argillic Poorer quality intermediate argillic	Generally outside major fault zones
HBx/FBx	'Clay breccia' (matrix supported) with numerous sheared zones and no drill water return	Intensely hydrothermally brecciated rock	Fault breccia
FC	'Crushed rock' typically characterised by very/extremely low strength rock and no drill water return	Independent of rock type	Fault crush seams

5.3.3 Porphyry copper example 2

A second porphyry copper deposit from Southeast Asia provides another example of using knowledge of the deposit's geological history to unravel the complexity of alteration and faulting controls on change in rock mass condition. The deposit comprises a classic telescoped porphyry alteration system with a late-stage supergene argillic cap. A transition zone between the two alteration systems marks a gradational change from dominant soil strength materials in the overlying argillic zone to rock conditions in the underlying porphyry-altered intrusive rocks. The presence of soil strength zones and very low intact strength rock in the transitional zone was controlling behaviour of the rock mass in stability analysis. Gaining an understanding of the distribution of the poor zones in this unit was important to the design.

Given supergene alteration is a 'top-down' process associated with the migration of meteoric fluids, the assessment started with the hypothesis that the distribution of soil strength to very low intact rock strength material in the transitional zone progresses with depth from the upper boundary with the argillic rock mass to the bottom boundary with the porphyry-altered rock. Detailed evaluation of core photos, televiewer images and engineering geological descriptions from geotechnical borehole logs enabled interpretation of two mixed-rock mass units in the transitional zone (Figure 11):

- TAP: mixed transitional and argillic altered intrusives which are immediately proximal to the overlying argillic altered intrusives. This unit is likely the result of higher leakage of percolating meteoric fluids into the transitional intrusives immediately below the boundary with the argillic zone. This process formed discrete, discontinuous semi-tabular to lensoidal shaped zones at the top of transitional intrusives comprising a mix of soil strength material and very low intact strength, intensely clay altered rock.
- TAF: mixed transitional and argillic altered intrusives which are controlled by faulting. This unit is likely the result of infiltration of meteoric fluids deeper into the transitional intrusives along major- and intermediate-scale fault structures forming steeply dipping zones of mixed soil strength material and very low intact strength, intensely clay altered rock. In general, the shape and thickness of the mixed soil-very low strength rock zones are related to the size of faulting controlling the zone, which typically thin with depth. These mixed alteration zones change into fault-damaged zones in the lower porphyry-altered intrusive rock below the transitional zone.

This additional detail to the rock mass model facilitated more accurate stability modelling for optimisation of the mine design to the expected geotechnical conditions.

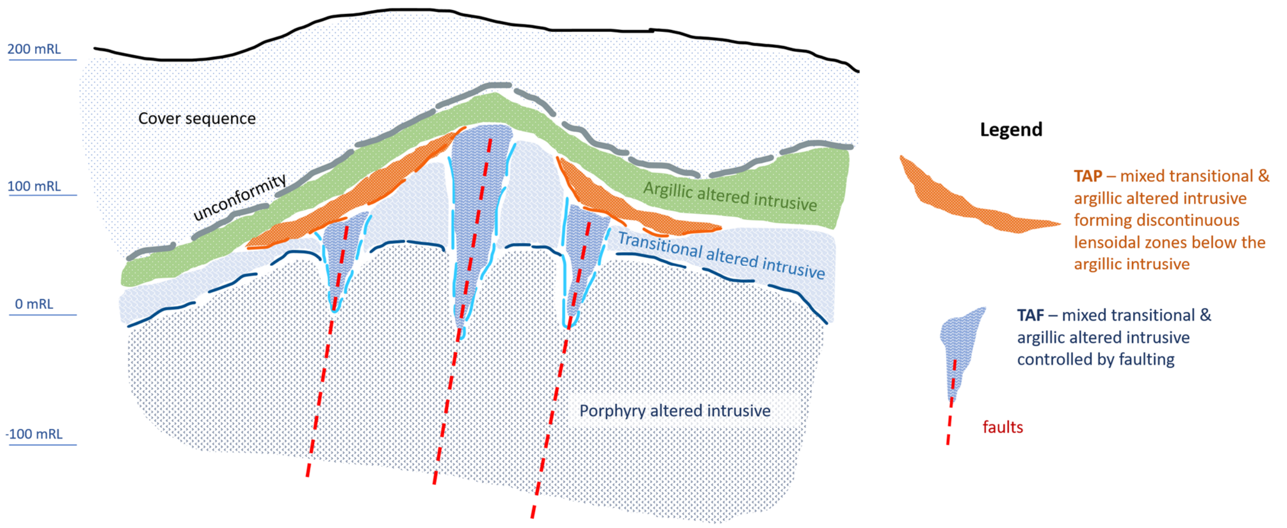

Figure 11 Schematic section showing the mixed argillic soil strength – very low rock strength altered zones

5.3.4 Pilbara banded iron formation example

Band iron formation (BIF) and associated shale bands in the Pilbara region of Western Australia have undergone a complex geological history, including:

- Diagenesis of original sediment.
- Metamorphism by burial.
- Structural deformation during several orogenic events.
- Alteration associated with the mineralisation process.
- Volume change associated with mineralisation.

Deformation and metamorphism generally increase to the south in the Hamersley Province associated with collision between the Pilbara Craton and Yilgarn Craton to the south during the Capricorn Orogeny around 2.2 billion years ago. As such, geological controls on BIF and shale band condition are correspondingly complicated, involving:

- Lithostratigraphic impacts on rock mass, structure and groundwater.
- Folding control on bedding, jointing and faulting.
- Faulting and shearing impacts on rock mass quality from multiple deformation events.
- Lithostratigraphic and folding controls on hypogene alteration of the BIF rock mass proximal to the orebody.
- Overprinting effects of supergene alteration and weathering.

The impact of shale bands on BIF rock mass condition is illustrated diagrammatically in Figure 12. The main factors which have resulted in degradation of BIF rock mass condition include (Eggers & Casparis 2007):

- Shearing along the shale-BIF contact of the shale bands by flexural slip during folding and synthetic faulting associated with continued shortening which forms faulted fold limbs.
- Alteration fluids leaking from the ore zone into the surrounding BIF during the mineralisation event, which are controlled by lower permeability shale bands acting as aquitards and resulting in desilification of the BIF rock mass.
- Concentration of groundwater flow in the BIF parallel to the lower permeability shale bands, resulting in leaching and oxidation.

Not all factors may have been active in every bedded Pilbara iron ore deposit, and other controls may also be important for specific orebodies. A conceptual model of the deposit will guide assessment of which factors should be considered in the rock mass model and wider EGM for pit slope design.

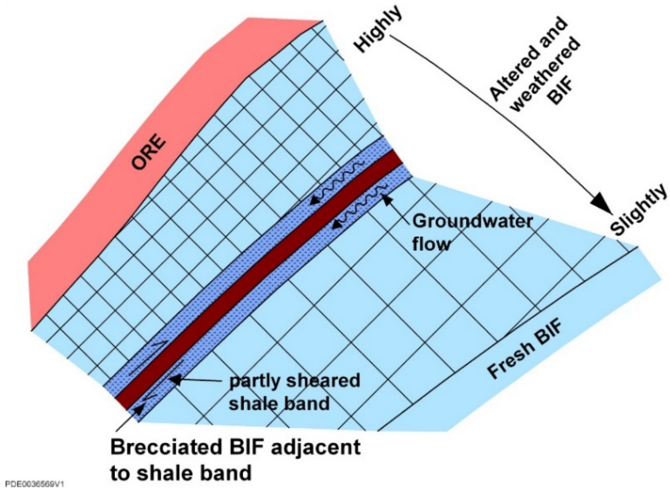

Figure 12 Diagram illustrating a range of possible geological controls on BIF rock mass conditions due to shale bands (Eggers & Casparis 2007)

5.3.5 Digital modelling and rock mass classification

Due to the small 'sampling' of the rock mass due to widely spaced geotechnical boreholes and lack of outcrop for mapping at the start of mining, digital modelling of rock mass unit boundaries can sometimes be based on selected elements of the geological model as a proxy. This should be based on the conceptual model and results of the engineering geological characterisation. However, caution is required when adopting geological proxies for modelling rock mass units. It is normally not appropriate to adopt all of the resource geological model; just the element of geology acting as the rock mass control — for example, alteration. The resource model is primarily compiled to explain distribution of mineralisation. In contrast, the EGM is formulated to explain change in engineering geological character, which is usually different to the form and function of the resource model.

Caution is also required with adopting a rock mass classification system as the main tool for geotechnical modelling. The ‘recipe approach’ provided by classification systems is sometimes seen to provide a quick and easy method of modelling the rock mass. Classifications use observations of several engineering geological characteristics and assign numbers which are summed in some way to give a single value.

The problem with this approach, as originally expressed by Bieniawski (1989), is that ‘…this single number is often used to represent total knowledge of the rock mass in the belief it has significance because it is “numerical”’. Applying a classification does not require much critical thinking and therefore it can stifle inductive reasoning. A classification rating provides no information on the collection of physical attributes that make up a rock mass and it is unable to promote an understanding of the geological controls on behaviour and mechanisms. Even in design, classification systems are no more than correlation tools taken from a finite database of case studies. Every time you use a classification system there is a degree of faith that the correlations used to formulate the classification apply to the rock mass being modelled.

When building the geotechnical model there should be less initial focus on the classification approach and more attention on the ‘big picture’ and conceptualisation to better understand the geological factors important for design. This is the essence of the EGM approach, where the focus is on rock mass behaviour and potential failure mechanisms, not just classification.

6 Conclusion

There is a need to bring the focus of geotechnical models back to the geology to enable more accurate predictions of slope stability conditions. This is to counter the tendency in recent practice to oversimplify the geological input by only using the resource model and to centre model development around rock mass classification systems when instead, structure and water are the dominant controls. The EGM is promoted as the best approach to understand the geological controls on rock behaviour and potential failure mechanisms to inform analysis and design.

An EGM is more than a multilayered presentation of datasets. It is a knowledge framework that operates within a heuristic thought system driven by the engineering objectives of the project. A key process in the model development is conceptualisation based on a ‘big picture’ understanding of the geological and geomorphological setting. The conceptual model allows anticipation of the geological features and processes important to the project and provides the context for interpretation of the investigation data to form the observational model. It is the observational model that constrains the model in space and time.

Overall, the main objective is to increase reliability of the slope stability predictions for better management of mining risks through the application of geological knowledge and expertise.

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Colleagues at PSM and fellow IAEG C25 members have contributed to concepts discussed in this paper: in particular, Tim Sullivan, Fred Baynes and Steve Parry. These ideas and concepts are also based on teaching models at the University of New South Wales in Sydney, Australia; the University of Canterbury in Christchurch, New Zealand; and the Arctic University of Norway in Tromsø, Norway, where ideas and theories on models are actively challenged and debated with students.

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