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Guidelines for the development and application of engineering geological models on projects

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Guidelines for the development and application of engineering geological models on projects

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Guidelines for the development and application of engineering geological models on projects

INTRODUCTION

The purpose of these Guidelines is to 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. The Guidelines are broad ranging, intended for use or reference by stakeholders in projects of all scales that interact with or require an understanding of the ground. They are intended to have worldwide application.

An Engineering Geological Model (EGM) is a comprehensive knowledge framework that supports the interpretation and assessment of the engineering geological conditions and allows the interaction of these conditions with the proposed project to be evaluated, so that appropriate engineering decisions can be made throughout the life cycle of the project from inception to decommissioning. In adopting this definition, the intention is to move beyond the concept that a ‘model’ is a simplified and static three-dimensional representation of the ground conditions and recognise that the formation and development of the EGM is an on-going process of knowledge accumulation that provides direction and control to the ground engineering throughout a project.

The Guidelines have been developed to provide guidance to practitioners on the ’EGM approach’, including 3D digital modelling techniques, and to inform consultants, clients, owners, government bodies and regulators about the use of Engineering Geological Models on projects.

The Guidelines were developed by members of the IAEG C25 – Commission for the Use of Engineering Geological Models – and represent the consensus views of the contributors.

It is intended that these Guidelines will be translated into other languages for dissemination internationally within the ground engineering community. The Guidelines will continue to be reviewed and revised in response to feedback from their use in different parts of the world.

The Guidelines comprise two parts:

1. Advisory Clauses for the development of EGMs (Part 1). Advisory Clauses indicate how an appropriate EGM should be developed for any project that interacts with the ground.
2. Commentary on the Advisory Clauses (Part 2). The Commentary provides additional supporting information, where necessary, for each Advisory Clause and is structured with the same paragraph numbering to allow ease of referencing; hypertext links are provided where relevant.

Notes:

1. The purpose of these Guidelines is to provide information and assist decision making; the Guidelines are not intended to define a standard of work.
2. The Guidelines should not be interpreted as prescribing a course of action or procedure on model building as there may be variations in approach and method to account for specific engineering geological and project needs.

Background

The use of 'models' in engineering geology was discussed by Zaruba and Mencl (1954 in Czech) and Morgenstern and Cruden (1977), although the first time a cross section through the ground was created to illustrate the geological conditions for an engineering project was, arguably, the first engineering geological model. An example is the work of William Smith and the development of geological maps and sections associated with canal construction in the UK in the 18th century. Fookes (1997) brought the idea of models in engineering geology to a wider audience but referred to the models simply as geological models. Fookes *et al.* (2000) refined the approach to include the concept of the 'total geological history,' that is, that the engineering characteristics of the ground result from the entire geological and geomorphological history of the area. Knill (2003) suggested that a 'geological model' is inadequate on its own for engineering purposes because it does not sufficiently define the engineering conditions within the natural ground or help deliver a design. He proposed that it was more useful to think of geological models, ground models and geotechnical models, with the type of model being related to the progression of the project. Bock *et al.* (2004) provided a perspective on the relationship between the disciplines of engineering geology, soil mechanics and rock mechanics, the areas of interest of the associated international learned societies and the nature of geological models and ground models.

IAEG Commission C25 published an interim report (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 examples. This approach has been adopted in recent guidelines (for example, The Geological Society, London, Engineering Geology Special Publication, 28, for glacial and periglacial terrains, Giles *et al*., 2017). However, the EGM approach has not yet been incorporated in National and International Standards.

Baynes *et al*. (2021) expanded on the C25 interim report and emphasised that the EGM is a knowledge framework that can be used to understand and communicate everything that is known about the geological and associated engineering conditions at any stage of a project.

These current Guidelines were developed by members of the IAEG C25 - Commission for the Use of Engineering Geological Models - following the IAEG 12th Asian Regional Conference in 2019 at Jeju, South Korea. A first draft of the Guidelines was presented at the IAEG 3rd European Regional Conference in Athens in October 2021.

The IAEG C25 EGM Guidelines version1.0 was made available as a freely downloadable pdf on the IAEG website from 14 December 2022.

In 2024 the Guidelines were revised in response to comments received and the examples which were included in version 1.0 were removed. However, some figures from the examples have been retained in the Commentary.

Contributors to the Guidelines and their countries of origin are listed in Appendix A.

1 ADVISORY CLAUSES

1.1 EGM DEVELOPMENT PRINCIPLES

1.1.1 Definitions

Important terms that are used throughout these Guidelines are defined here; other terms are defined where they appear in the text.

- Model – an approximation of reality created for the purpose of solving a problem.
- Engineering geology – The application of geological, geomorphological and hydrogeological knowledge to engineering.
- Engineering Geological Model (EGM) – 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. The EGM comprises both conceptual and observational components and may consist of a number of interrelated models and approaches. The Geological Model, the Geotechnical Model and a Geohazard Assessment are outputs from the EGM knowledge framework.
- Conceptual Model – a model based mainly on engineering geological concepts and interpretations and the knowledge that certain engineering geological conditions and processes are likely to have certain engineering characteristics. A temporal conceptual model (sometimes called an evolutionary model) illustrates how ground conditions may have evolved over both recent and geological time.
- Observational Model – a model based mainly on engineering and geological observations and measurements that are constrained in space by 3D data (xyz) or in space and time by 4D data (xyz plus time). Increasingly, the observational model is developed within a digital environment.
- Engineering geological units – volumes of the ground with a similar geological history and similar engineering characteristics that are established in the context of the project engineering.
- Engineering geological mapping – the preparation of a map depicting the distribution and surface boundaries of engineering geological units, geological structures, geomorphology and hydrogeological conditions that are of significance to the project using appropriate symbology carried out at a scale and level of detail determined by the purpose of the mapping, which might range from regional resource assessment to confirmation of foundation conditions.
- Geological Model – an output from the EGM knowledge framework that documents the distribution in 3D space of the engineering geological units, hydrogeological conditions and geological and geomorphological processes.
- Geotechnical Model – an output from the EGM knowledge framework that provides the engineering characteristics and/or geotechnical parameters of relevant aspects of the Geological Model.
- Analytical Model – a simplification of the Geological Model and the Geotechnical Model developed for the purpose of engineering assessment, analysis or design.
- Digital Model – collation and presentation of data within a software environment to allow visualisation, interpretation and aid in communication of parts of the EGM, increasingly developed in 3D.

- Digital visualisation – the output of a digital model, usually a graphic display in 2D or 3D of selected parts of the data.
- Ground Model – a type of model, often specified as a deliverable in contracts or required by standards, that provides a summary of the understanding of the ground and groundwater conditions at a site at a specific point in time. This may include geotechnical parameters for the various units contained within it. The meaning of this term varies in different codes and standards.
- Geohazards – geological and geomorphological processes or phenomena that can adversely impact a project, for example, karst development, landslides, underground mining, ground gas, seismic activity etc.
- Project – the purpose for which the EGM is being developed. EGMs are commonly used to assess the ground response to an engineering project but they are also used for broader application such as the assessment of natural resources, regional geohazard assessments etc.

1.1.2 Fundamental principles

1.1.2.1 The EGM evaluates interactions between the project and the ground

The purpose of the EGM is to evaluate the ground response to change and usually involves consideration of the possible interactions between the project and the ground. An effective EGM should anticipate what might be in the ground and how the ground might respond to the project.

1.1.2.2 The EGM knowledge framework

The EGM knowledge framework represents an understanding of the geological, geomorphological and hydrogeological conditions that are of engineering significance to the project and that can be used to solve engineering problems, (Figure 1-1). The EGM is not one 'model' but multiple dynamic models, as well as being the repository of the underlying data (if that is not held within the models themselves), the supporting documentation (for example, the site investigation reports) and the knowledge framework that holds these components together. To the extent that is practical, the EGM should be based on all available and relevant knowledge, should be logically constructed following the principles established in these Guidelines, should be focused on the relevant geological, geomorphological and hydrogeological conditions and engineering characteristics of significance to the project and should be clearly communicated.

Three key outputs from the EGM for a project are the Geological Model, the Geotechnical Model and a Geohazard Assessment.

1.1.2.3 EGMs comprise conceptual ideas and observational data

The balance of conceptual ideas and observational data within an EGM will vary depending on the project type, its scale, the geotechnical complexity of the site and the stage of the project (Figure 1-1). Evaluation of the ground at the start of a project is primarily conceptual in that it is based mainly on knowledge, experience and reference to other published examples of similar geological, geomorphological and hydrogeological conditions. As the project progresses and increasing amounts of observational data become available the EGM evolves but the conceptual model remains as the framework for assessing the interpretation of those data.

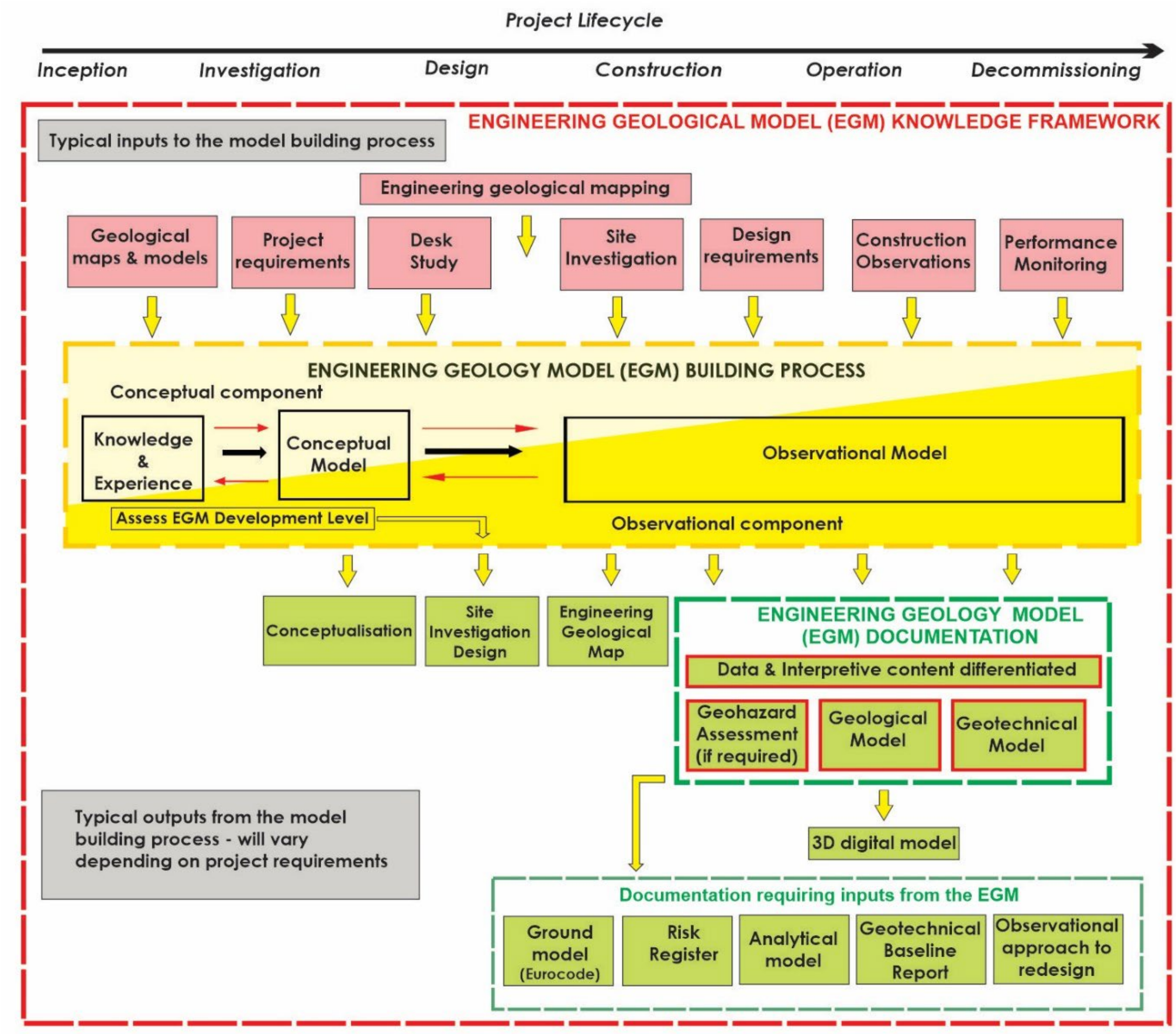


Figure 1-1 A schematic visualisation of the EGM development through the project lifecycle.

The techniques involved in developing conceptual models and observational models are different. The first involves the act of conceptualisation and the second involves the act of evaluating data and assembling information. However, their use in the development of EGMs is so profoundly interlinked that, in reality, they form two different but essential and complimentary tools that must be combined at all stages of the project to generate an appropriate EGM.

At any stage of the project engineering analysis should proceed cautiously until conceptual ideas and observational data have been reconciled and any residual discrepancies can be managed as project risks accepted by all relevant parties (Figure 1-2).

1.1.2.4 The EGM is relevant throughout the project life cycle

The EGM development should commence at the project inception stage and be revised throughout the life cycle of the project, potentially passing between multiple owners and consultants, and provides a transparent and logical framework for developing ground related project deliverables (Figure 1-1). The EGM knowledge framework should also be an integral part of the project management system because the EGM documents what is known about the ground and, therefore, should form part of the contract documentation (depending upon the contract delivery mechanism) and the basis of design.

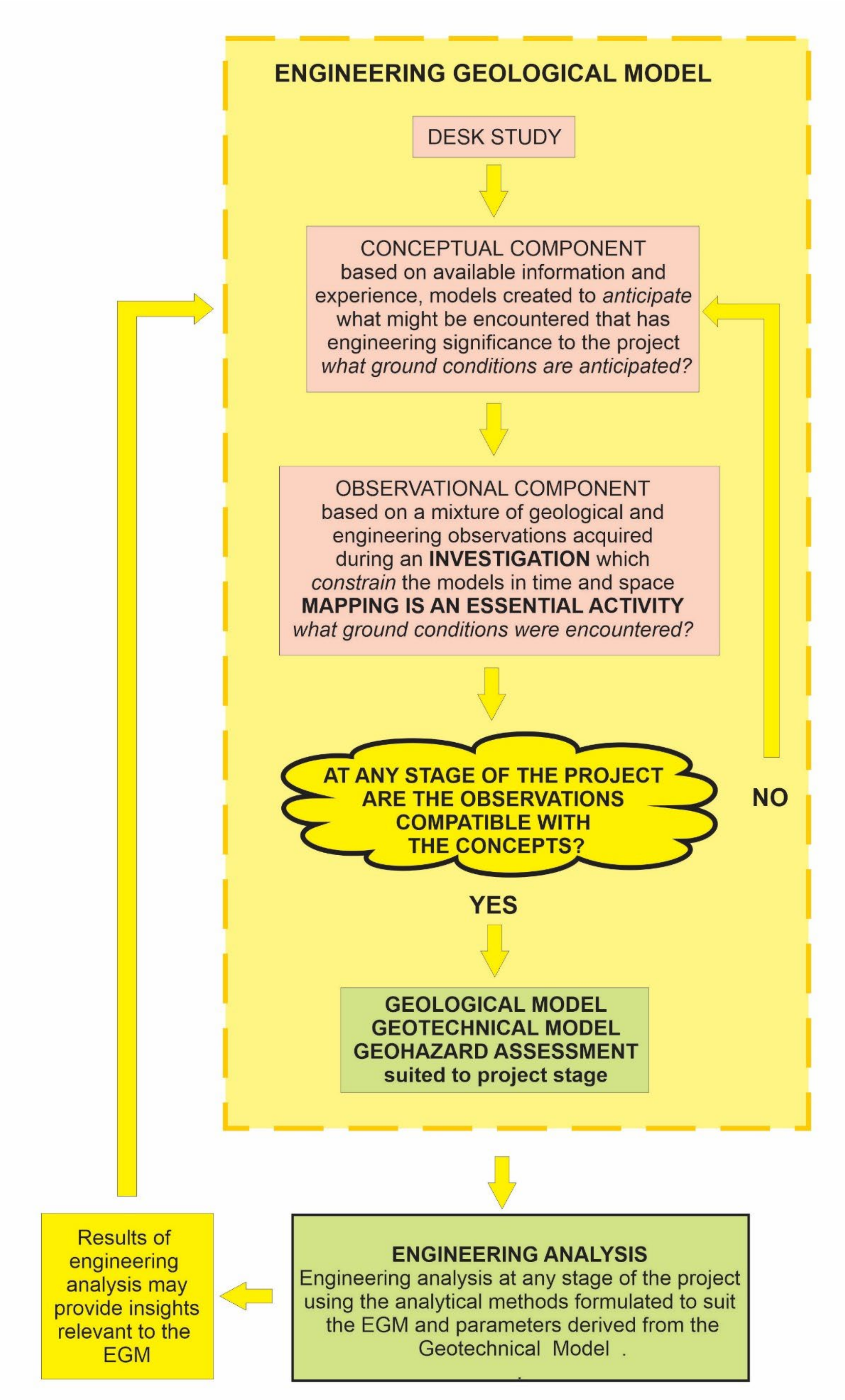


Figure 1-2 Engineering analysis should proceed when observations are compatible with concepts.

1.1.2.5 An EGM should be developed for all projects

An EGM should be developed for all projects that interact with the ground and is equally applicable for very large and very small projects and over a variety of geographical scales. Note that for very small, simple projects, the EGM can be presented in a single short interpretive report.

1.1.2.6 Knowledge of geology and engineering is required to develop an EGM

Knowledge and experience of both geology and engineering is required to develop an effective EGM but the emphasis should be on geology. This knowledge should be based on education, ideally involving at least a first degree in geology or a degree with geology as a major component and postgraduate training in engineering geology or geological engineering, or a significant period of mentoring under the supervision of an experienced engineering geologist. In some circumstances and on simple projects, a competent geotechnical engineer with significant geological knowledge and/or with valid practical experience in the geological setting of the project should be able to build a reliable EGM.

1.2 EGM DEVELOPMENT PROCESS

1.2.1 Overview of development process

1.2.1.1 The development process

The EGM development process involves the essential steps listed in Table 1-1, usually with repeated iterations of most steps:

Table 1-1 Essential steps in the EGM development process

1. Assemble team, define scope and purpose. Establish the likely EGM development level.
2. Assemble relevant engineering and engineering geological information of significance to the project in a desk study. If possible, undertake an initial reconnaissance mapping by a competent engineering geologist.
3. *Conceptualise* the likely engineering geological conditions based on the knowledge and experience and the desk study at the beginning of the project, but re-evaluate using other information as it becomes available at later stages of the project. Confirm EGM development level
4. Identify and document key hazards and uncertainties in an initial risk register. This register is used throughout the project's life cycle and needs to be updated on a regular basis.

~~5.~~ Acquire observations through investigations (these may include, but will not be limited to, remote sensing, mapping, geophysics, exploratory holes, sampling and testing); the importance of engineering geological mapping in investigations cannot be over emphasised.

6. Combine the observations and the concepts to develop an *interpretation* of the site conditions; define engineering geological units, interpret their distribution and generate a Geological Model. If necessary, re-evaluate the conceptual model.
7. Characterize the engineering geological units, the hydrogeological conditions and the geological processes using geotechnical parameters developed from the desk study, investigations and experience and generate a Geotechnical Model and, where required, a Geohazard Assessment.
8. Identify any further significant hazards, uncertainties, gaps and discrepancies within the knowledge framework; these are potential risks to the project and should be added to the risk register.
9. Evaluate the risks and, if necessary, undertake additional investigations to improve the knowledge framework, minimise unknowns and reduce risks or consider alternative engineering options to reduce risks to acceptable levels.
10. Document all of the above in a series of systematic reports with a significant graphic content.

1.2.1.2 Initial steps

The following key questions should be asked at the beginning of the project:

- Where is the project located (geography/geology/geomorphology/environment)?
- What is the type and scale of the project, how will it interact with the ground, what are the key dimensions and design requirements, including the design life, and what are the key geotechnical constraints, concerns or consequences of failure for a project of this type?
- What existing information with respect to the possible ground conditions is available?
- What is the geological/geomorphological/anthropogenic history of the region/site that might be of engineering significance to the project?

- What geohazards may be present?
- What are the groundwater and surface water conditions and how could they impact the project?
- What is the current status of the project, for example is it on hold, seeking financial backing, under construction etc?

Answering these key questions remains relevant throughout the project life.

1.2.2 Choice of development level of EGM

The level of development of the EGM that should be adopted is a function of the geotechnical complexity considered in the context of the project complexity and the consequences of failure; guidance on the choice of the level of development is provided in Tables 1-2 and 1-3. The development level should be revised if the investigation indicates that the geotechnical complexity is higher than anticipated.

Table 1-2 EGM development levels related to project and geotechnical complexity. **

	Geotechnical complexity of the ground that could influence the project - as indicated by the conceptual model developed in accordance with these Guidelines		
Project Complexity##	SIMPLE/UNIFORM: Gently dipping or horizontal strata, uniform soils, no geohazards, few geotechnical constraints	MODERATE/VARIABLE: Variable folding and/or faulting, variable soils, unconformities, few geohazards, some potential geotechnical constraints	COMPLEX/HAZARDOUS: Highly variable folding and/or faulting, deep irregular soils, unconformities, considerable geotechnical complexity, significant geohazards such as major landslide complexes, active faults, karst or the potential for geohazards magnitude and/or frequency to be increased by the project
Minor engineering development, small footprint, low consequence of failure	Level 1	Level 1	Level 2
Medium sized engineering development, with medium consequence of failure	Level 2	Level 2	Level 3
Major infrastructure, large linear projects, regional studies, high consequences of failure	Level 3	Level 3	Level 3

** When assessing the appropriate EGM development level, advice should be sought from a competent engineering geologist.

Project complexity is subjective; low and medium consequence of failure would typically be limited to financial impacts; high consequence of failure would typically be associated with loss of life; failure is when the project does not perform in accordance with the design/specified performance.

Table 1-3 Guidance on scope requirements for EGM development levels.

	Level 1	Level 2	Level 3
Specialist studies	None	None	Commission separate geohazard studies (where applicable) Possibility of specialised geological studies Possibility of ground/structure interaction studies
Mapping	Minimum of site visit, reconnaissance mapping, engineering geological sketch map/cross section of site	Engineering geological mapping including cross sections of site and surrounds	Engineering geological mapping including cross sections of project site and surrounds, at a variety of scales
Subsurface investigations	Single stage minor subsurface investigations for example, trial pits, boreholes as appropriate	Subsurface investigations as appropriate using boreholes, cone penetrometer tests, geophysics etc. Instrumentation	Multistage subsurface investigations using methods such as boreholes, *in situ* testing, geophysics etc., instrumentation and long-term monitoring as appropriate. Base line data collection
Laboratory testing	Limited or no laboratory testing	Laboratory testing as appropriate	Extensive and possibly specialised laboratory testing as appropriate
Documentation	Documentation of the EGM in a simple combined Data and Interpretive report	Documentation of the EGM in Data and Interpretive reports	Documentation of the EGM in Data and Interpretive reports. Consideration of 3D digital visualisation
Team	Possibly a single individual responsible for the works	Small team of engineering geologists and geotechnical engineers responsible for the works	Large multi-disciplinary group responsible for the works
Review	Internal Review++	Internal/External Peer Review++	External Review/Panel of Experts++

++ Company specific review requirements may exist.

1.2.3 Details of the development process

1.2.3.1 Assemble team, define scope and purpose

The composition of the team will depend on the likely complexity of both the project and the ground. This could range from an individual with the necessary geological and engineering knowledge for a small project to a multi-disciplinary group and a review panel for a major project. The roles and responsibilities of the team, the reviewer(s) and the approvers should be documented. The team should start off by defining the scope and purpose of the EGM and should take account of any planned changes to the ownership of the EGM, for example where the EGM is developed by a government agency then transferred to the winning bidder for the contract. Where the team joins the project at a later stage, or the project is transferred between contractually separate parties, then the existing project documentation should be reviewed to identify any gaps or inadequacies.

1.2.3.2 Assemble relevant engineering and geological information in a desk study

A desk study is an information gathering exercise to assemble relevant material so that the maximum value can be derived from existing available sources prior to spending time and money collecting new information. Primary information will likely be geological maps and memoirs, topographic maps, any existing site investigation data such as boreholes, remote sensing data, geohazard information etc. Historical data should not be disregarded as a consequence of being superseded by more recent datasets or being recorded in a style not in line with current standards.

As part of the desk study reconnaissance mapping should be undertaken where practical. This allows the evaluation of the desk study data and assists conceptualisation.

1.2.3.3 Conceptualise the EGM

Conceptualisation is the process whereby all the available information is considered and an understanding is developed of what the ground conditions at the site are likely to be and how they developed over time. This should take place initially after the desk study but then should be carried out periodically as additional information is acquired. Conceptualisation allows an assessment of what conditions and what variations may be present and the geological and geomorphological processes that have produced them and that could be of engineering significance to the project. It is sometimes useful to develop a temporal conceptual model to illustrate how ground conditions may have evolved over both recent and geological time.

During conceptualisation the following aspects of the site should be considered:

1.2.3.3.1 Project Setting

This should be based on an appreciation of:

- The overall tectonic setting and regional geology of the project location.
- The current, past and potential future climatic settings of the project location.
- The requirement to look beyond the immediate site area, for example the evaluation of landslide hazards originating from outside the site.

1.2.3.3.2 Stratigraphy – rock and soil types and relationships

This requires an understanding of rock-forming and rock-modifying processes as well as the processes of soil origin and transportation and deposition that produced the rock and soil types in the project area. This allows consideration of rock mass and rock and soil material properties, the likely characteristics of engineering geological units, including the boundary conditions of the units, plus their likely geometry, distribution and relationships - both with each other and with the project.

The stratigraphical age of the materials and the identification of the sequence of geological events that the materials have been subject to since their formation should be understood. This supports the application of the *total geological model approach* in which all of the engineering characteristics of the ground are interpreted as resulting from the entire geological and geomorphological history of the area.

1.2.3.3.3 Geological Structure

An understanding of geological structures should be developed, including the presence of tectonic features at all scales and the nature of the boundaries of engineering geological units and the discontinuities within them, their origin, geometry, spacing, persistence, extent, characteristic features and their engineering significance. This understanding should also include the timing and sequence of rock and soil forming events, deformation phases, landform development and stress relief effects.

1.2.3.3.4 Surface and subsurface processes

Identification of possible active or potentially reactivated geohazards and an initial evaluation of their likely variations in magnitude and frequency over time is required. The surface and subsurface water conditions and how they might change over time should also be evaluated.

1.2.3.3.5 Initial engineering geological characterisation

It may be possible to attribute geotechnical parameters to parts of the conceptual model, based on existing data or knowledge, insofar as is reasonable given the data available, for example, soil and rock strength, stiffness, permeability, geomorphological process rates, etc. Evaluation of potential geotechnical risks (and possible project opportunities) can be used to populate an initial risk register.

1.2.3.3.6 Initial Geological Model

Conceptualisation will generate an initial **Geological Model** that can be used to plan the site investigation. The initial Geological Model is then refined by acquiring observational data from the site investigations.

1.2.3.4 Acquire observations of the project area through investigations

Information acquired during the desk study is the starting point for developing both conceptual and observational models. However, most observations are acquired during the site investigation stage(s) of the project. Further observations should be added during construction and operation.

A geological interpretation of the environment of deposition and/or the stratigraphic age should accompany all material descriptions in the logs of boreholes, test pits, exposures etc.

Site investigations that consist solely of observations and interpretations without the use of a conceptual framework are likely to be fundamentally flawed and should not be accepted.

Following conceptualisation there should be a broad understanding of the possible characteristics and distribution of engineering geological units at the site, the nature of any geohazards and any suspected gaps in the knowledge framework. This understanding should then be focussed on the ground characteristics that are critical for design and used to identify investigation targets and plan investigations that will improve the understanding and reduce uncertainty in those critical areas.

The importance of systematic mapping in investigating any project is emphasised. The mapping should include acute, insightful observations over the entire project area and reasoned well founded interpretations of those observations. All projects should have an engineering geological map compiled and 'owned' by the team responsible for carrying out the investigations. Essentially, such maps must be developed out in the field, although increasingly the field component includes ground truthing of maps prepared in the office by combining observations derived from various data sets within a 2D or 3D digital environment or from interpretation of remote sensing imagery. It is essential that any engineering geological mapping also captures geological patterns (for example, lineaments, structural patterns, discontinuity types and contact traces etc.) as well as the geomorphology.

For larger projects or more complex sites or critical structures, the site investigation is usually multi-staged with the acquired observational data being compared to the conceptual model to determine which areas of uncertainty and which risks remain to be evaluated in successive stages of the investigation.

The investigations will acquire observational data that typically includes:

- Topographic survey, and increasingly using LiDAR (Light Detection And Ranging) generated DEMs (Digital Elevation Models).
- Engineering geological mapping at various scales ranging from regional studies, project area studies, geotechnical component studies and individual foundation studies. All mapping should be seamlessly integrated into the one data set that can be viewed at a variety of scales.
- Information from intrusive investigation techniques such as boreholes, test pits, shafts, adits etc.
- Downhole data such as borehole imaging, geophysics and other tools.
- Installed instrumentation and the results of monitoring.
- Laboratory and field test results.
- Groundwater and surface water measurements.
- Geophysical survey results.
- Descriptions and classifications (for example, rock types, rock strength classes using recognised systems and terminology).
- Measurements such as intersection depths of engineering geological units in a borehole, strikes and dips on strata and discontinuities.
- Remote sensing techniques such as InSAR (interferometric synthetic aperture radar).
- Other observational data including temporal observational models (for example, time series of seismicity, rainfall, landslides etc) that are critical for predicting the frequency of future geohazards.

1.2.3.4.1 Input data verification

Before any interpretation of the observational data there should be a data review and collation step where the key questions of accuracy, usefulness and representativeness should be tested for each dataset. Any concerns about accuracy and representativeness of the dataset should be documented with possible explanations discussed.

1.2.3.5 Combining conceptual ideas and observational data together in the EGM

Combining the conceptual and observational components involves *interpretation.*

This iterative process of combining the conceptual and observational components of the EGM in an interpretation should be traceable, documented and structured. Subjective judgments by those responsible for developing the EGM should be avoided and replaced with objective and assessable sources (for example, models and case histories from literature, mapping, geotechnical investigation, geotechnical monitoring, etc.) together with the reasoning behind their adoption in the interpretation.

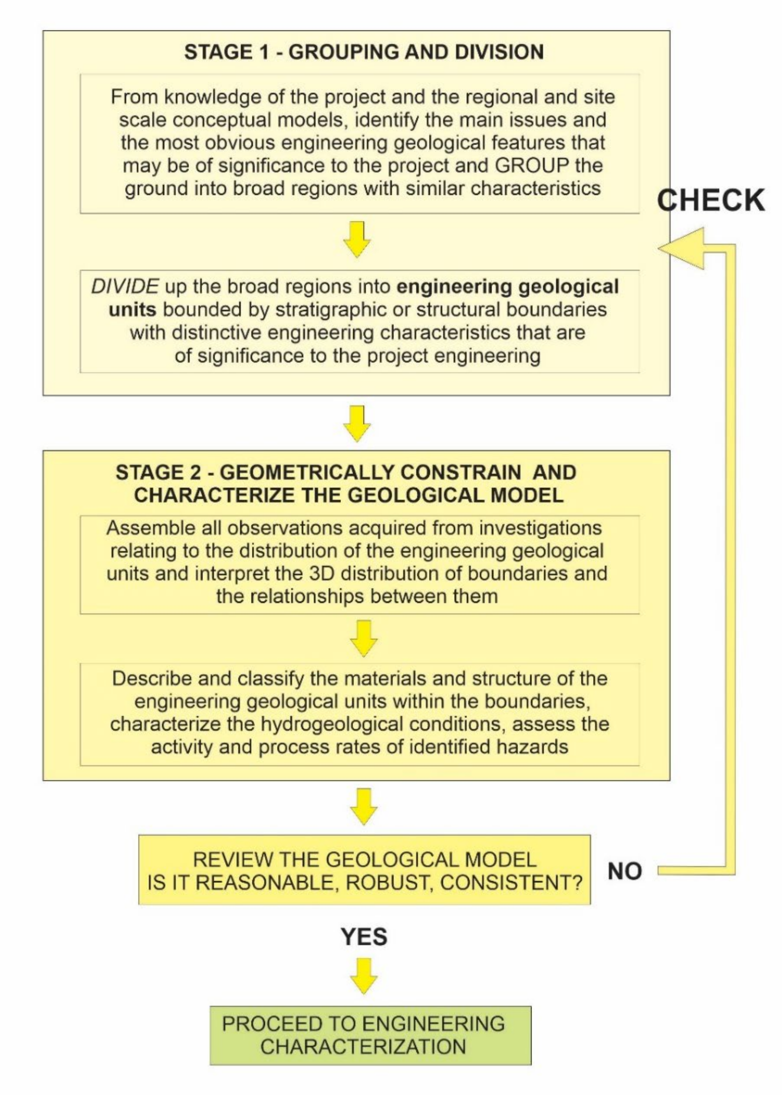
1.2.3.6 Defining and characterizing engineering geological units

A key product of any EGM is the definition of engineering geological units that are based on an understanding of their engineering geological characteristics/geotechnical behaviour and are appropriate for the project engineering. The definition of engineering geological units supports the development of the **Geological Model**.

A common approach is to adopt engineering geological units based on the distinctive litho-stratigraphical divisions identified on the site (that is, the units of soil and rock that can be differentiated) that are usually subdivisions of the chronostratigraphic units (age based units) provided on the geological map. However, lithostratigraphic units may not correspond to the most useful engineering geological units (that is, they may not take into account distinctive geomorphological processes, geotechnical behaviour, hydrogeological characteristics etc.) Furthermore, the resolution of stratigraphical units may not suit the purpose of the model.

Nevertheless, engineering geological units should not cross lithostratigraphic boundaries,. Lithostratigraphic units contains a distinct geological history and different geological histories should not be combined in a single engineering geological unit, even if the geotechnical characteristics are similar. The exceptions to this are fault zones that may need to be considered separately and that, by definition, cross the lithostratigraphic boundaries. Note that these boundaries will be scale dependent – the boundaries for a regional model may be different from the boundaries for a site scale model.

The engineering geological units chosen should reflect those conditions that are of significance to the project and may include geological controls such as weathering, alteration and faulting. Figure 1-3 outlines the operations involved in establishing engineering geological units and thus developing the Geological Model. As with other aspects of the EGM, the resolution and scale of the engineering geological units should be clearly linked to the EGM scope and purpose. The engineering geological units adopted should be reviewed as additional data become available.



From knowledge of the project and the regional and site scale conceptual models, identify the main issues and the most obvious engineering geological features that may be of significance to the project and GROUP the ground into broad regions with similar characteristics

DIVIDE up the broad regions into **engineering geological units** bounded by stratigraphic or structural boundaries with distinctive engineering characteristics that are of significance to the project engineering

Assemble all observations acquired from investigations relating to the distribution of the engineering geological units and interpret the 3D distribution of boundaries and the relationships between them

Describe and classify the materials and structure of the engineering geological units within the boundaries, characterize the hydrogeological conditions, assess the activity and process rates of identified hazards

REVIEW THE GEOLOGICAL MODEL
IS IT REASONABLE, ROBUST, CONSISTENT?

Figure 1-3 Establishing engineering geological units and the basis of the Geological Model.

1.2.3.6.1 Geotechnical complexity

In geotechnically complex areas, geotechnical properties may vary rapidly, potentially across a wide range, within the project site. Geotechnical complexity should, where possible, be reflected in the Geological Model in the form of sufficient engineering geological units with appropriate distributions and interrelationships. Where this is not possible, simplification may be necessary and the EGM documentation should describe the geological processes and geological history that produced the geotechnical complexity, the nature of any simplifying assumptions used in generating the engineering geological units and illustrate the potential complexity using a visualisation of the conceptual model.

1.2.3.7 Engineering characterisation

Engineering characterisation involves evaluating and assigning geotechnical parameters relevant to the project engineering to each engineering geological unit in the Geological Model, that then develops into a **Geotechnical Model**.

The process commences during conceptualisation although any parameters assigned at this stage will probably be associated with considerable uncertainty. The site investigation involves *in situ* and laboratory testing to assist with the evaluation of the relevant geotechnical parameters that will vary depending on both the ground conditions and the type of project. The results of the investigations will thus improve the characterisation of the engineering geological units and reduce uncertainty and will probably be an enhancement of what was envisaged in the conceptual model.

The Geotechnical Model might involve a simplification of the details contained within the Geological Model, for example, with respect to a complex fault zone, this might reduce to the bounding surfaces and some simplifying assumptions on the strength, stiffness and permeability of the entire fault zone. However, any simplification should not remove key engineering geological units that need to be considered separately due to their geotechnical behaviour.

The following approach should be adopted:

- The focus should be on engineering characteristics that are relevant to the project.
- Group the laboratory and *in situ* test results for each engineering geological unit identified.
- Material properties and geotechnical parameters should be assigned primarily from the site-specific investigations. However, these may be supplemented with values derived from experience, theory, correlation or empiricism provided that the method of determination is explained, justified and referenced.
- Consider bias resulting from sampling and testing difficulties and the number of tests for each unit and decide the range of representative values for the engineering geological unit. Averaging of material properties that masks the presence of significant weaker zones should not be undertaken, and the full range of results must be assessed to identify the probability of values being higher and/or lower than the representative values.
- Compare the representative values with experience and published values for similar units.
- Consider and explain any anomalous or extreme results. These may indicate that the engineering geological units may need refining.
- Highlight any limitations in the data or the analysis.

Note that the choice of engineering parameters for use in analysis by the designer should be based on the above information, ideally presented graphically, coupled with considerations of project engineering objectives, risk and possibly code requirements.

1.2.3.7.1 Zoning

Once the engineering geological units have been defined and the geotechnical characteristics assessed it may be useful to define zones or domains with the same geotechnical characteristics. The zones may be defined by geomechanical behaviour, seismic velocity, rock mass classification etc. but may also be based on any attribute of engineering significance to the project, for example acid sulphate potential, landslide susceptibility, or groundwater geochemistry, so that the EGM can be used for a variety of engineering analyses, risk assessment, constructability assessment etc. The decision on appropriate zoning should be made in conjunction with designers and the broader engineering team.

The scale at which zoning is undertaken should reflect the nature of the data and how the outputs are to be used. Zoning should neither be more detailed nor less detailed than the data allow.

A common mistake is to zone the ground at, say, borehole scale, then try to ‘join the dots’ between boreholes. It is almost impossible to factor in the broader geological setting and total geological history using this method. For the EGM to effectively contribute to engineering analysis and design, the sensitivity of the analyses to certain critical zones defined by the model should inform the resolution and scale of the zoning.

1.2.3.8 Uncertainty, gaps and discrepancies in the EGM

During the development of the EGM there should be periodic assessments of the degree of agreement between the evolving conceptual ideas and the progressively acquired observational data. These assessments will typically take place at agreed project reporting stages.

If there is a disconnect between what is anticipated to be present and what has been found during investigations, the reasons for this need to be identified and the EGM improved. If during design the EGM does not allow a realistic prediction of how the ground will respond to the project with the required level of certainty, then more information is needed to improve the EGM. Improvements to the EGM to mitigate identified risks may take the form of further investigations or design strategies such as increased conservatism or the adoption of the observational method during construction.

As a project moves into the construction phase, the exposed ground conditions should be evaluated against the conditions anticipated by the EGM. Then an assessment must be made as to whether or not these variations could potentially impact on the design or construction methodology and whether or not these methodologies need to be changed or if the risk register requires updating.

Throughout the development of the EGM uncertainty, gaps and discrepancies may be manifested as risks. Where potential risks to the project are judged to be significant, these should be recorded in the risk register. Management of those risks should be based on an understanding of the level of risk that is acceptable to the client, the general public and as determined by any legislation. The risk appetite/risk tolerance of the client should be based on an informed understanding of the known ground conditions that should be communicated using the EGM.

1.2.4 EGM and Eurocode

The approach described in these Advisory Clauses is an overarching process suited to developing an EGM knowledge framework for engineering decision making on any type of project at any stage of the project lifecycle. The Eurocode approach has a more restricted application to select stages of certain types of projects and there are terminological differences notably with respect to the components of a ‘ground model’, whilst the concept of an Engineering Geological Model developed throughout the project lifecycle is not mentioned.

Refer to Commentary Section 2.2 EGM DEVELOPMENT PROCESS for further information

1.3 ASSEMBLY AND COMMUNICATION OF THE EGM

1.3.1 Introduction

The EGM should be documented in a format that can be used to communicate the various components of the EGM, principally to consultants and contractors, but also to other audiences.

The documentation should include text, maps and sections as a minimum but more often will consist of detailed text and accompanying diagrams, tables, logs, photographs, maps, sections, data sets, processed data and digital models that should each be essentially transparent, self-explanatory, self-contained and be able to be clearly and easily understood.

All encoded EGM data should be processed/preserved within a centralised, standardised and integrated data management and presentation system. The data can range from hand-drawn maps and sections to 3D (spatial) models including, sometimes, sophisticated software-generated models and 4D (spatial and temporal) models that describe process rates.

1.3.2 Brief for documentation of EGM components

Table 1-4 is an example brief for consultants to follow when documenting the various components of an EGM. For small projects many of these items could be described in single paragraphs and the entire documentation presented in one brief report.

In some circumstances, a site investigation may be designed using an EGM but upon completion of the investigation the contractual requirement may the production of a Data Report only. The result will be that documentation of the EGM will be incomplete because it is lacking an interpretive content and this should be acknowledged and documented by all parties to the contract.

For large projects there may be several volumes of different reports in which the EGM components are included.

When tendering for geotechnical services for large projects the provision of all of the components of an EGM should ideally be a separate scope item alongside and related to the provision of Data and Interpretive Reports. In those circumstances, the Request for Tender documents should specifically describe the EGM development expectations, whilst the Tender evaluation process should consider the proponent's EGM capabilities and appropriate budget allowances should be made at project inception.

1.3.3 Project procurement implications

Documentation of the EGM components prepared in accordance with these Guidelines should ideally be included or referenced within the project documentation. Depending on the Client's project procurement strategy, there should be identifiable preservation points within the project schedule when the documentation of the EGM components should be completed and preserved as a record of what was known at that time. As the project progresses, the documentation of the EGM components can then be revised to reflect the changing knowledge. The following are typical preservation points:

- For small projects there will be a single preservation point, usually at the completion of the site investigation.
- For larger projects some, or all, of the following preservation points may apply:
    - At the completion of the Desk Study.

- At the completion of each stage of the Investigation.
- At completion of each stage of Design.
- At finalisation of the contract for the Main Works.
- At the agreement of Baseline Conditions, if applicable.
- At agreed milestones during construction related to the completion of various project elements, for example, dam foundations, tunnels etc.

When tendering for the main works the contract documentation should ensure that the EGM is transferred to tenderers, where contractual arrangements allow.

Table 1-4 Brief for documentation of EGM components.

1. Documentation of the EGM components should follow the IAEG Guidelines for the development and application of engineering geological models on projects.
2. The EGM Development Level agreed with the client (the scope of the study) should be indicated.
3. A Data Report should be presented that provides the results of all investigations, observations and laboratory testing including information from all previous studies.
4. An Interpretive Report should be presented (possibly as separate reports) that includes:
    - (i) The findings of the Desk Study.
    - (ii) The Conceptual Model and the initial key risks identified.
    - (iii) The rationale for the site investigation design taking into account the conceptual model and the key ground risks.
    - (iv) The identified Engineering Geological Units - volumes of the ground with a similar geological history and a similar geotechnical behaviour in the context of the project engineering.
    - (v) A Geological Model that documents the distribution in 3D space of the engineering geological units, hydrogeological conditions and geological processes and how those might change in time.
    - (vi) A Geotechnical Model that presents the engineering characteristics and relevant geotechnical parameters of every aspect of the Geological Model. For every engineering geological unit identified an engineering description and geotechnical parameters should be provided.
    - (vii) Maps, plans and sections at appropriate scales should be provided to illustrate the interpreted Geological and Geotechnical Models and to inform the engineering assessment of all geotechnical elements of the project. The combination of geological, geotechnical and project engineering information in the one drawing or set of drawings is often useful.
    - (viii) A Geohazard Assessment if needed
    - (ix) If a 3D digital model forms part of the documentation a 3D Digital Model Report should be provided.

1.3.4 Reporting the EGM

The reporting should be clearly differentiated into:

- Data information and observations.
- Interpretations, including conceptualisations.
- Opinions.

The recommended reporting requirements for the following report types are described below.

1.3.4.1 Data Report

A Data Report should include, but may not be limited to, the following information:

- Objectives and agreed scope.
- Location and description of the project site.
- Description of the regional and local geology and any anthropogenic modifications to the project site based on pre-existing data.
- Details of any previous investigations at the site or in close proximity.
- A plan showing existing and current investigation locations.
- Investigation methods employed.
- Results of investigations and information acquired.
- Laboratory and *in situ* testing carried out and a summary of the results.

Any interpretation undertaken as part of the Data report, for example, the assigning of lithological or stratigraphical units, or geophysical interpretation, should be clearly recorded as such and the uncertainty associated with it, including alternative interpretations, documented. A ’limitation statement’ relating to any interpretive aspects of what is primarily the Data content of the report may be included.

1.3.4.2 Interpretive Report

The Interpretive Report should include, but may not be limited to, the following components:

- Reference to the data upon which the interpretation is based (the data or a Data report).
- The findings of the desk study.
- The conceptual model and the initial key risks identified.
- The rationale for the site investigation design taking into account the conceptual model and the key risks and uncertainties.
- Based on the findings of the investigation, sufficiently detailed and documented information relating to the following aspects of the project is required:
  - Stratigraphy, lithology, age, weathering and alteration.
  - Structural setting, defect or discontinuity characteristics.
  - Geomorphology and relevant surface and subsurface processes.

  - Surface and groundwater conditions.
  - Total Geological History relevant to the likely ground conditions.
  - Details of any anthropogenic modification to the project site.
- The identified Engineering Geological Units and the basis for their adoption.
- A Geological Model that documents the distribution in 3D space of the engineering geological units, hydrogeological conditions and geological processes and how those might change in time, their controls and boundary conditions and groundwater, geomorphological processes and geohazards that have been observed or interpreted to occur on and around the site. The Geological Model should characterise units of the ground with similar engineering properties and describe boundaries where changes in conditions may occur. The regional context of the Geological Model should be discussed. Uncertainty in the Geological Model should be characterised. Depending upon project and reporting requirements, the Geological Model that is presented may have a specific project-related focus and may be better described as, for example, a hydrogeological model or a rock mass model.
- A Geotechnical Model that presents the engineering characteristics and geotechnical parameters of every relevant aspect of the Geological Model, considering the project to be procured. For every engineering geological unit identified an engineering description and geotechnical parameters should be provided. The range of material properties should be described and the typical range of parameters provided. Uncertainty in the Geotechnical Model should be characterised. The choice of engineering parameters for use in analysis should be based on the above information.
- Any zoning that has been used or domains that have been defined and the basis for their adoption.
- A Geohazard Assessment where needed.
- An engineering interpretation of the implications of the ground conditions for the project.
- Maps and sections at appropriate scales covering the site and surrounds should be provided to illustrate the interpreted Geological and Geotechnical Models and to inform the engineering assessment of all geotechnical elements of the project. Depending upon the project, the combination of information relating to the Geological Model and the Geotechnical Model in the one drawing can be useful as the basis for providing presentations to clients, shareholders, insurers, or the general public.
- If a 3D digital model forms part of the documentation a 3D Digital Model Report should be provided that communicates digital model uncertainty and reliability. All relevant database files that include interpreted data and the 3D data files (for example, the mesh files for the engineering geological boundary surfaces) should be included.
- Recommendations for further work, if relevant or necessary.
- Uncertainties remaining.
- A ’limitations statement’ relating to any aspects of the report, where this is deemed necessary.

1.3.4.3 Geotechnical Baseline Report

In some larger projects, particularly underground works, the Owner and their engineers may opt to prepare a Geotechnical Baseline Report (GBR) to allocate the risks associated with the ground between the employer and the contractor. The EGM knowledge framework supports the development of ’numerical baselines’, ’characteristic values’ and ’ground reference conditions’ that are all components of GBRs linked to contractual clauses.

1.3.4.4 Engineering Geological Maps and Sections

Engineering Geological maps and sections are a fundamental part of the EGM knowledge framework and should be prepared in accordance with these Guidelines.

1.3.5 Creating and visualising a 3D digital model

There has been a recent but fundamental shift to using software to create 3D digital models, typically for medium to large scale projects or where complex geology is encountered. This, in turn, has led to a step change improvement in the interoperability of the EGM knowledge framework with other disciplines. A typical 3D digital model development process is shown in Figure 1-4 below.

1.3.5.1 Modelling Software

There is a wide range of software packages that can be used to produce 3D and 2D digital models.

1.3.5.2 Data Sources and Management

Clear, retrievable records of how datasets are created/modified/interpreted/stored, as well as of verification and other stages of the development process should be retained. To assist in the check/review/verification/approval process it is important to retain clear, retrievable records (metadata) of how datasets are created/modified/interpreted/stored. The linkages between original datasets and the modified model datasets are useful to maintain consistency, accountability and to provide insight into model uncertainty.

1.3.5.3 3D digital model documentation

Each significant version of a 3D digital model should be accompanied by a 3D Digital Model Report.

The 3D Digital Model Report should document:

- The project, the purpose and the scope of the model.
- A summary of the site engineering geology.
- The geographical extent, scale and applicability of the model and the coordinate system used.
- The inputs into the model, including subsurface data, map data, surface and subsurface point data and surfaces and meshes that have been used to formulate the digital model, an assessment of the quality and reliability of the different datasets and what manipulation/transformation has been undertaken for them to be incorporated into the model.
- The units and bounding surfaces shown in the digital model, that may be geological, engineering geological, geomorphological, hydrogeological or geochemical, depending on the model purpose.
- The data that have not been used and why they have been omitted.
- The reliability and status of the model and an outline any other assumptions and uncertainties in the model, including model reliability and related risks.

- Evidence of verification.
- A summary of outputs produced from the model, including any limitations.
- The Model Decision Register and a listing of the data management/version development of the 3D digital model including:
    - Date of decision.
    - Detail of decision/change.
    - Justification for the decision/change.
    - Verification/review comments.

The 3D Digital Model Report should be updated each time the 3D digital model is re-issued. On larger projects where investigations are occurring on multiple fronts the model can be updated daily as the model can be linked directly to databases and new data are automatically incorporated. A competent engineering geologist should check new data when they are imported to confirm the appropriateness of the existing interpretation and to perform any manual editing required to incorporate the new dataset.

1.3.5.4 Review of 3D digital models

Review of 3D digital models should demonstrate their reliability with emphasis on the quality of the process involved in their construction, clarity of understanding and transparency with respect to uncertainties. Above all else, the review should demonstrate the agreement between the outputs of the digital model and the reality of the observed and interpreted engineering geological conditions.

Whenever 3D digital models are developed, it is recommended that illustrative 2D plans and sections should also be generated to ensure that linkage to the underlying EGM is transparent and can be explored without the use of proprietary viewing software. The development of illustrative plans and sections is also often a useful way of detecting engineering geological ’irregularities’ in the model.

The checklist in Table 1-5 below provides specific items for consideration during review and verification where a 3D digital model has been developed.

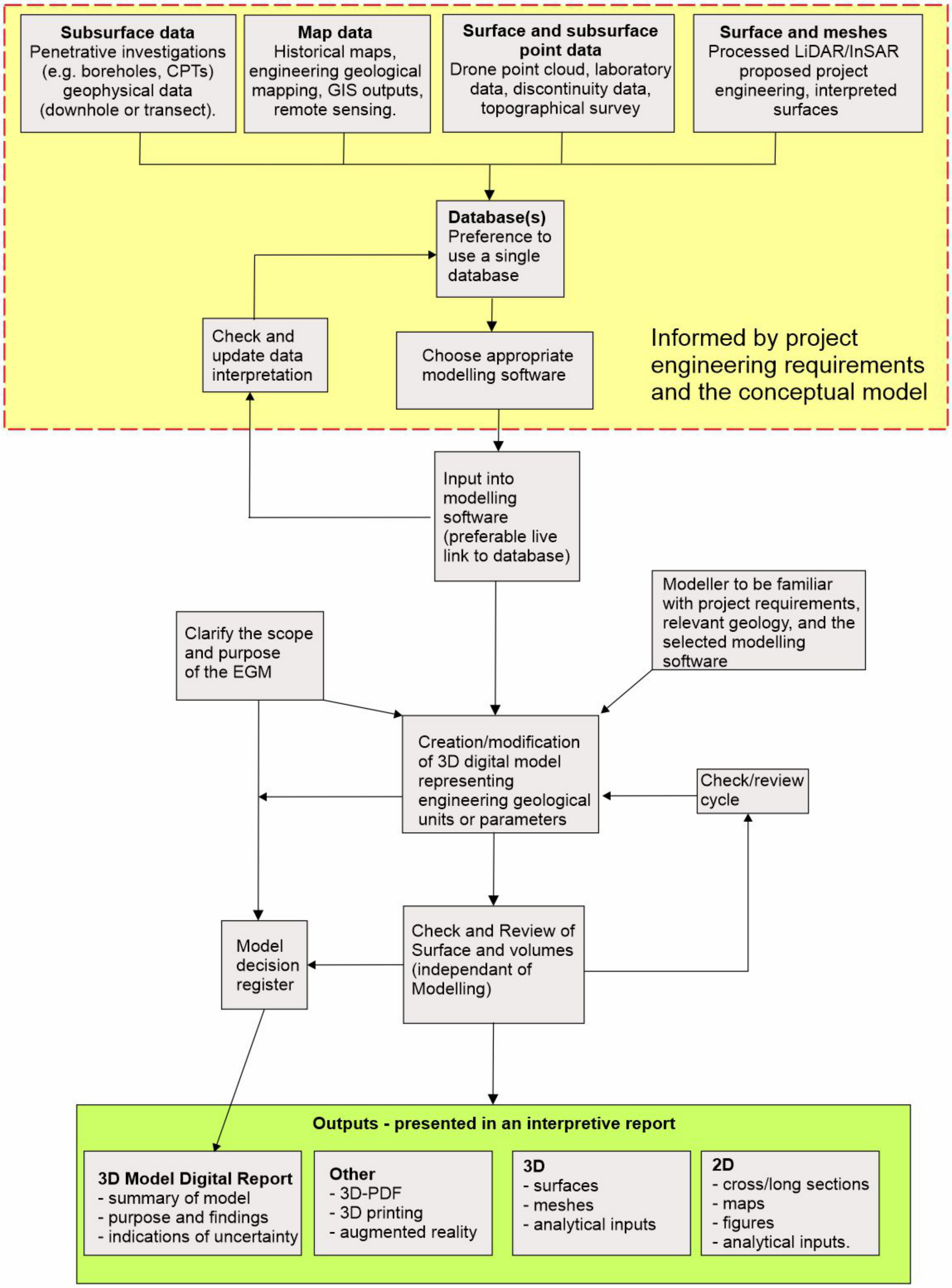


Figure 1-4 Typical digital 3D digital model development process.

Table 1-5 Checklist for review of 3D digital models.

Key activity	**Status**
Has the purpose of the model been clearly defined?	
Does the model extent cover the area of interest to the project and the extent of possible effects of the project, if the model is to be used for assessments of effects?	
Have the sources of data used to formulate the model been clearly identified?	
Is the quality of the data available sufficient for the purpose of the model?	
Do any other potentially useful data sources need to be incorporated into the model?	
Are data that have been specifically omitted from the model reasonable to disregard and have reasons been given why these sources have not been considered applicable?	
Are there an adequate number of data points and a reasonable distribution of points across the model area to make a reasonable representative interpretation?	
Is the manipulation of the data that has been used applicable and geologically reasonable?	
Has the model been reviewed in accordance with the EGM Development Level?	
Has the Reviewer been 'walked through' the model by the Modeller?	
Have illustrative maps and cross sections been provided?	
Has a 3D Digital Model Report been prepared that includes a Model Decision Register, identified uncertainties and associated risks and recommendations to improve reliability?	

1.3.5.5 Outputs of 3D digital models

Once the 3D digital model and the outputs have been checked and verified and are ready for issue the digital model itself and the specified outputs can be delivered. The nature of the outputs will influence how the information is presented. They might be 3D or 2D outputs (or both) depending on the project requirements but there may be no need for visualisation software if this is not the most effective method of communication – maps, charts, cartoons, presentations etc. may be more effective. The form in which the outputs are presented, and the level of detail included, should be tailored to the audience.

Refer to Commentary Section 2.3 ASSEMBLY AND COMMUNICATION OF THE EGM for further information

1.4 MANAGING EGM UNCERTAINTY

1.4.1 Introduction

Uncertainty within the EGM has the potential to reduce the reliability of the project engineering and increase the potential for project risks. The uncertainty should be assessed and strategies developed to reduce the uncertainty and the associated project risks to agreed levels.

1.4.2 Sources of uncertainty

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

- Uncertainty occurring in the conceptualisation process is due to a lack of knowledge or bias. This is also known as epistemic uncertainty but for ease of reference these Guidelines have adopted the term conceptual uncertainty. Conceptual uncertainty primarily reflects the appropriateness of the concepts underlying the EGM that, in turn, are heavily dependent on the knowledge and experience of those involved.

- Uncertainty in the data within the observational model is due to variability and randomness of the intrinsic properties of the ground and the measurement accuracy of the testing devices. This is known as aleatory uncertainty but for ease of reference these Guidelines have adopted the term observational uncertainty. Areas with fewer direct observations are likely to be more uncertain than areas with frequent direct observations. Note that any interpretation of the data within the observational model will be associated with conceptual uncertainty.

1.4.3 Holistic assessment of EGM reliability by review

Review of the project should assess the reliability of the observational and conceptual components of the EGM holistically, rather than separating them. The Development Level of the project provides guidance as to the type of review (Section 1.2.2. – Tables 1-2 & 1-3).

- For Level 1 projects internal reviews will provide a basic check of EGM reliability. Another engineering geologist from the project team responsible for the EGM should undertake a check of the development and refinement of the model. The reliability of the conceptual component should be benchmarked against appropriate conceptual analogues derived from education, experience and the literature and the compatibility of the observational component with the conceptual component evaluated.

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

- For Level 3 projects an expert review panel consisting of acknowledged experts should ideally be used to assess the reliability of an EGM by independently reviewing and commenting on the content, completeness and reliability of the project documentation. These should be appointed by the client as independent specialists.

1.4.4 Other methods of assessing the uncertainty and reliability of the EGM

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

1.4.4.1 Assessing the reliability of the conceptual component

An approach to the assessment of the conceptual component of the EGM is illustrated in Figure 1-5. This approach should be adopted at all stages of the project by individuals, peer reviewers and expert panels. However, basic qualitative checks of the conceptual reliability of an EGM should also made by the individuals involved as it is developed. Whenever self-checking or internal checking is carried out the results should be documented.

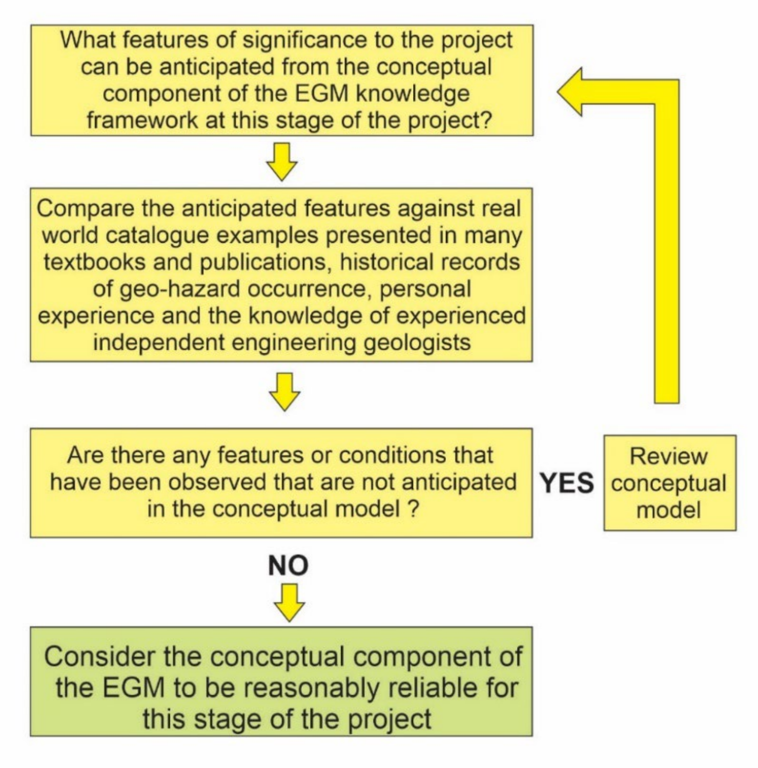


Figure 1-5 Approach for assessing the reliability of the conceptual component of the EGM.

1.4.4.2 Assessing the reliability of observational component - qualitative approaches

The reliability of the observational component of the EGM can be communicated qualitatively using methods such as thematic maps and the classification of the reliability of datasets.

1.4.4.3 Assessing the reliability of observational component - semi-quantitative approaches

Various methods have been devised in which the components of the EGM are graded and the various scores combined to provide an ordinal numerical assessment of reliability.

1.4.4.4 Assessing the reliability of observational component - quantitative approaches

Quantitative assessments are limited to evaluating the observational components of the EGM, and three families of tools can be employed:

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

Refer to Commentary Section 2.4 MANAGING EGM UNCERTAINTY for further information

1.5 ENSURING EGM QUALITY

1.5.1 Checking the quality of the EGM development process

An EGM of appropriate quality should be achieved if these Guidelines are implemented. A QA/QC (Quality Assurance/Quality Control) checklist for adherence to these Guidelines is set out in Table 1-6.

Table 1-6 EGM QA/QC Process Checklist

Key activity	**Status**
Has an effective, competent team, including a reviewer, been assembled?	
Has the scope and purpose of the EGM been clearly defined?	
Is the EGM compliant with the tender documents/specifications?	
Has the relevant engineering and geological information of significance to the project been assembled in a desk study?	
Has an appropriate geographical extent and scale been defined to present the EGM?	
Has an appropriate conceptual model been documented and is it reasonable based on the desk study?	
Was the ground investigation designed to reduce the uncertainties identified in the conceptual model?	
Have observations been acquired through investigations and documented as data?	
Are the sources of data used to formulate the EGM clearly identified?	
Is the quality of the data available sufficient to meet the purposes of the EGM?	
Are there any other potentially useful data sources?	
Have data been specifically omitted from the EGM and is that reasonable?	
Have observations been related to the concepts and a range of engineering geological conditions been conceptualised and interpreted?	
Have engineering geological units and their engineering characteristics been defined?	
Has a Geological Model been presented?	
Has a Geotechnical Model been presented?	
Has a Geohazard Assessment been presented?	
Have significant risks, gaps and discrepancies in the knowledge framework been identified?	
Has information for use in engineering analysis been provided?	
Has the entire EGM knowledge framework been documented?	
Have maps and sections been provided to illustrate the engineering geological conditions that are of significance to the project?	
Has further knowledge required to improve the EGM, reduce the risks, facilitate upgrade to the design or deal with claims been indicated?	
If a 3D digital model has been developed has the checklist in Table 1-5 been completed?	
Has the EGM been reviewed by a suitably qualified and experienced engineering geologist appropriate to the level of complexity of the geology and the project?	

Refer to Commentary Section 2.5 ENSURING EGM QUALITY for further information

2 COMMENTARY

2.1 EGM DEVELOPMENT PRINCIPLES

2.1.1 Definitions

No commentary.

2.1.2 Fundamental principles

No commentary.

2.2 EGM DEVELOPMENT PROCESS

2.2.1 Overview of development process

An overview of the EGM development process is provided in Figure 2-1.

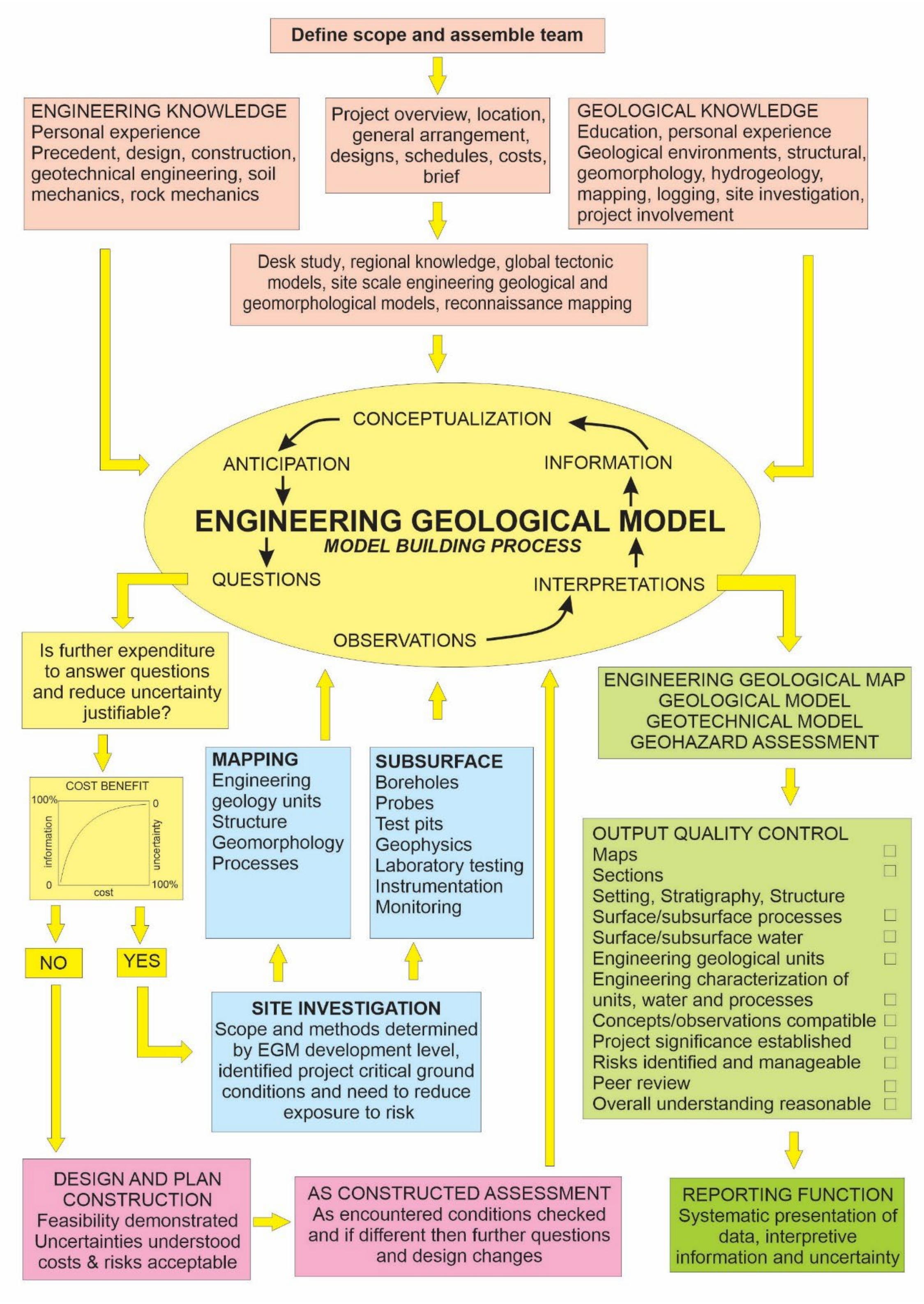


Figure 2-1 The EGM development process.

A view of the EGM development process for rock slope engineering is provided in Figure 2-2.

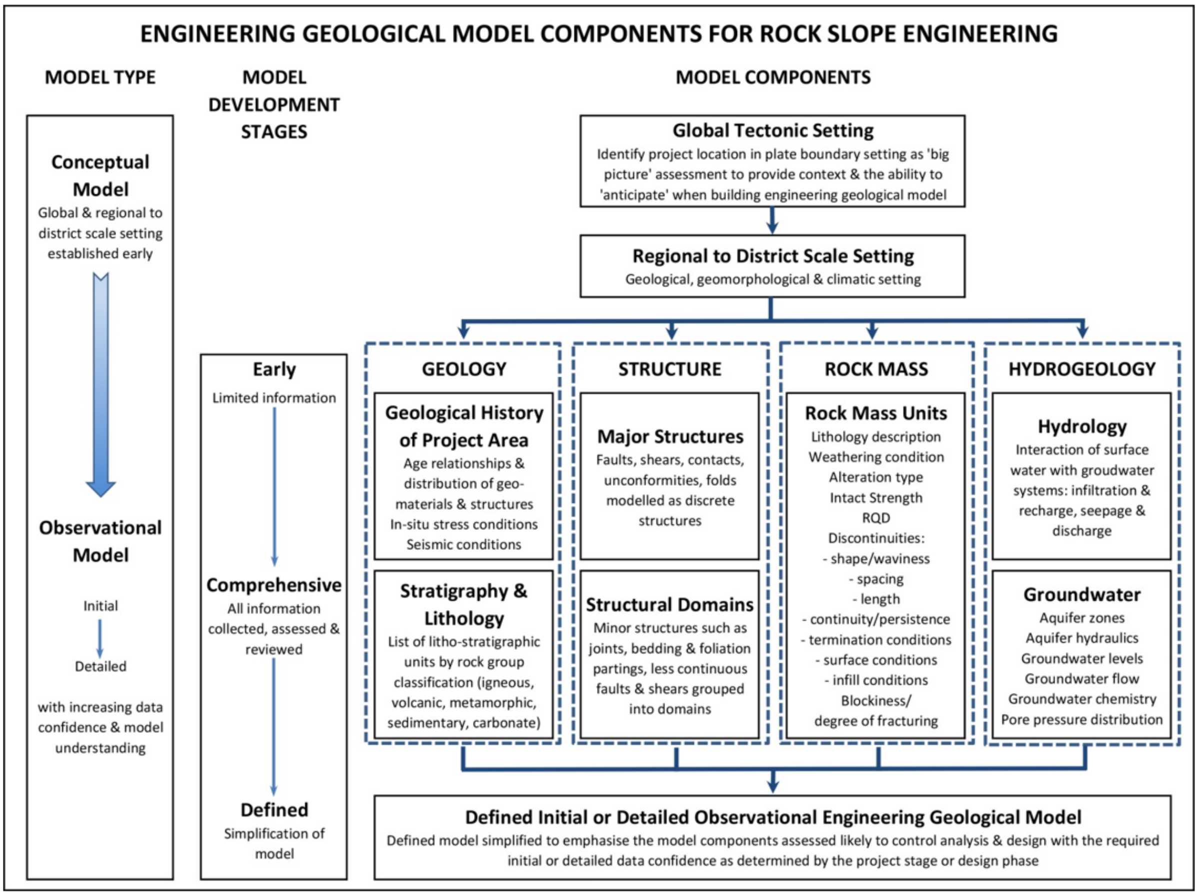


Figure 2-2 The EGM development process for rock slope engineering (from Eggers, M., EGMs for rock engineering projects in Baynes & Parry 2022).

A view of the EGM development process for offshore engineering is provided in Figure 2-3.

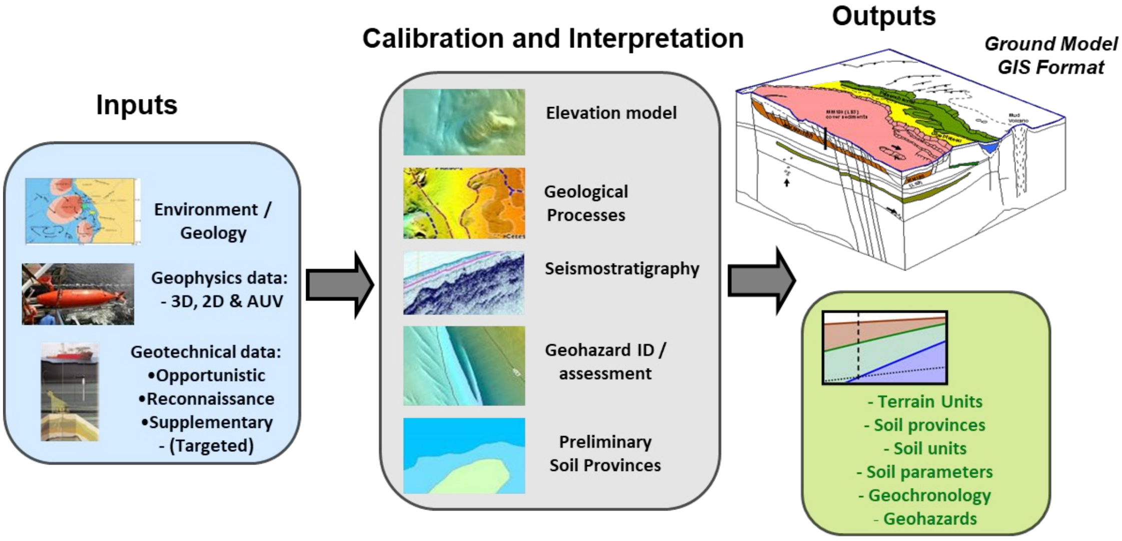
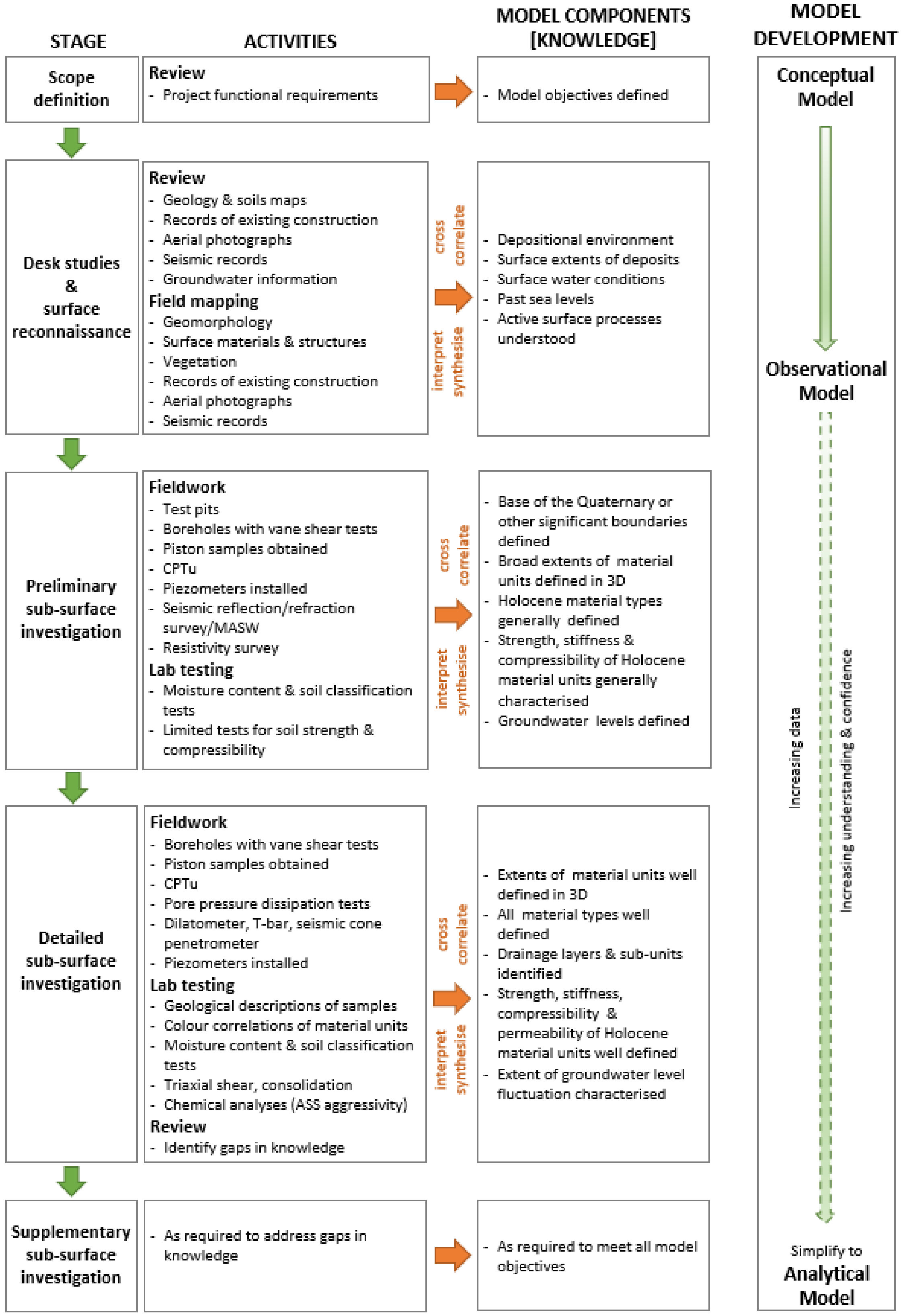


Figure 2-3 The EGM development process for offshore studies (from Waring, D., EGMs for offshore studies in Baynes & Parry 2022).

A view of the EGM development process for soils engineering is provided in Figure 2-4.



STAGE	ACTIVITIES	MODEL COMPONENTS [KNOWLEDGE]
Scope definition	**Review** - Project functional requirements	- Model objectives defined
Desk studies & surface reconnaissance	**Review** - Geology & soils maps - Records of existing construction - Aerial photographs - Seismic records - Groundwater information **Field mapping** - Geomorphology - Surface materials & structures - Vegetation - Records of existing construction - Aerial photographs - Seismic records	- Depositional environment - Surface extents of deposits - Surface water conditions - Past sea levels - Active surface processes understood
Preliminary sub-surface investigation	**Fieldwork** - Test pits - Boreholes with vane shear tests - Piston samples obtained - CPTu - Piezometers installed - Seismic reflection/refraction survey/MASW - Resistivity survey **Lab testing** - Moisture content & soil classification tests - Limited tests for soil strength & compressibility	- Base of the Quaternary or other significant boundaries defined - Broad extents of material units defined in 3D - Holocene material types generally defined - Strength, stiffness & compressibility of Holocene material units generally characterised - Groundwater levels defined
Detailed sub-surface investigation	**Fieldwork** - Boreholes with vane shear tests - Piston samples obtained - CPTu - Pore pressure dissipation tests - Dilatometer, T-bar, seismic cone penetrometer - Piezometers installed **Lab testing** - Geological descriptions of samples - Colour correlations of material units - Moisture content & soil classification tests - Triaxial shear, consolidation - Chemical analyses (ASS aggressivity) **Review** - Identify gaps in knowledge	- Extents of material units well defined in 3D - All material types well defined - Drainage layers & sub-units identified - Strength, stiffness, compressibility & permeability of Holocene material units well defined - Extent of groundwater level fluctuation characterised
Supplementary sub-surface investigation	- As required to address gaps in knowledge	- As required to meet all model objectives

Figure 2-4 The EGM development process for offshore engineering (from Shipway, I., EGMs for soil engineering studies in Baynes & Parry 2022).

A view of the EGM development process for small projects is provided in Figure 2-5.

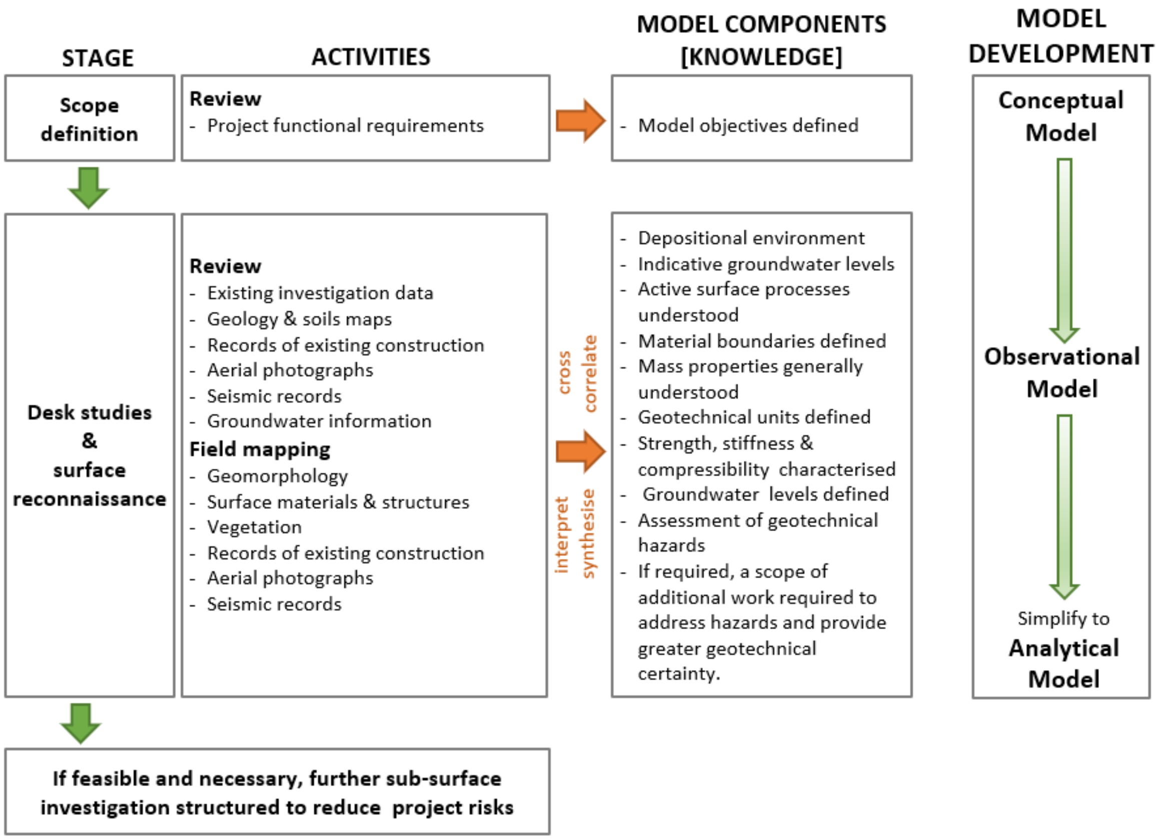


Figure 2-5 The EGM development process for small projects (from Shipway, I., EGMs for small projects in Baynes & Parry 2022).

2.2.1.1 The development process

No commentary.

2.2.1.2 Initial steps

No commentary.

2.2.1.3 Useful techniques for EGM development

Useful techniques to be considered when developing an EGM include:

- Continuously question the concepts, observations and interpretations as the models are being developed. Be flexible and prepared to change your mind.
- Big picture overview is essential - in developing the EGM work from the far-field to the near-field, that is, consider far-field concepts like past and present tectonic setting and the long-term geological and geomorphological history and then use that knowledge to consider site scale conditions as well as the area beyond the site that requires evaluation. It may be necessary to develop large-scale models from small-scale initial information sets.
- Very large-scale developments or very complex models with large amounts of information can be challenging. The EGM should capture the essence of the design/project issues but should also

be robust enough to evaluate the inherent engineering geological variability, as well as any changes to the project that might arise.

- The EGM should also take into account the dimension of time – for example, the rate at which geomorphological processes are occurring and any potential impact on the engineered structure over the design life.
- Where known, the proposed development (drawn to scale) should be superimposed on all plans, sections and 3D visualisations. This should include any revisions to the development such as facility additions, movements or deletions, as the project progresses.

Common mistakes made when developing an EGM include:

- Leaving out data or facts that do not fit or contradict a preconceived model. Data should not be left out unless the data can be demonstrated to be fundamentally flawed, in which case reinterpretation should be attempted before omission. Note that contradictory information may often indicate geotechnical complexity not considered during conceptual model development.
- Developing incorrect and inadequate conceptual ideas and/or conceptual ideas that are not relevant to the project.
- Discounting relevant historical data or information simply because it is not recorded to current Standards or has been acquired during earlier stages of the project.
- Using only subsurface data and omitting surface engineering geological and geomorphological mapping.
- Not carrying out systematic engineering geological mapping of the site and its surrounds or only carrying out mapping in selected easily accessible areas.
- Working backwards from the cause, result or solution.
- Using distorted or inappropriate scales. Collecting data at the wrong scale for the project. Using exaggerated scales on cross- and long- geological sections (if their use is necessary provide a natural scale section as well).
- Trying to include every piece of detail without discriminating the significance of the detail.
- Failing to look beyond the site or problem being considered. For example, in geomorphological terms a project needs to be placed in the context of its ‘landform situation.’
- Including data or information without reference to the degree of confidence in the data.
- Interpreting more detail than the data allows.
- Failing to consider and communicate alternative interpretations.

2.2.1.4 Skills required for EGM development

Knowledge and skills required to build good EGMs include:

- Knowledge of geological processes, rock/soil forming environments and rock/soil modifying environments such as weathering, slope formation and stress release (that is, geological knowledge).
- Thinking in 4D (that is, 3 spatial dimensions and time).

- An understanding of engineering geomorphology, in particular geomorphological processes with their frequencies (through time) and magnitudes (volume, spatial extent, speed of onset and propagation).
- An understanding of ground response to natural or anthropogenic modification (that is, engineering knowledge) in terms of soil mechanics, rock mechanics and hydrogeology,
- Ability to look at detail and place detail within the big picture setting and to critically assess information and override inherent and unconscious bias.
- An understanding of the geo-reasoning and the scientific method. The use of both inductive reasoning (the process of making simple observations of a certain kind and applying these observations via generalisation to a different problem to make a decision) and deductive reasoning (reaching conclusions based on logical rules applied to a set of premises).
- Experience of creating realistic and successful EGMs.
- Understanding when additional, often specialist, technical support is required. This support may include seeking inputs from fellow specialist professionals in such disciplines as hydrogeology, geo-environmental science, geomorphology, geophysics, structural geology, geohazards, pedology, plus relevant engineering disciplines such as geotechnical or dams engineering.

2.2.2 Choice of development level of EGM

No commentary.

2.2.3 Details of the development process

2.2.3.1 Assemble team, define scope and purpose

Different projects in the same location require different models to be developed due to the variability of the potential interaction between the geology and the project.

Figure 2-6 illustrates how different aspects of the same geology will be significant depending upon the nature of the project (A - single storey building, B - road bridge, C - tunnel). The building is expected to impart a small vertical stress to the ground surface. The bridge piles are expected to apply higher vertical and lateral stresses to the ground at depth and the tunnel is expected to drain and change the groundwater flow regime at depth (from Parry *et al.* 2014).

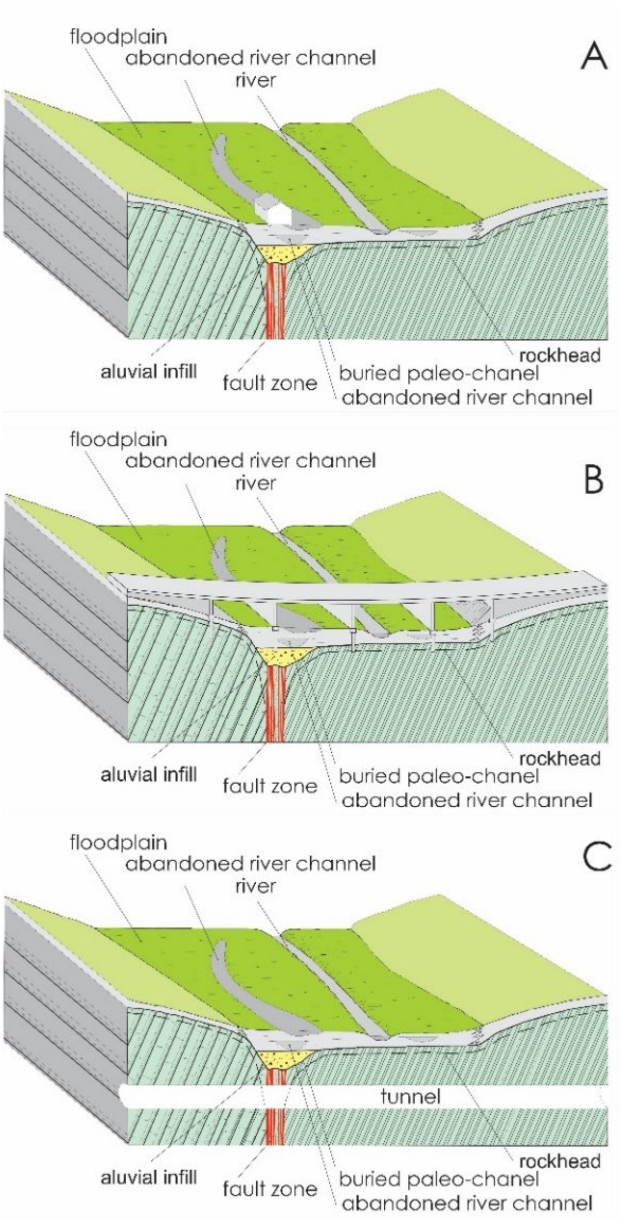


Figure 2-6 Influence of project type on the EGM. Reprinted with permission from Springer Nature. Bulletin of Engineering Geology and the Environment. Parry *et al.* 2014, Engineering geological models – an introduction: IAEG Commission 25.

2.2.3.2 Assemble relevant engineering and geological information in a desk study

Typical sources of information that should (where available) be accessed during a desk study are presented in Table 2-1.

Table 2-1 Sources for a Desk Study (from Shilston *et al.* 2012).

Topic	*Examples of sources of information*
Topography	Maps, aerial photographs, satellite and aerial imagery, DEM or DTM derived from LiDAR surveys, InSAR data
Geomorphology, geology, hydrogeology and engineering geology	Maps, memoirs and reports, aerial photographs, satellite and aerial imagery, (including hillshade or shaded relief from LiDAR), published papers and books, mine and quarry records, thematic databases, previous ground/site investigations, records of groundwater use, regional geohazard data, for example seismic hazards
Environment and land-use planning	Planning maps, aerial photographs, satellite and aerial imagery, Google Earth, urban geology reports and maps, archaeological site and historic building records, soil surveys, contaminated land records, Environmental Impact Assessments (EIA) or Surveys (EIS), climate records, river and coastal information
Site condition, land-use and history	Historical maps, historical documents, aerial photographs, satellite and aerial digital imagery, (including LiDAR sources), land-use and planning maps, site investigation reports, geotechnical properties and geohazards, databases, InSAR data, mapping from earlier construction
Initial site visit/walk-over	-´Skilled-eye´ inspection of site and its surrounds - ground-truthing reconnaissance - visits to specific localities
Local knowledge	Local history and geological societies, previous site use, construction records, building control offices, newspapers, regional and national geological surveys, investigations for adjacent sites
Precedent	Case histories, construction records
Codes, standards, regulations and guidance	Professional bodies and institutes, government departments, research organisations and universities

Any literature search needs to differentiate between fact and fiction. There is a multitude of websites that contain information potentially of relevance. However, not all can be trusted to provide reliable data. Accessing sites that can be trusted is vital and the most suitable are national, regional and local government departments and agencies, museums, universities, learned and professional bodies, standards organisations etc. (Griffiths 2019). Company websites, national and regional newspaper archives and anecdotal evidence should be treated with a degree of scepticism.

Many large projects will need to incorporate existing maps and sections documented on paper into the desk study and so some basic rules apply:

- Ensure that, as far as possible, all sources of data and archived materials are located; this may take considerable effort as archived records are often incomplete and chaotic. There may be questions over confidentially and copyright to be considered.
- Ensure that the projection and datum of any old records are understood and related to the projection and datum that are being used in the EGM and properly documented. GIS is invaluable in allowing the spatial evaluation of all the desk study records, to look for patterns in the data.

2.2.3.3 Conceptualisation

A fundamental strategy in developing the conceptual framework is that there should be an understanding of the "*total geological history*" of the site (Fookes *et al.*, 2000). This strategy is based on the premise that the engineering characteristics of the ground are the result of the total geological history of the project area, including subsequent anthropogenic modification.

Conceptualisation also provides the opportunity to articulate a deeper understanding of the possible geological influences on a project. based on knowledge and experience of similar geological settings, materials or processes and similar project types or levels of project complexity. This process is central to the development of the EGM and takes place throughout the life of the project. The conceptual approach generates hypothetical models and such models potentially involve a relatively high degree of uncertainty that is directly related to the type and amount of existing data and the knowledge and experience of those involved.

Conceptual models can be;

- Site specific, providing a framework for the interpretation of observational data and allowing anticipation of the ground conditions that may be present at the specific site being investigated.
- Generic conceptual models that are independent of a specific location and provide, for example, information on overall climatic or structural geological settings.
- Temporal conceptual model (sometimes called an evolutionary model) that illustrates how ground conditions have evolved over geological time.

The data sets listed in Table 2-1 can be used to interpret information that is relevant to the EGM as follows:

Topographical maps:

- Geographical location; hence, present climate and land use.
- Initial geomorphological mapping.
- Identification of structural lineaments.
- Identification of main streams and other water bodies.
- Anthropogenic modification – mapped quarries, landfills, mine shafts, embankments, cuttings etc.
- Possible superficial deposits with distinctive landforms such as floodplains, glacial outwash, loess, landslides etc.

Geological maps, reports, memoirs, publications

- Geological maps generally present the distribution of chrono- and litho-stratigraphical units – which is why standard geological maps need considerable interpretation before forming the basis of an engineering geological map.
- Lithology. These units provide the basic building block of the EGM and consideration of the environment of formation can provide insights into possible variations in lithology that may be present but not mapped. Knowledge of the lithology will also indicate the type, orientation and spacing of discontinuities likely to be present and the type and geometry of external boundaries (geological contacts) of both the geological unit and internal sub-units.
- Stratigraphy (Age) – this allows an evaluation of the relationship between the geological units and the subsequent rock/soil modifying process, for example, diagenetic changes, tectonic modification, weathering, development of duricrusts etc.
- Mapped geological structures, for example, folding and faulting that allow an evaluation of their possible effects on the rock mass such as joint development associated with folding, the zone of influence of faults that, in turn, influences depth of weathering.

- Quaternary deposits. Note that these may not be mapped or only mapped when exceeding a fixed thickness. For example, in the UK superficial deposits less than 1 m thick are not typically mapped. Where they are mapped they are often considerably simplified.
- Geological boundaries, often with degrees of uncertainty indicated, for example, observed, inferred, interpreted.
- Anthropogenic modification – workings associated with mineralisation, made-ground, landfills, shafts or adits.
- Although the most recent geological maps at the appropriate scale should be used, it may be necessary to consult older maps because they may show important features, for example, abandoned mine workings or structures not shown on later maps. The mapped geology may change with each generation of map as geological paradigms are revised and it can be useful to understand why this is the case.

Aerial photographs, remote sensing imagery

Mapping using aerial photographs, airborne multispectral scanners or satellite imagery greatly assists in the development of conceptual ideas. Whilst specific imagery may be limited, Google Earth imagery is available for virtually the entire globe. The mapping should include but not be limited to:

- Geomorphological setting.
- Past and present geomorphological processes (and likely rates of change). For example, relict periglacial processes and present-day river incision.
- Specific geological structures and overall geological structure.
- Regolith, when using multispectral data interpretation of the lithology and clay mineralogy.
- Outcrop, and in some cases, when using multispectral data, a provisional interpretation of the surface lithology
- Anthropogenic modification.

LiDAR

In some countries extensive publicly available LiDAR is available but for many projects site-specific LiDAR is flown. Using Digital Terrain Models, hillshade/shaded relief images can be generated that can be interpreted to provide information on:

- Geomorphology – for example, landslides, abandoned river channels etc.
- Outcrop delineation.
- Superficial mapping.
- Major geological structural features.
- Anthropogenic activities and/or for archaeological investigations.

Existing ground investigation data

Many projects will have existing investigation data. Depending on the age of the existing records, varying degrees of uncertainty may be associated with the data. Consequently, the data may have to be interpreted prior to conceptualisation.

During the assembly of all the relevant information the process of conceptualisation should be developed systematically under the following headings:

2.2.3.3.1 Project setting

Global/regional summaries of geological and geomorphological conditions, tectonic settings, present and past climates and associated land forming processes, *in situ* stress etc. provide an overall context for the conceptualisation.

2.2.3.3.2 Stratigraphy – rock and soil types and relationships

The soil and rock types that are present and the stratigraphical relationships between those units may be deduced from geological maps and is often expressed as a "rock relationship diagram" on the map. The knowledge derived from geological maps supports the development of a conceptual model that anticipates the presence of certain geological units and features, the nature of their boundaries and the spatial relationships between the units etc. that is, the geological map and any accompanying memoirs or reports can be used to deduce the *total geological history*. This part of conceptualisation is based on fundamental geological knowledge of different rock types and the engineering significance of their characteristic features. From a geological perspective there are many different rock types but for engineering purposes the simplified classifications contained in most descriptive standards are normally sufficient. Initially, this type of evaluation will be based on experience and reference to relevant literature, particularly generic models and compilations of engineering characteristics. For visualisations of different generic conceptual models see Fookes *et al.* (2015) and Fell *et al.* (2015). For example, Figure 2-7 shows the conditions that can be anticipated in granitic terrain that has been subject to deep chemical weathering.

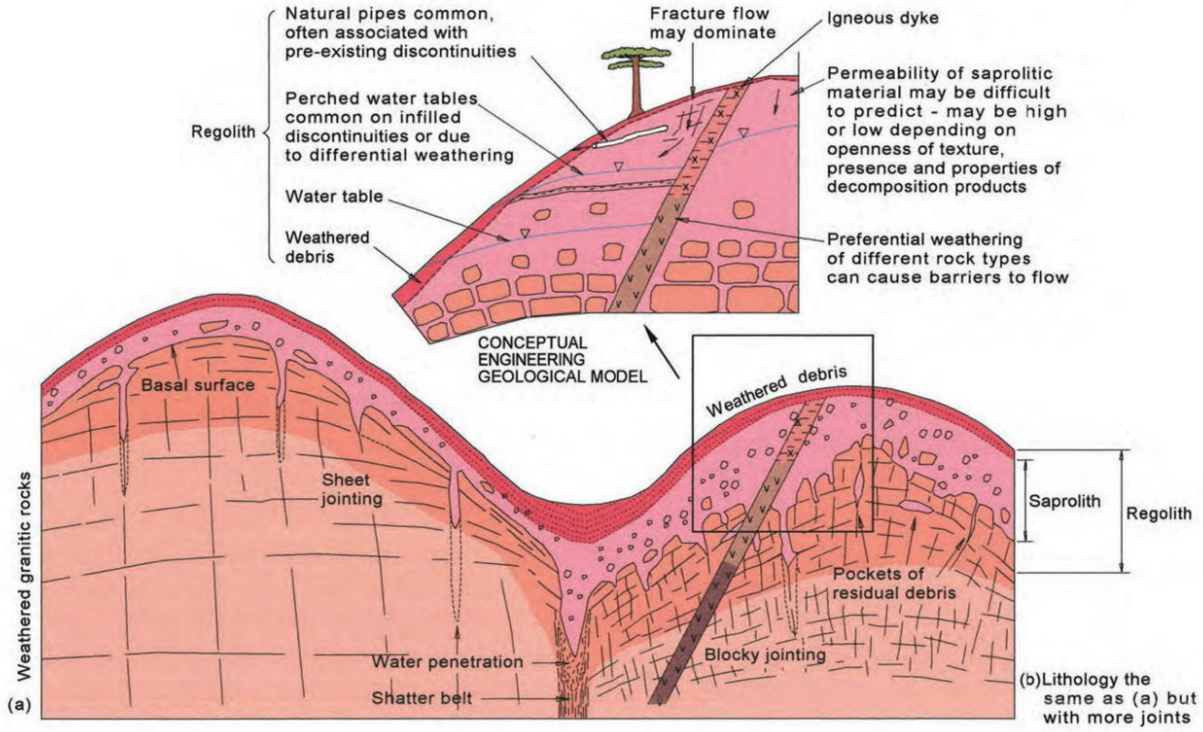


Figure 2-7 Typical granite characteristics. Reproduced from Fookes *et al.* 2015. Geomodels in engineering geology – an introduction. © Whittles Publishing 2015.

2.2.3.3.3 Geological structure

The likely structure can be extrapolated from the geological map or knowledge and experience of similar geological settings. What can be anticipated is, again, best appreciated by considering relevant generic conceptual models, for example, see Figure 2-8.

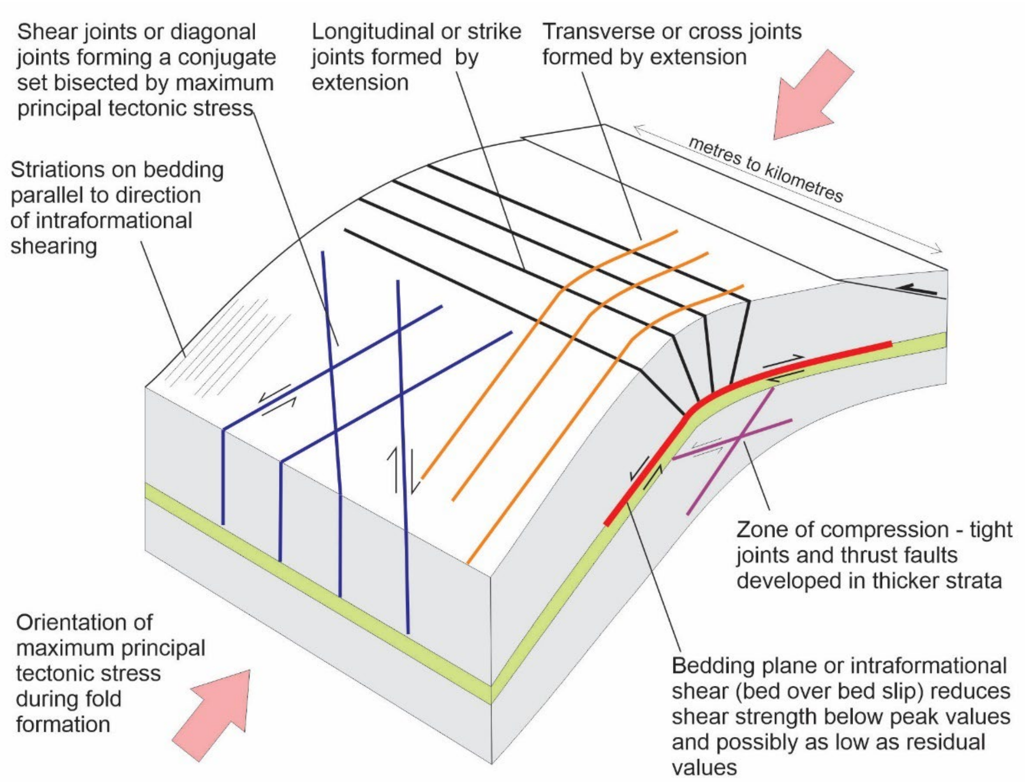


Figure 2-8 Structures associated with open folding (based on Price & Cosgrove, 1990).

2.2.3.3.4 Surface and subsurface processes

This requires knowledge and experience of geology and geomorphology to evaluate what processes may have occurred in the past, as well as what processes are active, or could be reactivated, by the project. For example, the possible presence of valley stress relief effects that could impact slope stability, rock mass permeability, groundwater controls and inflows into tunnels.

Generally, it involves classification of the process and developing information on the relevant process rate. An example of how the knowledge framework developed for landslides affecting the project site can be presented in a form suitable to support a hazard assessment is shown in Figure 2-9.

The palimpsest concept (literally overprinting of different ages of writing) should be considered in any investigations of the landscape. Most landscapes are a combination of relict and active landscape components and processes produced under a range of environmental conditions.

As result, the landscape may contain a combination of:

- Relict landforms that contemporary processes do not affect.
- Relict landforms that are affected by contemporary processes or could be reactivated if changes in conditions occur.
- Active landforms.

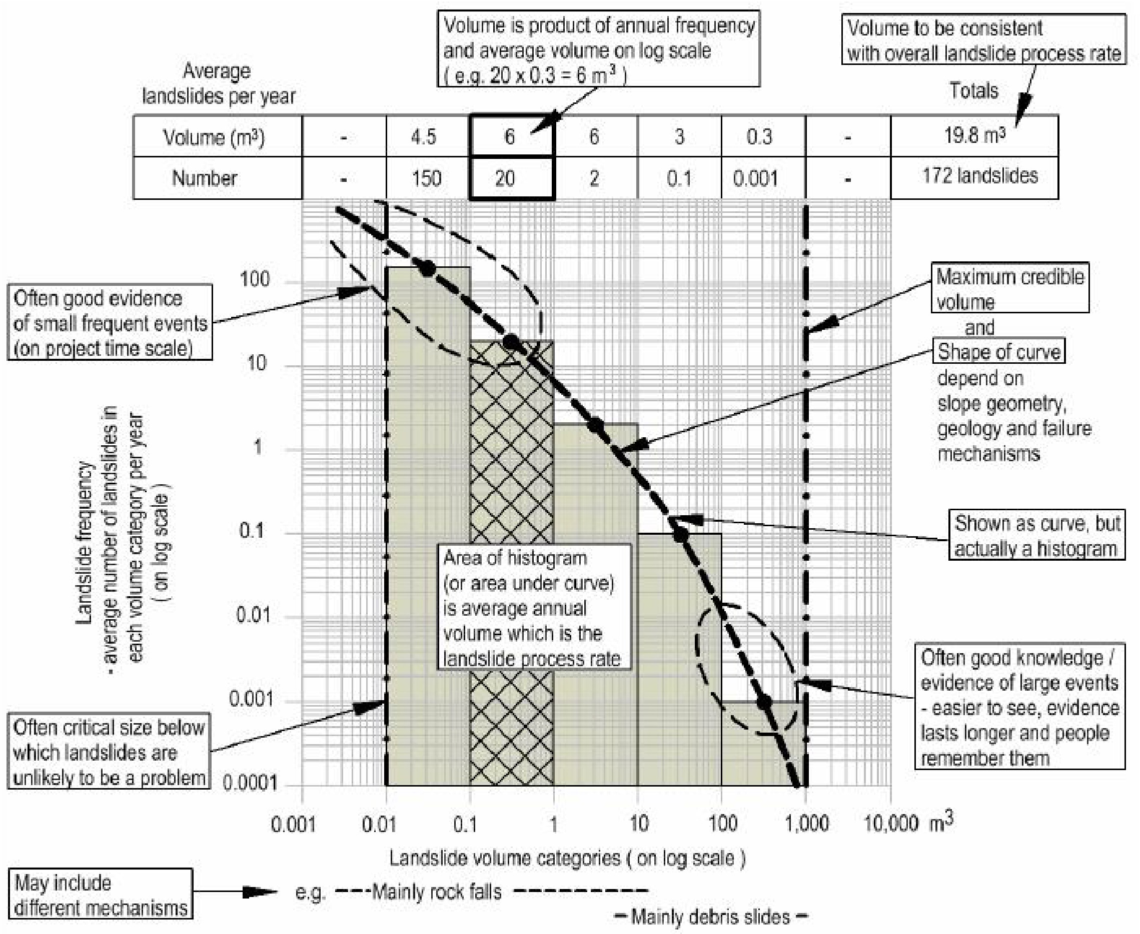


Figure 2-9 A generic landslide magnitude frequency model (Moon *et al.* 2005). Reproduced with permission of the authors.

The conceptual model should explain the evolution of the present-day landscape and anticipate how the landscape may be affected by, or may affect, the project. To understand the possible geomorphological processes, it is useful to develop a generic conceptual model of the *morphogenetic landforms* that characterise the area – these are identifiable assemblages of landforms that results from distinctive climate types acting over a period of time. The generic conceptual models can help in the creation of site-specific conceptual models. They also provide a checklist of the type of features and geohazards that might be encountered in these areas. For visualisations of different generic conceptual landform models see Fookes *et al.* (2015).

2.2.3.3.5 Initial engineering characterisation

Based on knowledge and experience, the possible engineering characteristics of the various components of the conceptual model can be documented. Numerous publications summarise the typical engineering characteristics of different engineering geological materials. For example, the rock mass properties of different grades of weathered granite and gneisses were summarised by Dearman *et al.* (1978). Where there is considerable existing knowledge and experience, it may be possible to develop initial estimates of characteristics such as strength and stiffness from rock mass descriptions using a variety of methods, for example, the GSI approach (Hoek and Brown 2019). However, the uncertainties associated with such an approach should be fully documented.

In addition to initial risk registers, the conceptual model can be used to generate initial 'Reference Conditions' that contractually define the conditions to be expected for projects (Baynes *et al.* 2005).

2.2.3.3.6 Initial Geological Model

Depending on the project, the initial Geological Model may include a significant amount of existing observational data or it may be based almost entirely on conceptualisation and hence the uncertainty within the model can vary significantly. However, as the Geological Model is developed it provides a logical framework for the design of the site investigation that should aim to reduce the model uncertainty.

2.2.3.3.7 Example of conceptualisation

An example of a visualisation of a conceptual model is provided in Figure 2-10.

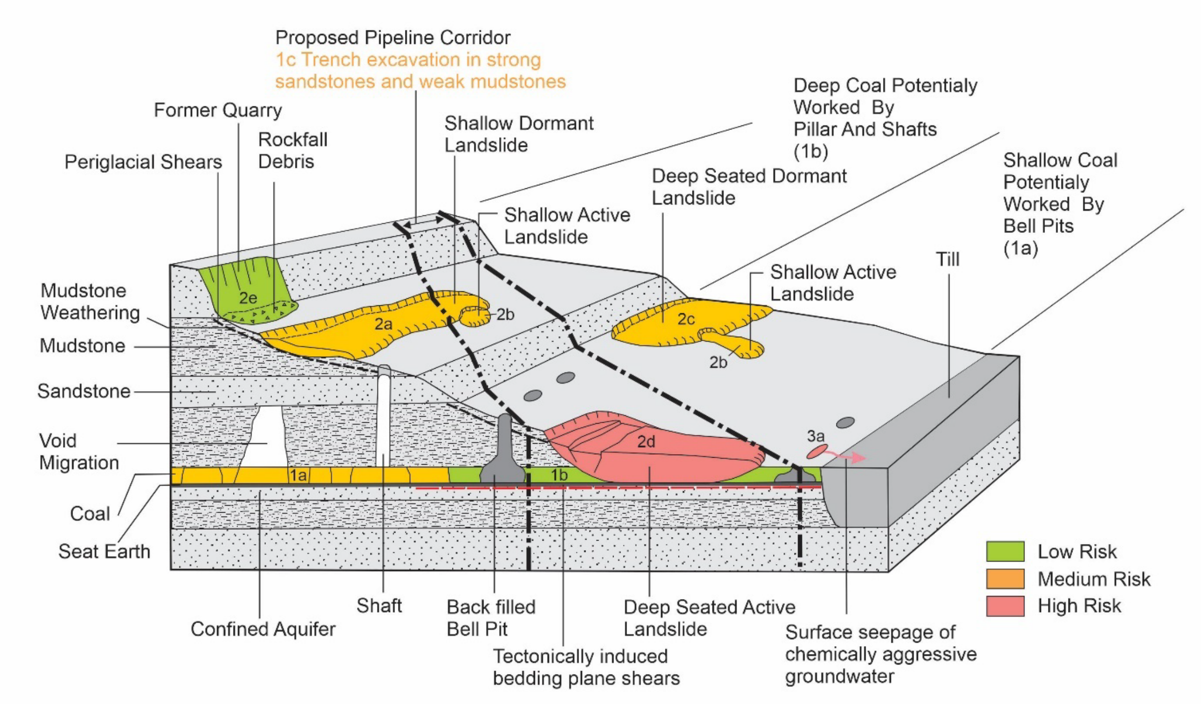


Figure 2-10 Visualisation following a desk study of the conceptual component of an EGM for a pipeline crossing unstable ground affected by mining and landslides (from Baynes *et al.* 2021).

2.2.3.4 Acquire observations of the project area through investigations

'Data' records of the ground are produced by logging in accordance with national standards or international guidelines. However, such logs can induce limitations and loss of observational data if the logs in question reflect minimum standards. There is a need for flexibility in the logging systems to focus the data collection on the key factors that the conceptual model/early observational model indicates will most likely control design.

A geological interpretation of the environment of deposition and/or the stratigraphic age should accompany all material descriptions in the logs of boreholes, test pits, exposures etc. (as mandated in the Australian Standard, AS1726 2017), as this indicates when and how the geological materials were formed, which in turn will be reflected in their engineering characteristics. However, this requires the interpreter to have knowledge of the EGM. Incorrect interpretation is possible, so an indication of the confidence of the interpretation is essential.

Observers should interpret what they are observing and should decide what else or where else the conditions should be observed and measured, based on their developing observations and interpretation. Clearly, more experienced persons have an advantage. If the observer is provided with the EGM prior to making further observation the likelihood of the correct interpretation being made significantly increases. Furthermore, outliers and anomalies are easier to recognise, document and evaluate.

Note that field interpretation may change with additional data or knowledge/experience and as the EGM develops it may be necessary to re-evaluate earlier logs; when changes to the interpretation are made this should be documented.

Despite the move to digital data entry, some data are not easily amenable to this. For example, logging in complex ground and the complex relationships illustrated by such logs are not necessarily amenable to digital data entry. In those circumstances the original logs with paper and pencil sketches should also be provided.

Detailed mapping can be undertaken using a variety of techniques ranging from simple tape measure surveys from control points to locating the observations on a high-resolution DEM (where available) or orthophotos.

2.2.3.5 Combining conceptual models and observational models into the EGM

Interpretation has traditionally involved the creation of paper-based maps, sections, sketches and text but is now increasingly carried out in a digital model environment. This involves 'surface interpretation' during the development of a 3D digital model in which engineering geological maps, geomorphological maps, LiDAR, topography, field mapping and observations etc. are collated and used to interpret the ground conditions. It is essential that such surface interpretation should be ground truthed in the field.

Field-based engineering geological and geomorphological mapping is rarely undertaken as a matter of course on projects, yet it is a technique that requires both field-based observation and conceptual interpretation to be carried out concurrently and, in doing so, generates the quintessential 2D visualisation of the EGM in the form of the map.

2.2.3.6 Defining and characterizing engineering geological units

No commentary.

2.2.3.6.1 Geotechnical complexity

No commentary.

2.2.3.7 Engineering characterisation

No commentary.

2.2.3.7.1 Zoning

No commentary.

2.2.3.8 Uncertainty, gaps and discrepancies in the EGM

No commentary.

2.2.4 EGM and Eurocode

The latest version of Eurocode 7, Part 2 (in preparation for implementation in April 2023) describes an approach for the investigation and design of the geotechnical components of a project. Norbury (2020) noted that there were two distinct types of models in Eurocode 7.

(1) The Ground Model (in EN 1997-2:2004) which includes geology and the presentation and evaluation of test results.

(2) The Geotechnical Model (in EN 1997-1:2004) which covers design of the structure and so includes selection of the geotechnical design parameters.

Although the terminology is different, the Eurocode approach fits within the overarching EGM approach for civil engineering projects. However, the Eurocode approach is not so well suited to the broader range of geotechnical engineering decision-making that often occurs outside of civil engineering design, for example, offshore geohazard studies, quarry resource evaluation, the preparation of Geotechnical Baseline Reports etc. where the overarching EGM approach is more effective.

Back to Section 1.2 EGM DEVELOPMENT PROCESS

2.3 ASSEMBLY AND COMMUNICATION OF THE EGM

2.3.1 Introduction

No commentary.

2.3.2 Brief for preparation of EGM components

No commentary.

2.3.3 Project procurement implications

No commentary.

2.3.4 Reporting EGMs

The EGM is primarily documented via project reports. In those parts of the world where litigation has often been associated with the procurement of major projects, conventionally, and often as a contractual obligation, two main types of report are produced following site investigations - a Data Report and an Interpretive Report. The 'Data Reports' are usually regarded as 'Rely Upon Data', whilst the 'Interpretive Reports' often may have a limited interpretive content, are usually 'For Information Only', and have a lesser standing contractually. In these circumstances an effective EGM knowledge framework may not be presented and it may not be fully utilised in the project life cycle.

2.3.4.1 Data Report

In some cases, owners choose to issue only 'Data' information (that is, borehole test pit logs, laboratory test results etc.) in the belief that providing any 'interpretations' will somehow increase their exposure to geotechnical risk. It is accepted that this a common practice but withholding interpretations from subsequent designers or contractors can only reduce their ability to reasonably foresee the ground conditions that they might encounter and, therefore, they have to price their bids accordingly.

2.3.4.2 Interpretive Report

Interpretive reports rarely document the conceptual components of the EGM and commonly present a single 'ground model' with no explanation of how this was derived and if there is any associated uncertainty. These problems are further compounded by contractors who make the observations on site during investigations often being responsible for the data reporting and consultants who may never have been to site responsible for the interpretive component. This compartmentalisation of the investigation can lead to incorrect and misleading interpretation of the ground.

2.3.4.3 Geotechnical Baseline Reports

Interpretive Reports are now increasingly being used to generate Geotechnical Baseline Reports (GBR) to establish more clearly defined risk sharing by providing a *contractual interpretation* of ground conditions (Davis 2017). The International Federation of Consulting Engineers (FIDIC) has a contract book (Emerald Book) specially designed for use of Geotechnical Baseline Reports (FIDIC 2019).

A GBR sets the risk boundaries between the employer and the contractor by including statements ('baseline statements') that define the relevant engineering geological or geotechnical conditions that the contractor can expect to encounter during construction and those conditions that are deemed to have been allowed for at tender. GBR's can also provide a balanced interpretation of ground conditions from the data available or be pitched at better or worse conditions depending on the client's risk profile and appetite for risk. Differences in actual ground conditions encountered on site, and their impacts on contracts, are typically arbitrated through an ‘Independent Third Party’ during the construction works. The GBR may comprise multiple reports that are progressively developed during contract negotiations.

In its simplest form the GBR is used by all tenderers as a common basis for pricing geotechnical risk alongside pricing the works set out in the tender drawings and specifications. At contract award the successful contractor is deemed to have allowed for the range of ground conditions set out in the baseline statements in the GBR. The baseline statements establish what is ‘foreseen’ and provide a contractual test for what might be claimed to be ‘unforeseen’ in relation to the ground conditions encountered during construction. Post-contract award, the GBR is then used to judge the validity of any ground-based compensation claims for those issues covered by the GBR. The EGM knowledge framework supports the development of ’numerical baselines’, ’characteristic values’ and ’ground reference conditions’ that are all components of GBRs linked to contractual clauses.

2.3.4.4 Engineering geological maps and Sections

Engineering geological maps and sections are a fundamental part of the EGM knowledge framework. All maps and sections should contain a scale, a legend and a north arrow and should differentiate between observations and interpretations using linework conventions such as in Figure 2-11. When developing digital-based maps, observed, projected and interpreted boundaries should be differentiated in a similar manner.

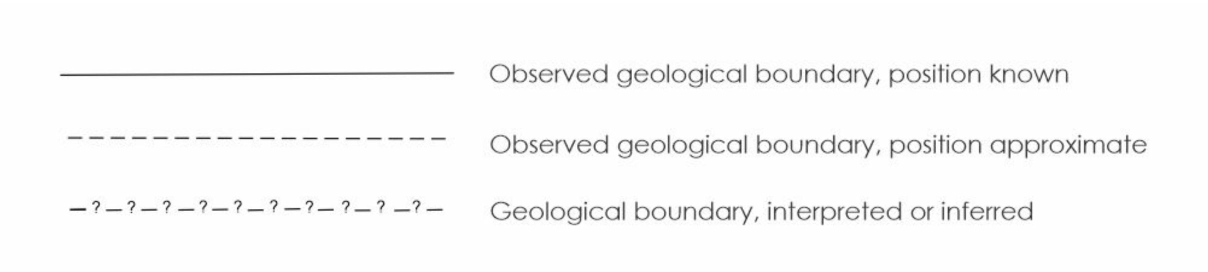


Figure 2-11 Geological linework conventions.

A large proportion of engineering geological knowledge predates the development of computer techniques and digital geological visualisation. These are the traditional ’static’ products and include drawings, diagrams and graphs, photographs, maps, cross sections and physical models. However, on many projects these traditional techniques still contribute to conceptualisation and ’truthing’ of the 3D digital model and, particularly in the case of smaller projects, may be the key EGM outputs.

On most large projects, the large quantities of data that are involved and the modern methods of acquiring those data electronically will mean that processing the data with computers will be the most efficient and probably the only practical way of collating the data.

It seems possible that ’machine learning’ may become increasingly important/necessary to interpret/process the ’big data’ being acquired in site investigations using multi-sensor remote sensing (LiDAR, photogrammetry, thermal, hyperspectral) borehole instrumentation and monitoring (for example, RADAR, InSAR, MS/AE). This prospect raises concerns regarding the ability of ’machine learning’ to conceptualize and interpret in a geologically reasonable manner.

2.3.4.4.1 2D mapping data

2D visualisation of geological data will normally be processed within a GIS (Geographic Information System) that is ideally suited to collate the different geospatial data types, with the data being presented in discrete layers within the GIS system. Note that it is possible to produce simple geological maps and sections using CAD (computer aided drafting) systems but these are more suited to engineering design and do not generally have the functionality necessary for producing good geological drawings.

The architecture of the GIS layers should reflect the different sources of data and, where possible, layers consisting of observations should be differentiated from interpretations. Typical layers for GIS within an EGM are illustrated in Figure 2-12.

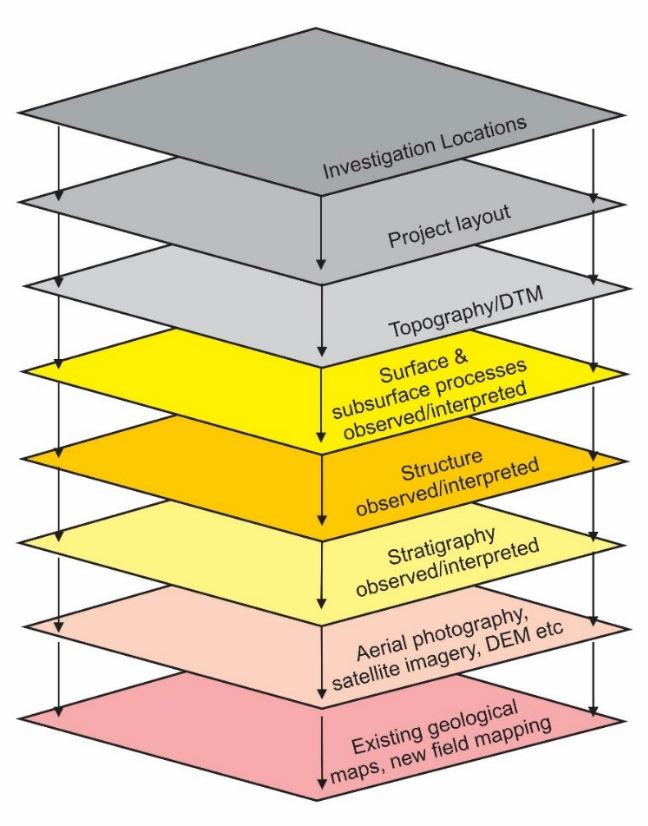


Figure 2-12 GIS architecture for an EGM.

2.3.4.4.2 2D sections

In addition to maps, 2D sections will need to be developed based on an interpretation of the data within the EGM. These sections should be used to inform further analyses, design, construction or as visualisation tools. Cross- and long-sections can be hand-drawn or developed using either 2D or 3D software programs. In 2D software the sections may be drawn digitally by the user, whereas 2D sections exported from 3D digital models may be automatically generated along a section line determined by the user. Irrespective of how the sections are created, they should follow the same basic principles:

- Sections should be located where they can best illustrate the relationship between the project component, the loads or changes imposed by the component on the ground and the data/information available to support the interpretation of the engineering geological units. Section locations may be chosen by designers to explore the effects of particular load cases.

- Where data are projected on to a section, the assumptions made and method of projection should be stated.
- Sections should be drawn perpendicular to the contours or the feature of interest, unless otherwise necessary (for example, for a long-section along an alignment or along the direction of displacement).
- Sections should be drawn through the centre line of critical project elements where there should be the best control (that is, data) and the data on which the section is based should be documented on the section. Where the best control is not along the centre line, judgement must be used to place a section in an appropriate place and may involve additional section lines.
- The vertical scale of a section should (unless scale does not allow for visualisation) be the same as the horizontal scale (that is, no vertical exaggeration). Where an exaggerated scale is used a section without exaggeration should also be provided.
- The symbology of the engineering geological units should match those used in the model and/or map.

3D digital models are not usually able to show dashed boundaries or include question marks on surfaces, so it is often difficult to identify where boundaries are inferred or approximate. One method to help identify such conditions is to include 2D fence sections and maps within the 3D model space as these can include the above mentioned linework conventions.

2.3.4.4.3 Considerations of spatial extent and scale

The spatial extent of the maps and plans that document the EGM knowledge framework should be a function of the area of ground that could be affected by the project, (for example, the area that would respond to loading by a foundation), as well as the area of ground that could affect the project, (for example, an area where a landslide from offsite might originate from that would impact the project). Consequently, these could range from regional maps to plans of individual outcrops or foundations.

The presentation scale of the maps and plans should relate to the scale at which the data were collected. If conventional sections and maps are being prepared then the level of detail of any particular drawing should be related to what is discernible at the scale of the drawing when viewed full size. With 3D digital models scale can be dynamic so it is imperative that the implications of the scale selected to present the data are taken into account when the level of detail that is to be presented is decided.

Caution should be exercised, and limitations documented, when datasets used for the model compilation are presented at scales with higher resolution. For example, scaling boundaries on a 1:100,000 scale map to 1:5,000 on the project engineering geology plan can lead to unreliable models, especially without any field verification and correction.

Note that the scale of the required outputs could change through various stages of a project but the scale of the input data will remain the same and may constrain the way the EGM is developed.

2.3.4.4.4 Stereographic representation

This technique can be used to help assess defect/structure patterns and how/where these change in space. Hence, it is an important tool for assessing and presenting structural data and essential to any EGM being used where the geometry of the discontinuities is of significance (for example, joints, faults, cleavage). This is particularly important for rock engineering but also will apply to projects involving engineering soils that contain defects. Note that stereographic data are a representation of the geometry of defect sets for part of an engineering geological unit, zone or domain or a specific defect set, but do not represent the geometry or real space co-ordinates of those specific defects. Such representation is best achieved through the use of structure contours.

2.3.5 Creating and visualising a 3D digital model

3D digital models enable an understanding and communication of the subsurface conditions in a way that was not previously possible with a 'pencil and paper' approach. For large datasets, 3D digital models allow in-depth verification and interpretation of the data and support greater integration of EGM outputs within other disciplines. 3D digital modelling software allows the visualisation of a wide range of observations (boreholes, CPT, LiDAR, geophysics, groundwater levels, mapped boundaries etc.) together with the interpretations of boundaries of engineering geological units as surfaces, all being created within a single digital modelling environment. From these surfaces 3D volumes can be calculated that reflect engineering geological units in 3D space.

However, there are dangers associated with the development of a 3D digital model if the limitations of the model and numerical methods, particularly the assumptions used in both these elements, are not understood and communicated. 3D digital models can be presented with far greater apparent accuracy and certainty than is actually the case and it is important to communicate this uncertainty. A 3D digital model in isolation is not an EGM, as it does not provide a knowledge framework. The development of the 3D digital models must be performed, or overseen and verified, by suitably qualified and knowledgeable engineering geologists, consistent with the development of other components of the EGM. If not, there is a risk of creating inaccurate, flawed and geologically unreasonable (that is, unreliable) models.

An extensive treatise on digital geological modelling is provided by Turner *et al.* (2021).

2.3.5.1 Modelling software

2.3.5.1.1 Selection of appropriate software

The selection of software packages should involve consideration of:

- The model purpose - which may require that the software allows for visualisation of both engineering structures and engineering geological features.
- The project design phase - different phases of development may require different tools/level of detail.
- The likely model size and complexity – is the geological setting a simple layered stratigraphy or a complex folded/faulted system?
- The size of the data sets - automated/scripted tools may be suited to large data sets versus time-intensive manual interpretation and data manipulation, which is feasible for small data sets.
- Modelling flexibility - manual modification and control of data and surfaces allows the modeller, as well as possible, to create geologically feasible and realistic features.
- Digital model update requirements – will the model require frequent updates? If so, what tools does the software have for limiting rework/reinterpretation?
- Spatial uncertainty – can the software be used for statistical and/or probabilistic analysis of variability and uncertainty within datasets and the wider model?

- Functionality and ease of use – what analysis methods are available? What is the user interface? What incumbent skillsets are required? What is the operational complexity? What is the compatibility with existing software models?
- Can the software produce both 2D and 3D outputs to inform analyses, assist with transparent integration with other disciplines, as well as providing a communication tool to aid in engineering and related decisions?
- Will the software package be suited to the available skills within the organisation? Who will develop, check and review the 3D digital model? Do they have a suitable understanding of the software and its functionality as well as engineering geological knowledge and experience related to both the project type and the ground conditions?
- Specialised 3D models may be developed with a specific analytical outcome in mind. These types of models may require software-specific modelling techniques that are likely to be restricted to providing outputs for a very limited set of analytical methods.
- Will there be a requirement to share digital models – who can edit versus view? How is that controlled? What other models will it need to interface with?

2.3.5.1.2 Modelling in CAD

Computer Aided Design (CAD) methods can be used to generate 3D visualisations of engineering geological conditions. However, CAD systems do not have topology capabilities so the inadvertent intersection of layer boundaries may occur, especially when thin or discontinuous layers are involved, and correcting the model representation in the software may become a major task. In addition, CAD systems are not designed to input and process the wide array of engineering geological information that may be available to a project, tend to use straight, geologically unrealistic boundaries and may not have suitable symbology.

Modelling geology in CAD is not recommended, although it can be used to model simple engineering geology, usually limited to 2D maps and sections. However, CAD is one of the primary ways in which the model is communicated because this is where the Geological Model is integrated with project elements. So that whilst modelling using CAD is not recommended, CAD is a useful platform for communicating the model.

2.3.5.1.3 Explicit modelling software

In explicit modelling the modeller manually defines the nature and distribution of the surfaces that constrain the engineering geological units and the investigation data on which the interpretation is based is represented in 3D. Explicit modelling is what is considered the ‘traditional’ manual method of wire framing and digitising. The modeller interprets the investigation data then defines the surfaces that constrain the engineering geological units.

An example of the output from an explicit modelling package is provided in Figure 2-13.

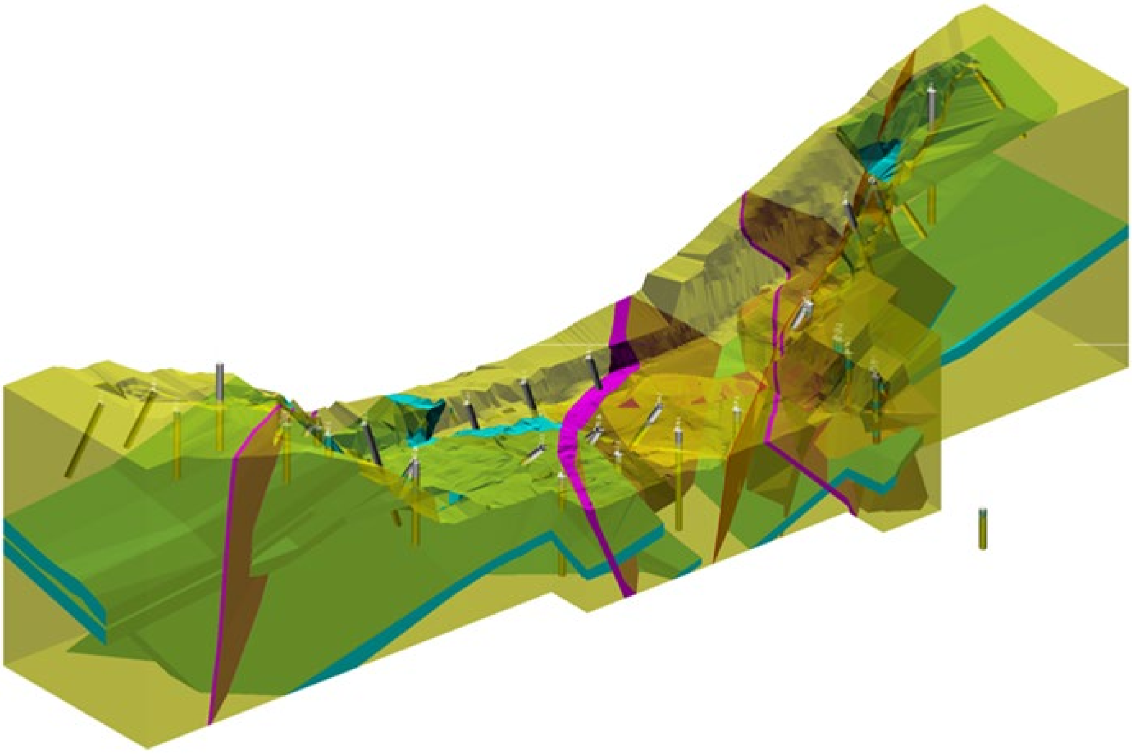


Figure 2-13 Explicit visualisation of the foundation geology of a concrete gravity dam including gently dipping andesites and fault zones intruded by late stage felsite dykes (image provided by Richard Brehauss and reproduced with his permission).

2.3.5.1.4 Implicit software modelling

In implicit modelling the software implements user-defined algorithms to interpolate and extrapolate between data points. The outputs define the distribution of the attributes that characterise the engineering geological units. This distribution can be a continuum or defined by boundaries. This allows the creation of more complex surface shapes than is typically observed in explicit models. However, the results should be evaluated to ensure the modelling produces geologically sensible shapes based on the engineering geological setting and honours geological principles.

An example of the output from an implicit modelling package is provided in Figure 2-14.

Where sub-stratigraphical heterogeneity is relevant the framework model can be 'discretised' to form a 3-D cellular grid (or 'voxels'). The voxels can be assigned material properties such as electrical resistivity, permeability, porosity, shear strength, etc. based on geostatistical algorithms. These voxel representations can be used to generate finite-difference or finite-element meshes for calculations and modelling.

2.3.5.1.5 Comparing explicit and implicit digital models

Either explicit or implicit methods can be used to develop 3D digital models and these can often be integrated. Modern implicit-based modelling software packages typically include explicit modelling functionalities to facilitate the refinement of surfaces. Irrespective of the modelling method, engineering geological knowledge and the use of appropriate geological principles are required. If modelled appropriately both methods will result in robust models with similar interpretations. Table 2-2 below summarises the advantages and limitations of each approach.

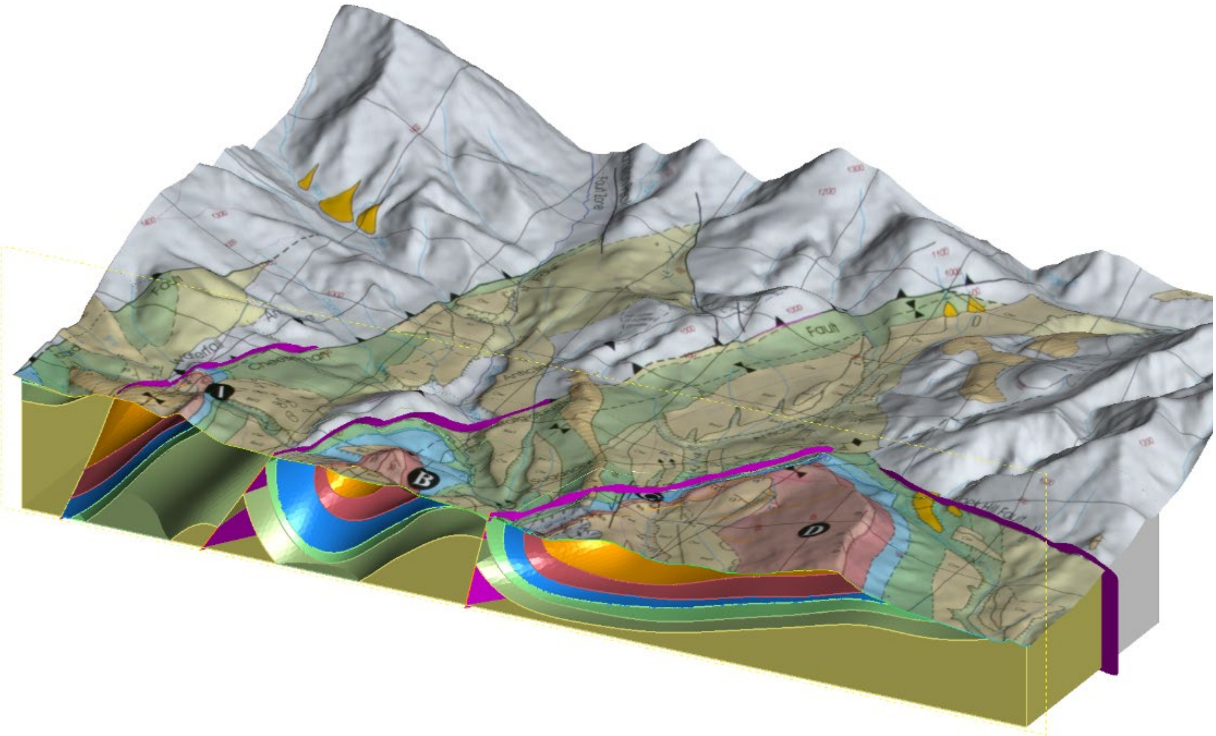


Figure 2-14 Implicit model developed from surface observations using algorithms to project sub-surface boundaries (image provided by Pat McLarin and reproduced with his permission).

2.3.5.1.6 Modelling stratified geology using GIS

Stratified geological environments to depths of 100-200 m are commonly encountered in engineering and environmental projects and a digital model can be created by stacking a series of surfaces. This method allows the incorporation of legacy gridded surfaces developed by GIS procedures or from digital borehole records and interpreted engineering geological cross-sections and is an attractive and efficient model generation procedure when modelling areas of relatively undeformed sedimentary strata. However, representing faults that disrupt simple stacked surfaces may be difficult.

2.3.5.1.7 Discrete fracture networks

A ‘discrete fracture network’ (DFN) is a model that explicitly represents the geometrical properties of each individual fracture (for example, orientation, size, position, shape and aperture) and the topological relationships between individual fractures and fracture sets. A DFN can be generated from engineering geological mapping, appropriate photogrammetry and its applicable analysis or by stochastic simulation. These all aim to represent different types of rock fractures including joints, faults, veins and bedding planes. DFN’s may have to be an interpretation based on available data or a computational model of the rock mass because often not all the discontinuities in the rock mass can be observed in 3D with sufficient resolution at all scales. Computational models of a 3D fractured rock mass are generated from a population of defect sets whose parameters are drawn from statistical probability distributions derived from mapping and borehole logging observations. The resultant computational model can be used to undertake probabilistic analysis of slope stability, tunnel stability etc.

Table 2-2 Comparison of explicit and implicit models.

	Explicit Models	Implicit Models
Advantages	• Can be as simple or as complex as the modeller chooses • Does not necessarily require specialised software applications • The modeller can define cross-cutting features and geological structures such as faults by explicitly drawing them on regularly spaced sections and joining them • Can be manually digitised, as individual cross-sectional interpretations, through the full extent of the site and subsequently joined to create pseudo cross-sections • Alternatively, the modeller can use specialist software to process and manipulate the spatial data constraining the units and connect boundaries to form a wire-framing of surfaces • The resulting model is, therefore, a function of manually constructed surfaces. • Additional (arbitrary) points between observed contact locations may be used to smooth the surfaces and make them more realistic	• Ability to rapidly build and analyse 3D models to visualize and test multiple scenarios • Dynamic modelling can occur with rapid model updates as soon as new data are acquired and input • Ability to process large and varied datasets on a personal computer • Different points in the modelling process can be captured as revisions (at specific points in time), thereby exploring alternative hypotheses • Ability to model iso-grade directly from borehole data without domaining and variography • Ability to create multiple, reproducible models that are conditional to the data itself, not modelling intuition. Note that this means that geological judgement also must be used to assess the reasonableness of the resultant models. • Many implicit modelling software packages allow for explicit editing of surfaces
Disadvantages and limitations	• Manual digitisation can be time-consuming • The final model is a product of the modeller's interpretation and may not be reproducible between modellers • Uncertainty is difficult to quantify • May not be updated automatically as new or different information becomes available. Edits, therefore may be more time consuming than in implicit models	• Documenting the specifics of the way the model works or providing a well-documented audit trail from the model back to the raw data may be difficult making it important to record key inputs rigorously • The uncertainty in digital models remains and effort needs to be made to quantify or make clear sources and impacts of uncertainty • The interpolation algorithms may be difficult to independently reproduce and verify

2.3.5.1.8 Groundwater, contaminant and heat flow models

A range of digital models may be used to predict changes with time of such things as:

- The effects of hydrological changes (like groundwater pumping or irrigation developments) on the behaviour of an aquifer.
- The natural groundwater flow in the environment and the chemistry of the groundwater. Such groundwater models try to predict the fate and movement of the chemicals in natural, urban or hypothetical scenarios.
- Heat flow through the ground. Such models try to predict the periodic variation of the ground temperature with depth.

All of these models are developed from an appropriately attributed well-constrained 3D digital model. Differential equations that can often be solved only by approximate methods using a numerical analysis are then used to predict changes in time.

These types of models should be calibrated, which involves running the model against real observed data and changing the model/parameters until close agreement is obtained.

2.3.5.2 Data Sources and Management

Information sources for engineering geological characterisation may be acquired from a wide array of investigative methods and techniques. These data may be collected, recorded and displayed as points, on linear logs, as 2D plans or sections, or as 3D voxels or polygons. This variety should be catered for by the provision of a suitably flexible generic data structure.

To incorporate logs or records of investigations (boreholes, probes etc.) into a 3D digital model, a relational database is required. Relationships between records/entries in this form of database are provided through two related tables:

- A table of data sources (collar file) presenting coordinates, orientation/azimuth, inclination etc. and other positional information.

- A table of attributes (downhole file) recorded for depths or depth intervals for each data source.

These two tables are related together by a key that is typically a single attribute or a group of attributes. The key is a critically important part of a relational database and is used to establish and identify relationships between tables and also to uniquely identify any record or row of data inside a table.

From a data management point of view, it is recommended to use universal project files, where possible, to minimise reliance on transient software-specific project files that have limited inter-software or inter-version functionality. Fixed or factual data are usually encoded in a standardised fashion that may be tailored to a National Descriptive Standard or an International Descriptive Standard such as the Association of Geotechnical and Geo-environmental Specialists [AGS] format in the UK and the Data Interchange for Geotechnical and Geoenvironmental Specialists [DIGGS] format in the USA. Text-based formats can be accessed without any specific modelling software although the file sizes can be large.

Data transfer standards exist that allow the transfer of geotechnical observational data throughout the project life cycle.

As with all data, robust verification is required to ensure that the geographical information and the observed attributes are reasonable and within acceptable margins of error (as chosen and documented by the modeller). Based on this assessment, decisions can be made as to whether specific datasets should be included in the model and the level of reliance that should be placed on each different dataset. The assessment and decisions should be documented in the 3D Digital Model Report by the modeller.

2.3.5.3 3D digital model documentation

There are risks with providing 'static' outputs to design teams when the EGM is continuously updated through a project. A process is required to ensure design teams are using the most up-to-date EGM information. Information may need to be classified as fixed (for example, data/information that is not anticipated to be changed such as laboratory test records) as well as interpretive information (for example, engineering geological boundaries/surfaces) that may evolve as new data/information are obtained.

During the later stages of projects, especially during construction, the 3D digital model should be revisited and updated with new information/data and a reinterpretation of the associated engineering implications considered. This could be the responsibility of the Owner's Engineer or the Contractor but the responsibility should be clearly allocated.

Transparent 'versioning' of the digital model and its components used within a decision support framework is important. The outcome of court proceedings can depend on demonstrating the model represented the best information at the time, not what was discovered later. The digital model history should be documented manually via, for example, a spreadsheet or automatically with a software or internet-based tool.

2.3.5.3.1 Importance of an efficient data management workflow

Efficient data management is a pre-requisite to establishing an efficient workflow for the 3D digital model development process. This has major economic benefits to the overall cost of model development and use. The following workflow is suggested:

- Plan: description of the data that will be compiled and how the data will be collected, managed and made accessible throughout its lifetime. This is likely to involve the client or other stakeholders. Owners should be encouraged to preserve their own data.

- Collect: capture and acquisition of site and laboratory data as a standardised data file, or hard copy Data Reports, or spreadsheet/database data-capture templates (pro-forma).

- Assure: quality of the recorded data are assured where possible through checks via quality assurance (ISO 9001, UKAS, AGS) procedures using the appropriate in-house verification and validation procedures.

- Describe: data are tidied (cleaned and weeded) accurately and thoroughly described and understood by the end-user. Where data are to be excluded the rationale for doing this must be clearly documented.

- Preserve: data are submitted to an appropriate long-term archive either on an indexed cloud system or in project folders and files.

- Discover: potentially useful data are located and obtained, along with the relevant information about the data (metadata).

- Integrate: data from disparate sources are combined to form one homogeneous dataset that can be readily analysed. Here it is critical that any data limitations or scale issues are clearly identified and recorded.

- Analyse: data are employed to create visualisations (cross-sections or 3D digital models) and assessed using spreadsheets or more sophisticated methods for data analysis.

2.3.5.4 Review of 3D digital models

The checker and reviewer should be suitably experienced in the engineering geological conditions of the site, the project requirements and the software package used to create the 3D digital models.

Before the review of the 3D digital model, a check of the modelling system should first be completed. The checking engineering geologist should be familiar with the software package and able to check the following factors:

- The inputs are up to date and the correct columns have been imported from the database(s).
- Resolution of topography and 3D model are suitable.
- The selection of surfaces for each engineering geological unit.
- The relationship between each surface and the other engineering geological units.
- The nature of the surfaces in 3D and how they respect the basic conceptual model, borehole and input data.
- Any sections or other deliverables produced.

The check, review and verification of 3D digital models is a critical step in the modelling process and provides quality assurance. As the 3D digital model is an aspect of the EGM, the processes and principles outlined in Section 1.1, as well as the development steps outlined in Section 1.2, should be followed. The review and verification of 3D digital models can be more difficult and time consuming than the review of conventional maps and sections as all areas of the surfaces and volumes must be checked and verified that they adhere to the EGM.

If 2D sections and mapping are produced and delivered with the 3D model being used as a basis for interpretation of data and not provided as a deliverable, the 2D sections should be reviewed as per standard practice (borehole data assessed, geological ’logic’ assessed etc.)

2.3.5.5 Outputs of 3D digital models

It is important for the uncertainty in the 3D digital model to be documented and clearly communicated. Surfaces or other model elements that are extracted should have an attached metadata statement indicating uncertainty.

Although the visualisation may have been created in 3D, not all projects require 3D outputs from the model. For some projects, 2D outputs from the 3D digital model may suffice or even be preferable. Many modelling software packages are now set up so that 2D outputs can be exported from the software in various formats, including viewing formats (for example Portable Document Format) and digital drawing files (for example *.dwg) that can be directly imported into other programs for analyses.

3D digital models can also be imported into other 3D modelling and design software to directly inform design of elements reliant on ground conditions. Care must be taken in these scenarios to clearly communicate uncertainty to all current and future users of the 3D digital model.

It may be useful to incorporate 2D details within a 3D output. An example of this is the inclusion of typical or specific detailed 2D sections within a 3D digital model. These sections may be annotated. This provides a level of detail to the output that cannot easily be captured in a 3D format and assists in communication of EGM details and uncertainty.

A 3D Digital Model Report should accompany any outputs.

Other visualisation techniques include 3D pdfs, various specific digital model visualisation tools, animations and videos, virtual reality or augmented reality, 3D printing etc.

2.3.5.5.1 EGM and Building Information Modelling

Building Information Modelling (BIM) is a process involving the generation and management of digital representations of physical and functional characteristics of a building or places. This is to ensure that appropriate information is created in a suitable format at the right time so that better decisions can be made throughout the design, construction and operation of built assets (Kessler *et al*. 2015). Combining a 3D visualisation of the ground with the man-made components of the project (sometimes called a federated model) can be highly beneficial, for example during design evaluation.

However, it is important to understand the key differences between above ground structural models/BIM and the EGM in terms of uncertainty and the way the models have been developed. Problems may occur with digital outputs of the EGM being imported into BIM systems and then relied upon as being accurate and reasonable when further refinement is appropriate and/or necessary.

Also, it is important to recognise or remind users/modellers of the level of uncertainty and how this relates to the corresponding scales between EGMs and BIM. In a BIM model works are commonly viewed at millimetre accuracy whereas EGMs may have an accuracy in terms of tens of metres, appropriate to the interpreted ground conditions. This will impact on the applicability of any such model within the hierarchy of BIM in terms of The Level of Development (LOD) (BIM Forum 2019).

Back to Section 1.3 ASSEMBLY AND COMMUNICATION OF THE EGM

2.4 MANAGING EGM UNCERTAINTY

2.4.1 Introduction

Uncertainty within the EGM is caused by imperfectly known or completely unknown aspects of the knowledge framework. This uncertainty can adversely affect the reliability of the EGM, which is the degree to which the predicted engineering geological conditions provide an accurate and reasonable approximation of the actual conditions or performance, as they influence the project. Reduced reliability will lead to increased risk, which is the probability of an adverse outcome and is often expressed in terms of a combination of the consequences of a series of events or scenarios and the associated likelihood of their occurrence.

Increases in reliability and reduction of risk occur through the accumulation of both conceptual and observational knowledge within the EGM, usually through various stages of investigations that are carried out as the project progresses (Figure 2-15).

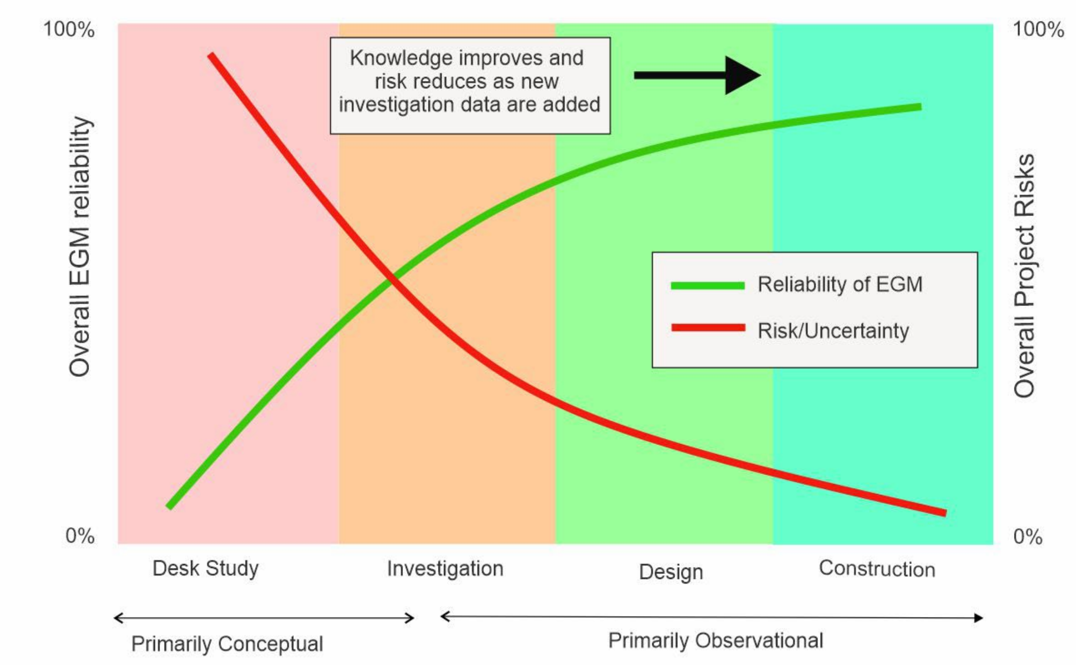
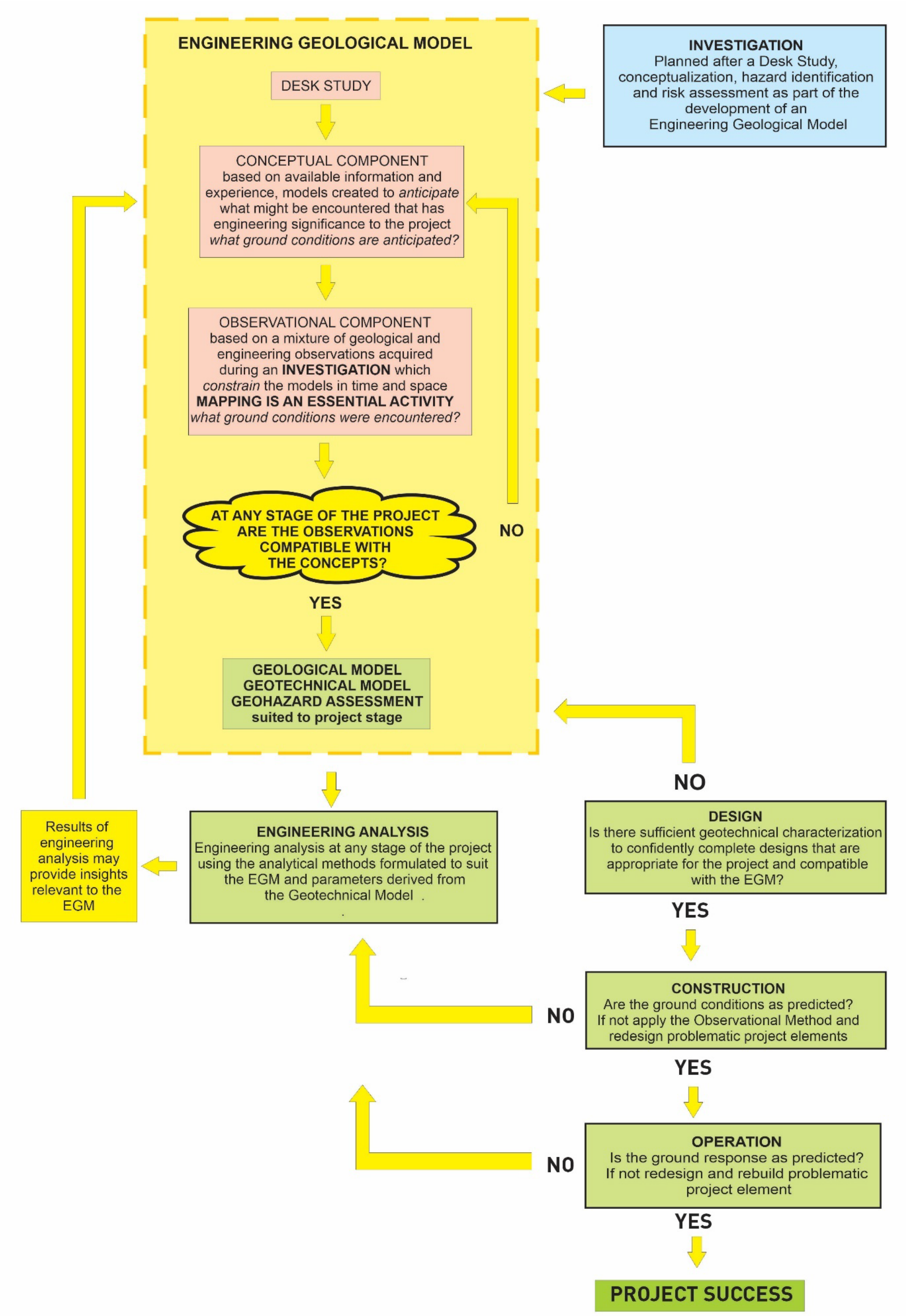


Figure 2-15 Idealised improvements in EGM reliability as project progresses.

However, the classic assumption that progressive risk reduction and associated reliability increase will be created through sequential steps of investigation, then design, then construction, can be misleading. Meaningful reduction of risk and improvement of understanding requires feedback loops during each stage of the project (Carter 1992, Carter & Marinos 2020). It is essential that as the project progresses the EGM is reviewed, verified and, where necessary, improved or altered. Improved reliability is achieved through improved understanding when conceptual ideas and observational data have been reconciled through an iterative process of review, comparison, modification and verification.

True verification of the EGM against a natural, real-world, complex, geological environment is problematic. However, feedback loops in the EGM development process (Figure 2-16) allow the EGM to be constrained against project derived observations. If these comparisons show improved reliability as a project proceeds, then construction can often be completed more efficiently, even though the EGM is not always totally accurate.



INVESTIGATION Planned after a Desk Study, conceptualization, hazard identification and risk assessment as part of the development of an Engineering Geological Model

CONCEPTUAL COMPONENT based on available information and experience, models created to *anticipate* what might be encountered that has engineering significance to the project *what ground conditions are anticipated?*

OBSERVATIONAL COMPONENT based on a mixture of geological and engineering observations acquired during an **INVESTIGATION** which *constrain* the models in time and space **MAPPING IS AN ESSENTIAL ACTIVITY** *what ground conditions were encountered?*

AT ANY STAGE OF THE PROJECT ARE THE OBSERVATIONS COMPATIBLE WITH THE CONCEPTS?

GEOLOGICAL MODEL GEOTECHNICAL MODEL GEOHAZARD ASSESSMENT suited to project stage

Results of engineering analysis may provide insights relevant to the EGM

ENGINEERING ANALYSIS Engineering analysis at any stage of the project using the analytical methods formulated to suit the EGM and parameters derived from the Geotechnical Model

DESIGN Is there sufficient geotechnical characterization to confidently complete designs that are appropriate for the project and compatible with the EGM?

CONSTRUCTION Are the ground conditions as predicted? If not apply the Observational Method and redesign problematic project elements

OPERATION Is the ground response as predicted? If not redesign and rebuild problematic project element

Figure 2-16 Feedback loops to progressively upgrade the EGM during the project life cycle.

The level of risk to the project that is deemed to be acceptable reflects the owner's appetite for risk and varies considerably across the ground engineering industry and around the world. This target risk profile should be considered early in the project, as it ultimately guides the level of uncertainty that is acceptable within the EGM knowledge framework and, thus, the nature and extent of the investigations that are required to reduce the uncertainty to acceptable levels. The target risk profile can be expressed in a variety of ways ranging from simply stating a qualitatively expressed acceptable risk level to the use of sophisticated quantitative risk assessment and precisely defined acceptance criteria.

Throughout the project life cycle the uncertainty within the EGM knowledge framework also will have to be communicated to different project stakeholders, some of whom will have no technical knowledge, using methods that are relevant to them and their needs. Simple transparent classifications of risk level are preferred, such as below.

Project Risk Level Rating

EXTREME	Significant threat to project; immediate action required
HIGH	Risk may pose a threat to the project; recovery possible; senior management attention needed
MODERATE	Risk may pose a threat to the project; almost immediate recovery possible; management responsibility must be specified
LOW	Risk poses minimal threat the project; manage by routine procedures

2.4.2 Sources of uncertainty

2.4.2.1 Uncertainty in the conceptual model

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

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

The following factors are also important:

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

- The geotechnical complexity.

However, the overall reliability of the conceptual model is primarily dependent on the level of experience and knowledge of those involved in its development.

2.4.2.2 Uncertainty in the observational model

Provided that an adequate amount of observational data is considered within a robust conceptual model, the uncertainties in the observational model will be due to:

- Inherent variability: the natural spatial variability of the geological environment that cannot be reduced.
- Limited data: the impossibility of measuring geological and geotechnical properties at every point within the ground; uncertainty can be reduced by increasing the number and distribution of measurements.
- Testing uncertainty: uncertainties related to the measurement accuracy of testing devices which cannot be removed without improving the quality of the testing instrument.

2.4.3 Holistic assessment of EGM by review

A reliable EGM has been established when there is sufficient ’compatibility’ or ’harmony’ between the evolving conceptual model and the acquired observational data. It is the conceptual model that is used to measure this compatibility or harmony, as it embodies the fundamentally correct engineering geological thinking that needs to be developed for a site. This comparison also allows an evaluation of the adequacy of the conceptual model - if there are too many discrepancies between the conceptual model and the observational data and they are increasing as more observations are acquired, then the conceptual model should be reviewed and revised. Previous versions of a conceptual model should not be branded as wrong or inaccurate but should be recognised as part of an iterative process and documented as part of the development of the EGM.

Whilst expert review will include evaluation of the conceptual components of the EGM, such reviews usually take place over a limited time and often cannot delve into the details of the model sufficiently to unearth fundamental development issues that could impact ultimate reliability. To minimise the impact of this inherent limitation of the review process, the optimal approach is to initiate expert review at the earliest possible opportunity as soon as the project has commenced and then continue to review regularly until project completion. This will not be possible where the Expert Review is commissioned part way through the project, for example, in response to some major project failure.

2.4.4 Other methods of assessing the uncertainty and reliability of the EGM

2.4.4.1 Assessing the reliability of the conceptual component

The EGM should be self-checked at agreed points throughout development and refinement of the model so that the reliability of the conceptual model can be benchmarked against appropriate conceptual analogues of the same geological characteristics as the site area being modelled. Thus, self-checking should aim to compare the envisaged concept against real world catalogue examples.

2.4.4.2 Assessing the reliability of the observational component – qualitative approaches

There are multiple ways of communicating the reliability of the observational model to the users of the model, including graphs and thematic maps. Figure 2-17 shows a reliability diagram in the form of a heat map as an example of how to graphically communicate uncertainty in the observations.

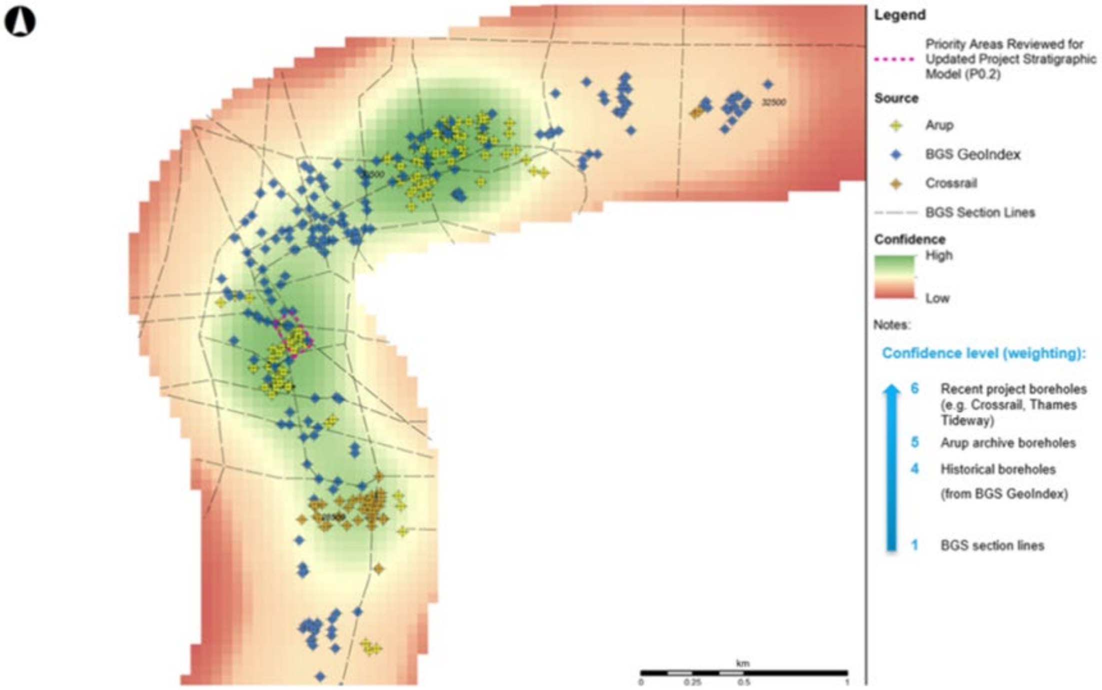


Figure 2-17 Confidence heat map for strata levels (from Ting *et al.* 2020).

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

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

2.4.4.2.1 Relative reliability of Geotechnical Observations

A qualitative approach to assessing the relative reliability of data can be applied to EGMs to classify reliability of datasets (in order of certainty from least to most) under the headings ’Implied,’ ‘Qualified,’ ‘Justified’ and finally ‘Verified’ (see Table 2-3).

2.4.4.3 Assessing the reliability of observational component - semi-quantitative approaches

2.4.4.3.1 The R-Index for tunnelling

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

Table 2-3 Uncertainty related to available information

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

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

- Quality of the geological and geotechnical investigation. The method provides rating tables for each one of the parameters that are subdivided into:
    - Engineering geological mapping, including aerial photograph and satellite image interpretation.
    - Geophysical investigation (indirect investigation).
    - Borehole drilling and logging, site tests and laboratory tests (direct investigations).
- Complexity of the site, that can be described by means of the three following geological parameters, called System Parameters (the method provides a table with the ratings to be used for the anticipated geological conditions):
    - Complexity of the litho-stratigraphical setting (LC).
    - Complexity of structures related to ductile deformations (DC).
    - Complexity of structures related to brittle deformation (BC).

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

The computation of the R-Index is provided along the longitudinal geological and geotechnical profile of the tunnel. The alignment is divided into homogeneous stretches, to which the ratings of the parameters described above are assigned, that allow the calculation of the R-Index for each stretch. The R-index values range from 0 to 10. Its significance in terms of reliability of the model has been deduced by the examination of several case histories and is expressed in four classes (A, B, C, D) as described in Table 2-4.

Table 2-4 Geological and geotechnical model reliability in tunnel projects using the R-Index (modified from Dematteis and Soldo 2015).

R-Index		Reliability	Description
Class	**Value**		
A	10 – 7.6	Good to very good	Limits and faults reported in the section will be encountered within an interval of ± 25-50 m; the margin of error for the thickness of lithological layers may be between 10% and 20%.
B	7.5 – 5.1	Average to good	Limits and faults reported in the section will be encountered within an interval of ± 50-100 m; the margin of error for the thickness of lithological layers may be between 30 and 50%. In addition to those indicated, other minor faults could be present.
C	5 – 2.6	Poor to average	Limits and faults reported in the section will be encountered within an interval of ± 100-200 m; the margin of error for the thickness of lithological layers may be between 50 and 100%. In addition to those indicated, other major faults could be present.
D	2.5 – 1	Not all reliable or unreliable	Limits and faults reported in the section may be absent, and other elements may be present. The thickness of lithological layers is not defined. Geological elements other than those forecasted may be present.

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

2.4.4.3.2 Uncertainty Assessment

After a site investigation has been completed, the level of uncertainty and reliability of different parts of the EGM knowledge framework may be systematically assessed to identify project implications, for example, using the method devised by Paul (2018).

2.4.4.3.3 Use of metadata statements

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

2.4.4.4 Assessing the reliability of observational component - quantitative approaches

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

2.4.4.4.1 Random field approach

This method enables the users to interpret the spatial variability uncertainty through a deterministic trend function and random fluctuations. By implementing the random fluctuation properties within a

Monte Carlo simulation, the users can calculate the spatial standard deviation related to the estimated values of the parameters over the whole domain of interest (Vanmarcke 1984).

2.4.4.4.2 Kriging Methods

Kriging methods are a set of univariate and multivariate techniques pertaining to geostatistics that allow mapping of the spatial distribution of quantitative georeferenced data, such as mechanical and hydraulic properties of soils and rocks, as well as contained fluids. These methods are based on the Regionalized Variable Theory that considers quantitative attributes of a certain domain (for example, an engineering geological unit), measured in a discrete way, as random and spatially dependent variables. That is, values related to close measurements are likely to be more similar than if they were more separated. These geostatistical techniques provide a quantification of the uncertainty associated with the estimates in terms of kriging variance that, in turn, can provide a standard deviation value (within the same engineering geological unit) or required confidence interval limits (Vessia *et al*. 2020). For kriging to give meaningful results this should be undertaken for the engineering geological units developed with the EGM.

2.4.4.4.3 Stochastic Simulation methods

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

2.4.4.4.4 Incorporation of data uncertainty in design parameters

Comments on these aspects of design are outside the scope of these Guidelines.

Back to Section 1.4 MANAGING EGM UNCERTAINTY

2.5 ENSURING EGM QUALITY

2.5.1 EGM overall quality objectives

The EGM should aim to satisfy a number of objectives and should be:

- Compliant with the project tender documents/specifications.
- Robust - created from a logical understanding based on assimilation of all available information, with input of considerable experience and following geological logic.
- Transparent - easily accessed and understandable even to non-technical people.
- Defensible - of sufficiently high quality to withstand reasonable criticism.
- Consistent - everything should work in harmony and should be free of major flaws.
- Sufficient - it should document and explain all important engineering geological conditions at the site.
- Necessary - parts of the EGM that are not essential should be removed.

2.5.2 Checking the quality of the EGM development process

2.5.2.1 Standardisation of Model Data Inputs

Standardisation of model input data will reduce difficulties in the development of models in different stages of the same project (that could be carried out by different organisations or individuals) and/or help to standardise data input formats across asset portfolios. This is to ensure that users/clients can distribute these models internally within their business to allow the most use to be gained from them and allow the models to be better understood by those outside of geology, geotechnical and civil engineering disciplines. Table 2-5 below is not intended to be exhaustive with regard to the spatial layer categorisation but to provide a guidance as to the level of detail for information that users/clients would like to see on 'typical' information.

Note that older information that lacks the ’standard’ format can be classified as ’inaccurate or incomplete’ and omitted from the database. However, as such information can provide invaluable insights into the ground conditions, it is imperative that it should be incorporated into the model. It is important to ensure that input standardisation protocols are not used to filter out and omit non-standard but possibly critical data.

On some projects the model data inputs may have to comply with a project specific digital engineering management plan.

Table 2-5 Standardisation of inputs

Data Type	Sub-type	Required information
Topography		Date acquired, acquisition method, description of topography (for example merged from surfaces x & y etc), superseded or current? stated accuracy, scale
Borehole/excavation data	Collar	Hole id, collar xyz, projection & datum, depth, inclination, azimuth, logging standard, hole/test pit/costean type, method
	Downhole data (baseline dataset for all derivative data)	Hole id, from, to, rock/soil type, rock/soil description normally this is in a database in a recognised data format, for example AGS and the entire database is provided.
Structural (geological measurement) data		Date acquired, defect type, magnetic or true north azimuth measurement
Piezometer data		Hole id, date drilled, hole collar, RL, hole depth, piezometer type, date of measurement, water level, *in situ* permeability test result
Geological sections		Section title and short description, date, drawn/produced, drawn by/approved by, section offset tolerance, orientation, scale, borehole/pit projection methods
Major geological structural features (faults, dykes, shear zones, anticline and syncline axis)		Fault id (if applicable), confidence (conceptual, inferred/low, moderate or high), extrapolation distance and justification, estimated fault/zone width (if known), description of fault characteristics, descriptive standard (for example, as AS 1726:2017)
Georeferenced Maps	Aerial imagery/terrestrial remote sensing	Date acquired, type - Lidar, aerial photo, satellite image etc. acquisition method, wavebands, processing methods, superseded or current, estimated accuracy of georeferencing, scale
	Drawings (information to be included on the drawing itself or within the naming convention as appropriate)	Drawing number, date created, scale, drawing legend (if available), datum of original drawing, estimated accuracy of georeferencing
Geophysics	Survey lines (for example, seismic)	Date acquired, acquisition method, land or overwater, legend, estimated accuracy of georeferencing
	Aerial surveys (for example, gravity or radiometric)	Date acquired, acquisition method, legend, estimated accuracy of georeferencing, scale
	Downhole geophysics (for example, wireline traces (density) or visual (ATV)	Survey type, date acquired, measurement scale (as appropriate)

Back to Section 1.5 ENSURING EGM QUALITY

2.6 EGM AND PROJECT ENGINEERING

2.6.1 Overview

The EGM knowledge framework supports project documentation, project procurement, investigation, design, construction and risk management. As such, the EGM is relevant to the Project Owner, the Project Engineer, the Contractor, the Regulator and other project stakeholders.

2.6.2 EGM and project stages overview

The EGM plays a key role in the modelling-analysis-design-construction-operation progression. Although not every project will develop in the same way, and different terms are used to describe project stages in different ground engineering industries, an outline of how the EGM may develop over the course of a project is set out below:

Concept/Pre-Feasibility

- Largely based on a desk study and existing information.
- Low reliability, especially at the near-field (project site) scale; better reliability at the far-field (regional) scale.
- Mainly conceptual.
- Initial Geological Model and, where required, initial Geohazard assessment produced.
- Informs high level geotechnical issues and hazards and subsequent investigation stages.
- 3D visualisation might commence at this stage.
- Visualisation may be relatively simple, for example, an emphasis on aiding interpretation of geomorphology and stratigraphy or lithology or may be more complex, for example if reconnaissance mapping is undertaken.

Feasibility

- Site specific investigation data available. Conceptualisation reviewed and amended if necessary.
- Geological Model produced.
- Undertake qualitative or quantitative assessment of EGM reliability. Question what the key engineering geological controls on ground behaviour and critical failure mechanisms might be.
- Design further investigation to reduce uncertainty and achieve synergy between conceptualisation and observation.
- Geotechnical Model and Geohazard assessment produced
- Initial analytical models developed to inform specific analysis.
- Check EGM reliability is consistent with design stage.

Schematic Design/Tender Design

- Greater detail in Geological and Geotechnical Models and Geohazard assessment due to additional site investigation.
- Analytical models developed to inform design.
- Develop additional sub-models to provide better reliability at larger scale as needed.
- Ensure EGM is transferred to tenderers, where contractual arrangements allow.

Detailed Design Stage

- Visualisation may be a 3D digital model.
- Reliability consistent with objectives at the scale required.

- Analytical models developed from the Geological and Geotechnical Models and Geohazard assessment with confidence.

  The key questions at this step include:

  - What are the engineering geological controls on design as informed by the EGM prior to commencement of the analysis?
  - How do the analytical results inform the understanding of mechanisms and ground behaviour and is this consistent with the conceptual understanding?
  - How does the engineering geological and analytical understanding inform the selection of design parameters? How does the project risk profile impact on design decisions?

Construction

- EGM is used as a predictive tool for construction work and is updated repeatedly in response to ground information observed during construction.
- Construction observations and monitoring, design verification.
- Serves as an 'as built' record of conditions encountered.
- Integration with BIM.

2.6.3 EGM in site investigations

Following the development of the initial Geological Model, together with the initial risk register, the site investigation can be planned to test the model and to investigate areas of uncertainty. From an engineering geological perspective, the focus of the investigation should be on the acquisition of information relating to the following key objectives:

- Confirmation of the understanding of the setting, stratigraphy, structure and surface processes in and around the site. Data can be acquired at locations specific to the project lay-out, such as the corners of a structure, but those points may change with time as the lay-out is modified. The most critical data should be acquired at locations that are optimal for understanding the initial Geological Model such as the depth to important engineering geological unit boundaries. However, as budgets are limited and all parties should be involved in planning the investigations, there will always be compromise in planning investigation locations.
- Evaluation, characterisation and documentation of the engineering geological units and conditions by means of surface and subsurface observations and testing.
- Investigation and characterisation of any geohazards or ground response hazards that have been indicated in the conceptualisation.
- Evaluation of any problematical engineering geological conditions that are known to exist but are so complex that it is impractical to investigate them in sufficient detail.
- Look for evidence of any problematical engineering geological conditions that have been anticipated by the conceptualisation process but have not been observed and, therefore, if encountered unexpectedly during construction, could potentially be regarded as unforeseen ground conditions that could form the basis for a claim.

Figure 2-18 provides a generic process diagram for using the EGM knowledge framework to plan and execute site investigations.

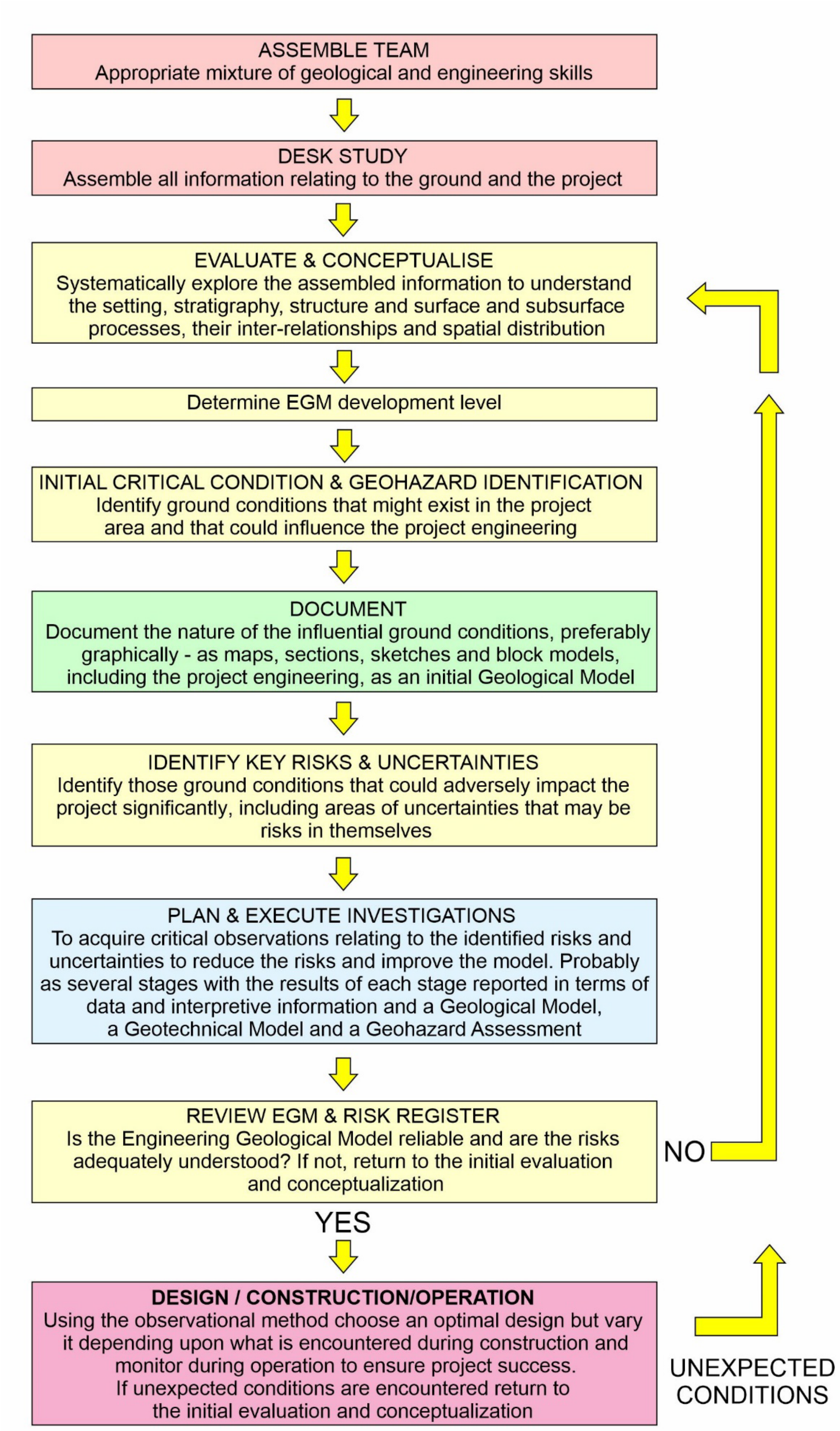


Figure 2-18 EGM components and site investigation (after Baynes *et al.* 2021).

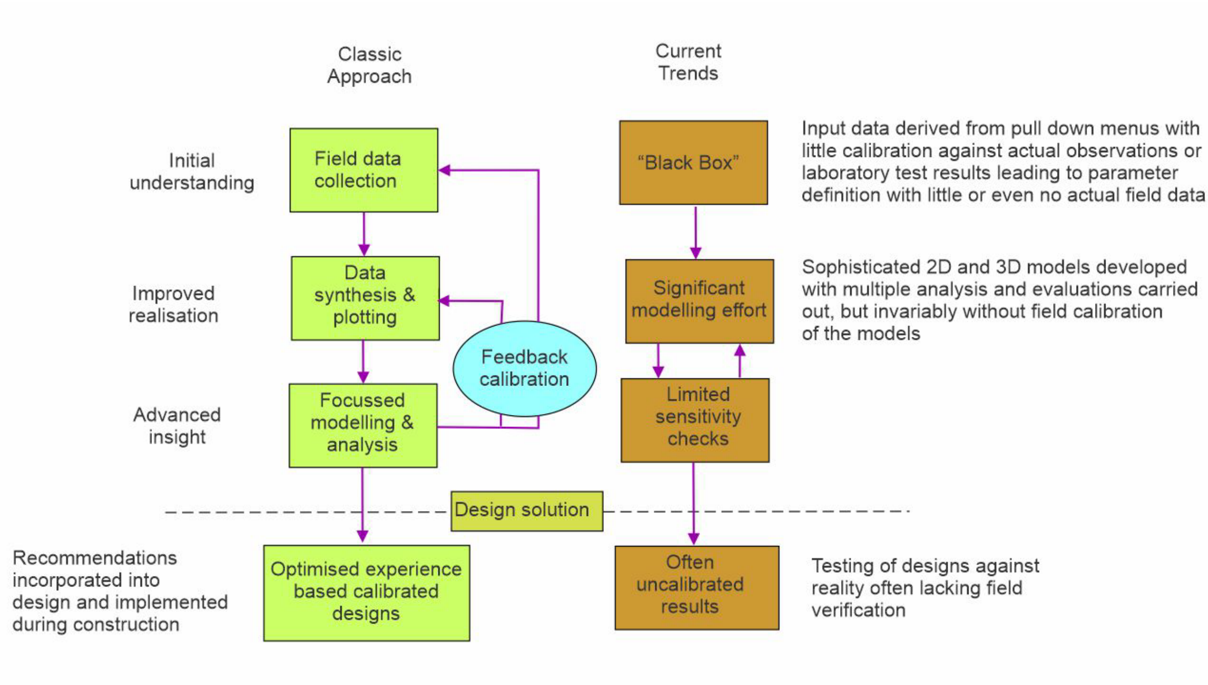


Figure 2-19 Comparison of the classic approach versus current design practice (after Carter 2015).

2.6.4 EGM in construction management

As a project moves into the construction phase, the exposed ground conditions should be evaluated against the potential variations anticipated by the EGM and an assessment made as to whether or not these variations could potentially impact on the design or construction methodology and whether or not the geotechnical risk assessment requires updating.

The EGM also plays a role during construction when the Observational Method is adopted. The Observational Method, as proposed by Peck (1969), is a design and construction methodology that is distinct from the observational model and essentially involves the following steps:

- Consider the engineering implications of a range of engineering geological conditions that can be reasonably anticipated from the EGM.
- Design for the most probable engineering geological conditions but conceive designs suited to the range of possible engineering geological conditions and ensure the contract allows for such changes.
- During construction, if the as-encountered engineering geological conditions differ from those that were expected, the designs should be modified accordingly. This requires very close liaison between the design teams, the on-site engineering geologists and the construction engineers to ensure differences in observed conditions from those that are anticipated by the EGM are acted upon swiftly.

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