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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 be reviewed and revised after one year in response to feedback from their use in different parts of the world.

The Guidelines comprise three 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.
3. Examples of EGM applications (Part 3). The Examples provide overviews of the application of EGMs to a variety of project types.

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 C25 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 information 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 Guidelines were subsequently revised following comments received at and after the Athens meeting, including a contribution from IAEG C28 - Commission for Reliability Quantification of the Geological Model in Large Civil Engineering Projects.

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

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

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.
- 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, that might range from regional resource assessment to confirmation of foundation conditions.
- Geological Model – an output from the EGM knowledge framework that represents 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 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 – 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 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 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 and geomorphological 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.

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.

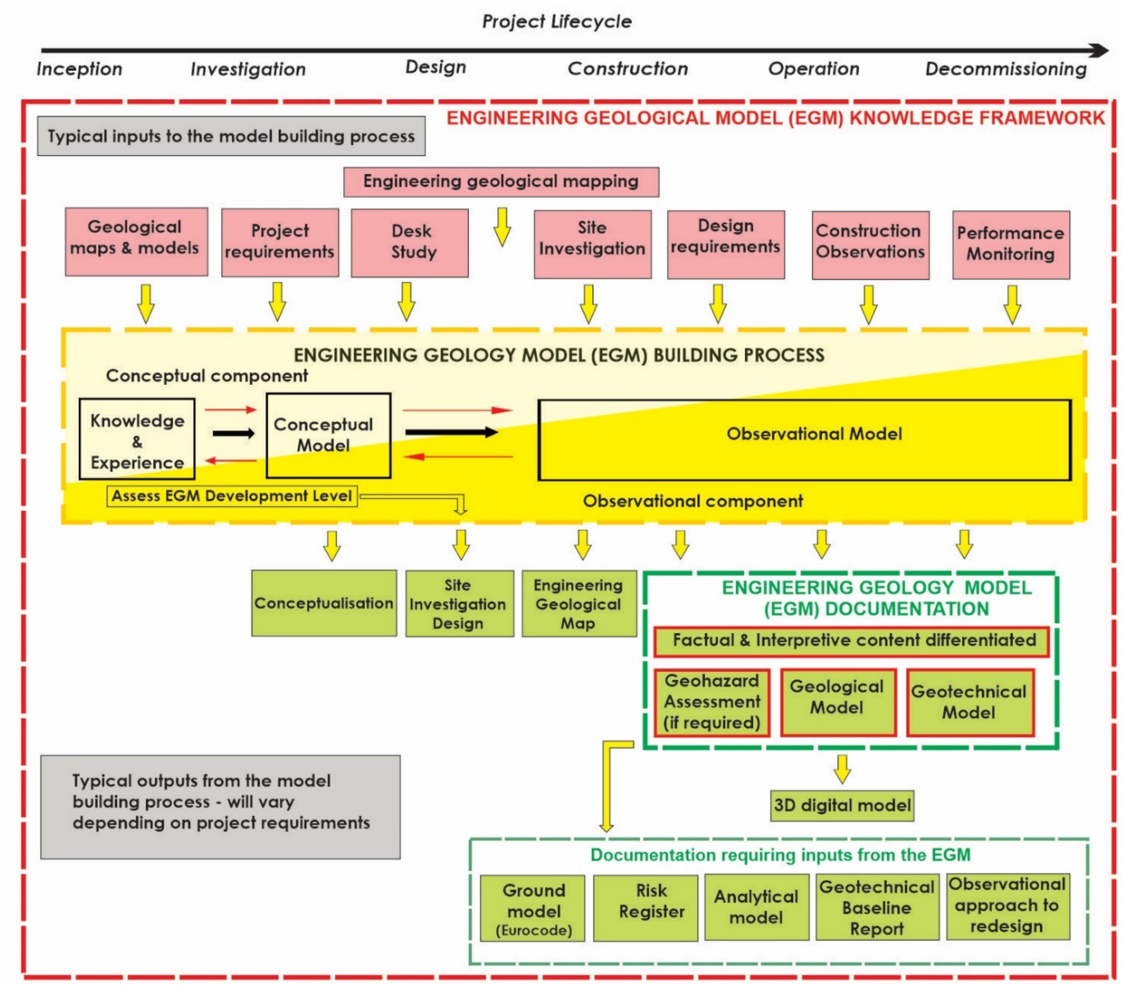

Figure 1-1 A schematic visualisation of the EGM development through the project lifecycle.

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 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.

1.1.2.5 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.

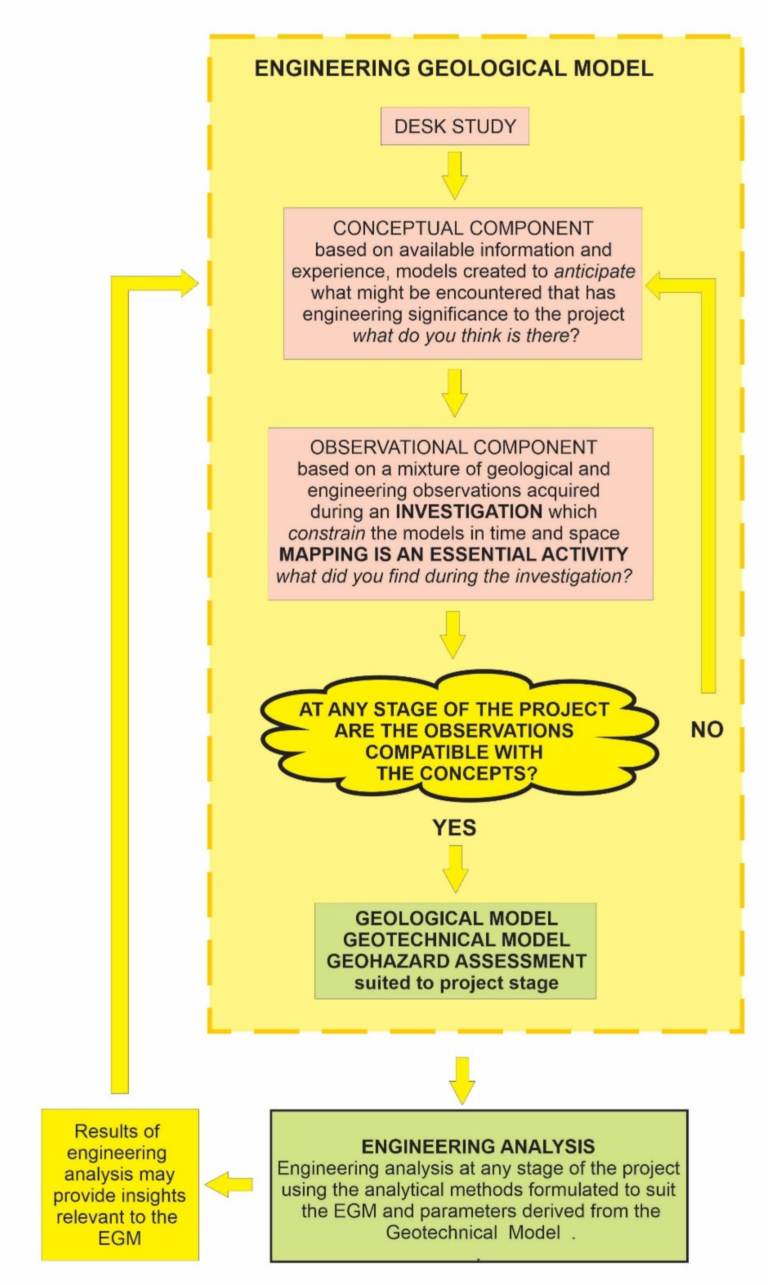

Figure 1-2 Engineering analysis should proceed when observations are compatible with concepts.

1.1.2.6 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, ideally, 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 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.

1.2.1.2 The development process

The EGM development process involves the following essential steps, usually with repeated iterations of most steps:

- Assemble team, define scope and purpose.
- Assemble relevant engineering and engineering geological information of significance to the project in a desk study.
- Undertake an initial reconnaissance mapping by a competent engineering geologist.
- 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.
- Identify and document key uncertainties in a risk register. This register is used throughout the project's life cycle and needs to be updated on a regular basis.
- 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.
- Combine the observations and the concepts to develop an *interpretation* of the site conditions; if necessary, re-evaluate the conceptual model.
- Define engineering geological units, interpret their distribution and generate a Geological Model.
- 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.

- Identify significant uncertainties, gaps and discrepancies in the knowledge framework; these are potential risks to the project and should be added to the risk register.
- Evaluate the risks and, if necessary, undertake additional investigations to improve the knowledge framework, minimise unknowns and reduce risks.

The EGM development process is illustrated in Figure 1-3 and detailed below.

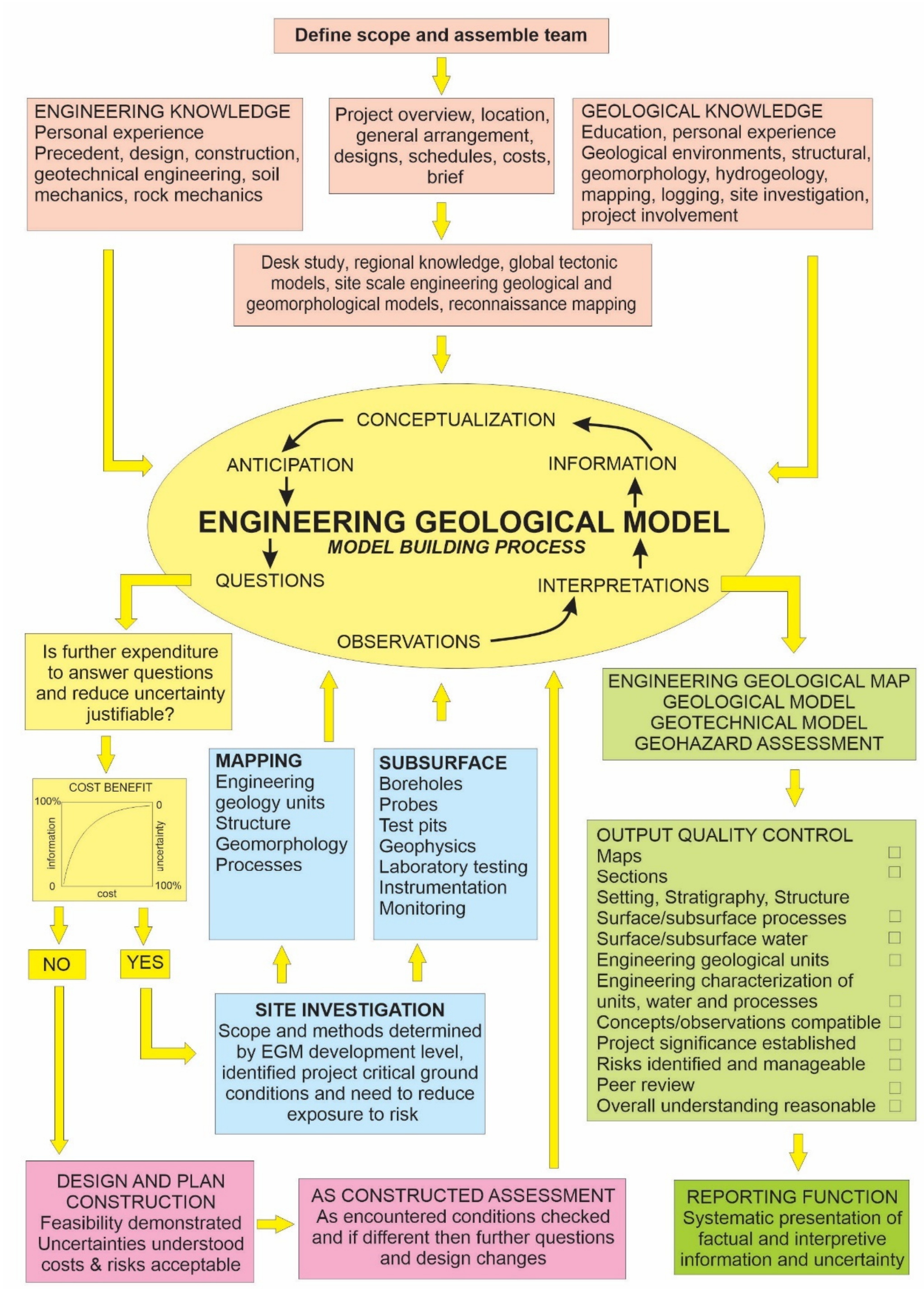

Figure 1-3 The EGM development process.

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 1-1 and 1-2. The development level should be revised if the investigation indicates that the geotechnical complexity is higher than anticipated.

Table 1-1 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 1-2 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 factual and interpretive report	Documentation of the EGM in factual and interpretive reports	Documentation of the EGM in factual 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. 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.

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 area.

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, 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 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.

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 mapping that includes observations and interpretations in investigating any project is emphasised. 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 involves 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.

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 see which areas of uncertainty and which risks remain to be explored 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, landsides etc) that are critical for predicting the frequency of future geohazards.

Mapping should commence following the development of the conceptual model and can initially be based on remote sensing; where practical, this can be evaluated during field reconnaissance. 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.

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.

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.*

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.

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.

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. Some form of engineering geological and geomorphological mapping should be an essential part of every project.

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 chronostratigraphical units (age based units) provided on the geological map. However, lithostratigraphical 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 published lithostratigraphical boundaries, such as boundaries shown on geological maps. The lithostratigraphical unit 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 lithostratigraphical 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 1-4 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.

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.

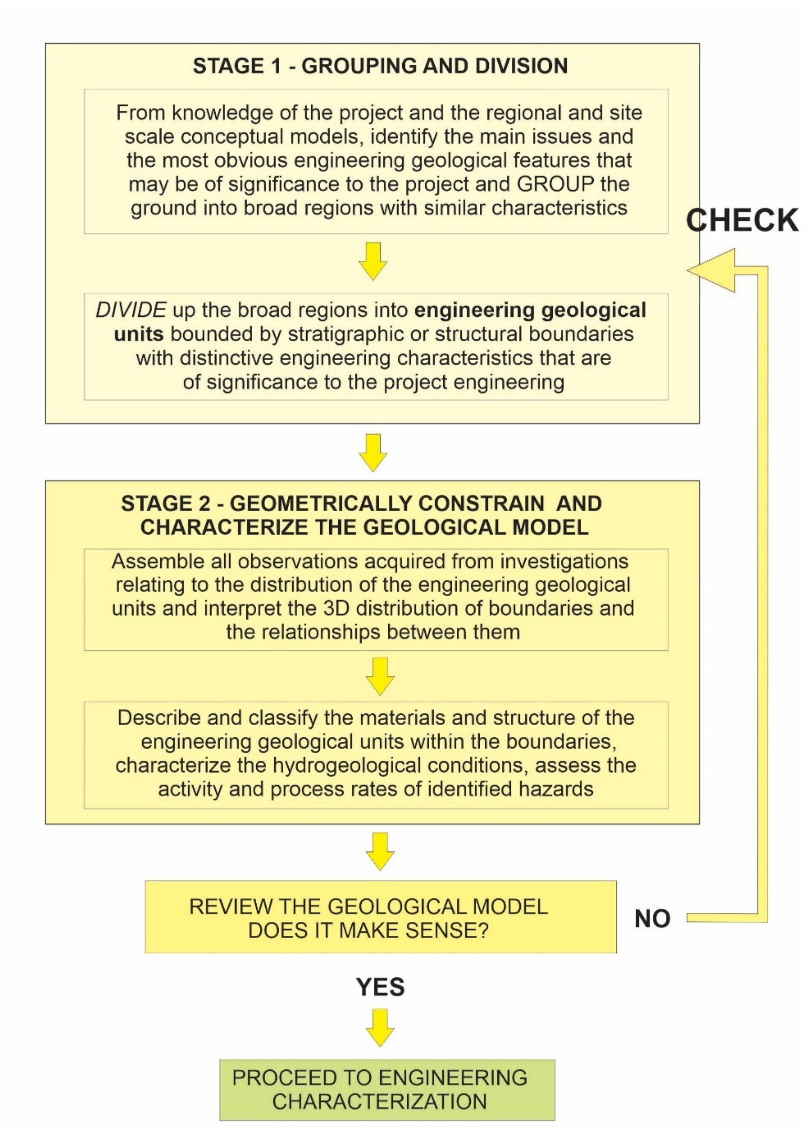

Figure 1-4 Establishing engineering geological units and the basis of the Geological Model.

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 evolves 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 improve the characterisation of the engineering geological units and reduce uncertainty but may differ from 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 this section 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 1-3 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 Factual 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 Factual 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 1-3 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 Factual 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 presents 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:

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

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

1.3.4.1 Factual Report

A Factual 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 factual 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 factual 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 factual or 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 presents 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.

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 1-5 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 by non-technical individuals 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 1-4 below provides specific items for consideration during review and verification where a 3D digital model has been developed.

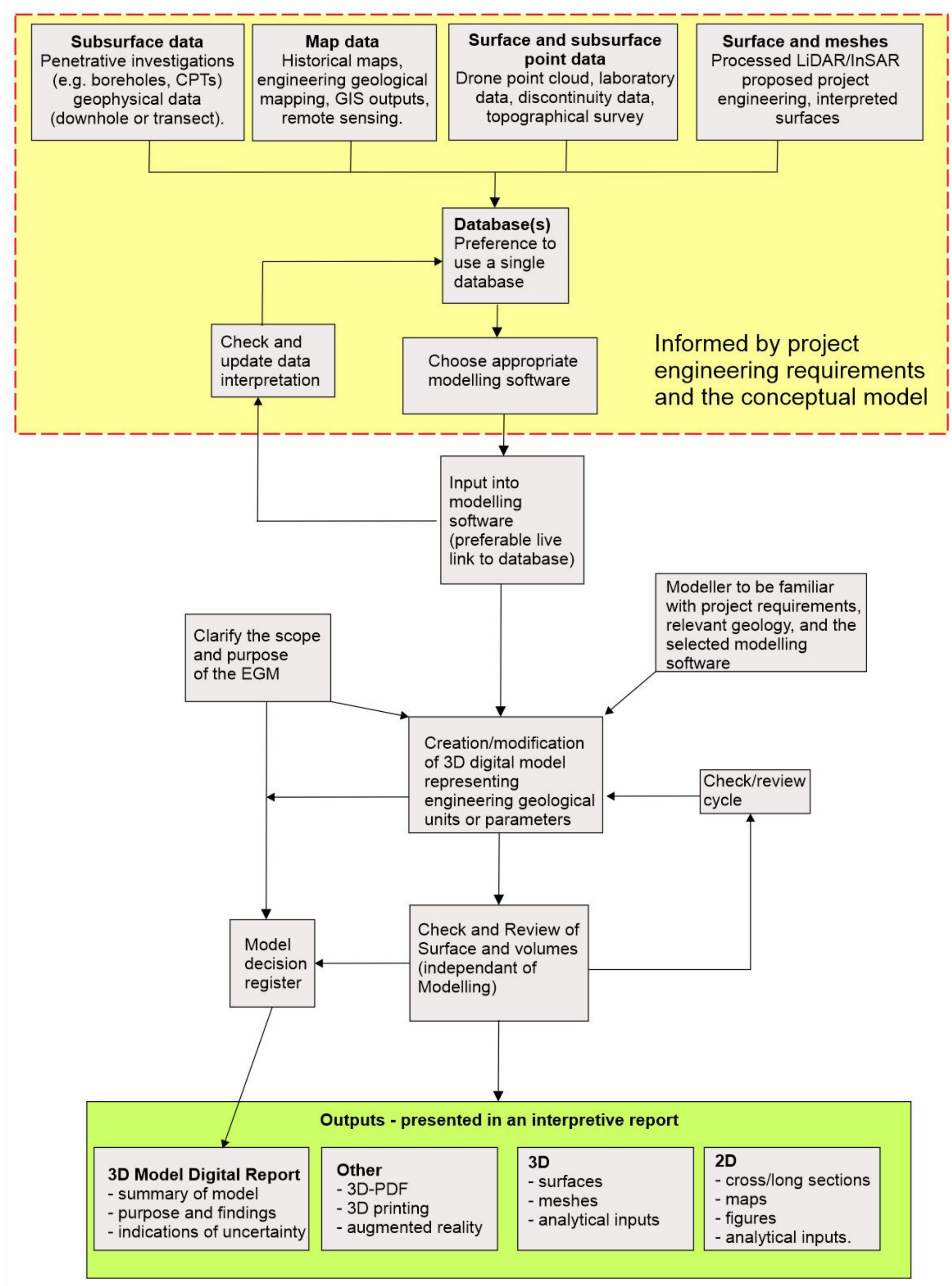

Figure 1-5 Typical digital 3D digital model development process.

Table 1-4 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 1-1 & 1-2).

- 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 1-6. This approach should be adopted at all stages of the project by individuals, peer reviewers and expert panels.

The best means for assessing the reliability of the conceptual component is through expert panel or peer review. However, basic qualitative checks of the conceptual reliability of an EGM should also made as it is developed. Self-checking, as well as internal checking, should always be carried out, the results of which should be documented.

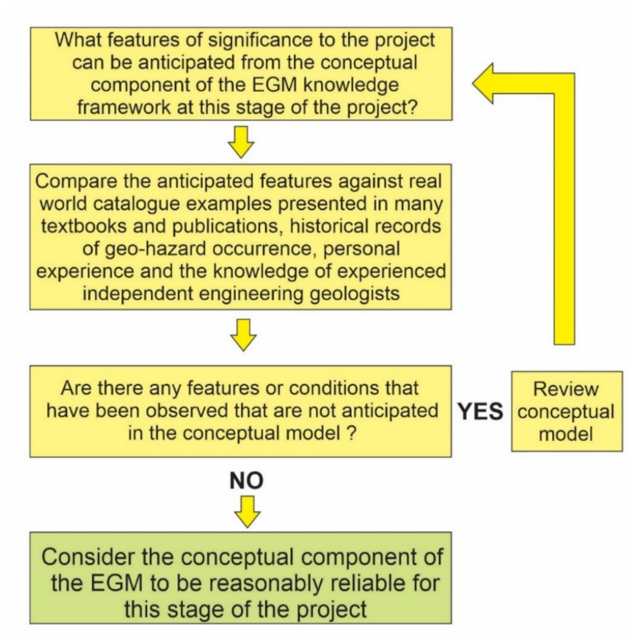

Figure 1-6 Approach for assessing the reliability of the conceptual component of the EGM.

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 1-5.

Table 1-5 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?	
Have observations been acquired through investigations and documented as facts?	
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 1-4 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

No commentary.

2.2.1.1 Initial steps

No commentary.

2.2.1.2 The development process

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 shall 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).
- 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 2-1 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).

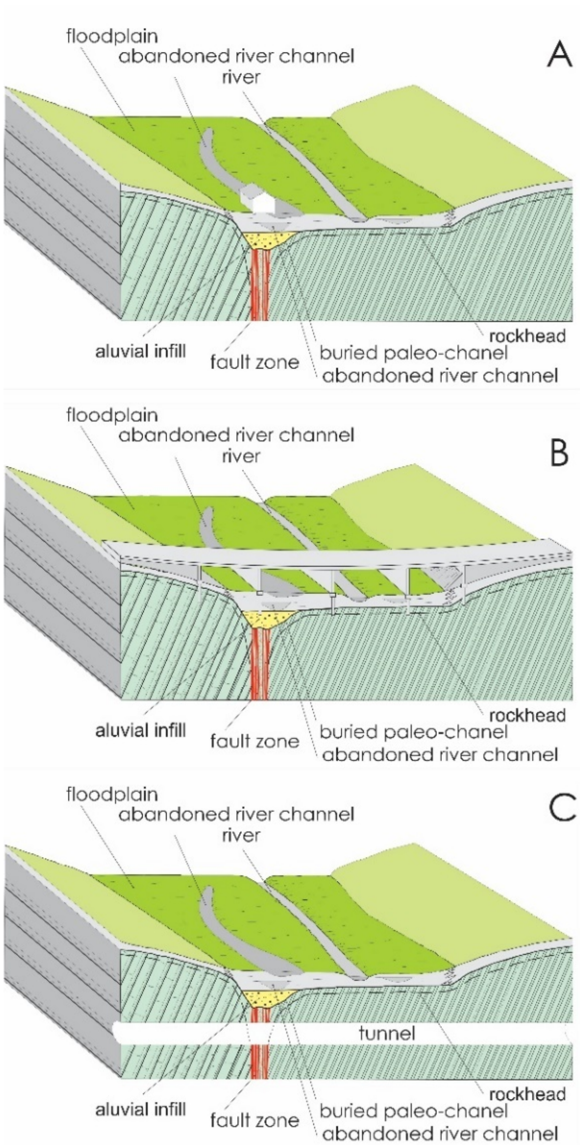

Figure 2-1 Influence of project type on the EGM. Reprinted with permission from Springer Nature. Bulletin of Engineering Geology and the Environment. Parry *et al.* 2014, Engineering geological models – an introduction: IAEG Commission 25.

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 district, - 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 is being used in the EGM and 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 Conceptualise the EGM

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 2-2 shows the conditions that can be anticipated in granitic terrain that has been subject to deep chemical weathering.

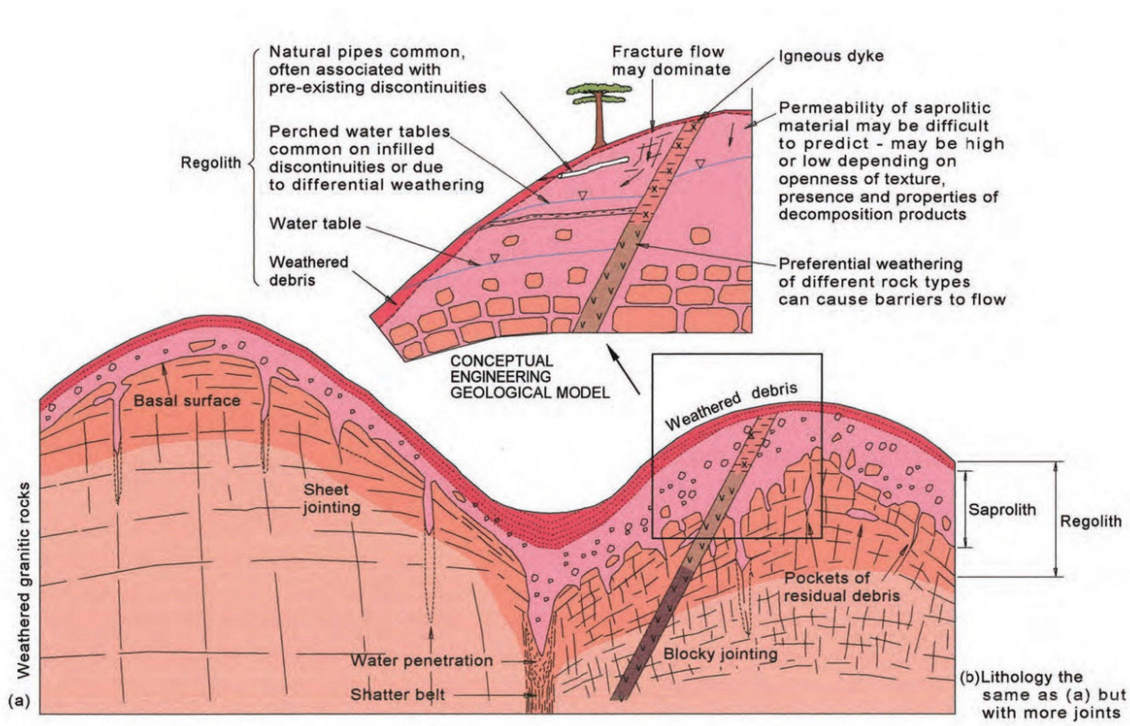

Figure 2-2 Typical granite characteristics. Reproduced from Fookes *et al.* 2015. Geomodels in engineering geology – an introduction. © Whittles Publishing 2015.

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 2-3.

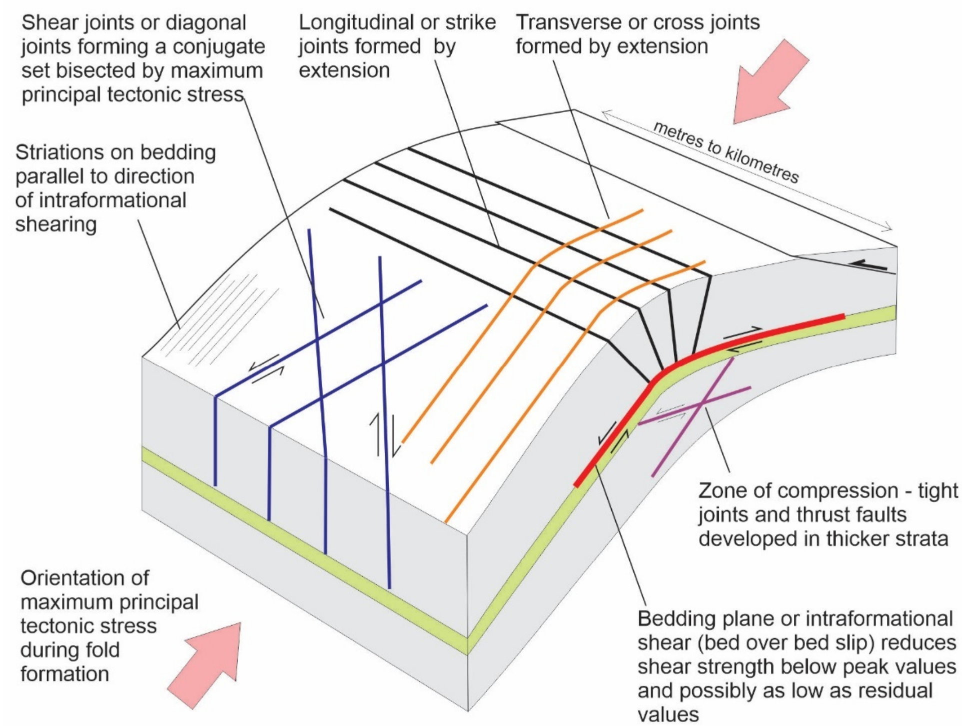

Figure 2-3 Structures associated with open folding (based on Price & Cosgrove, 1990).

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 2-4.

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.

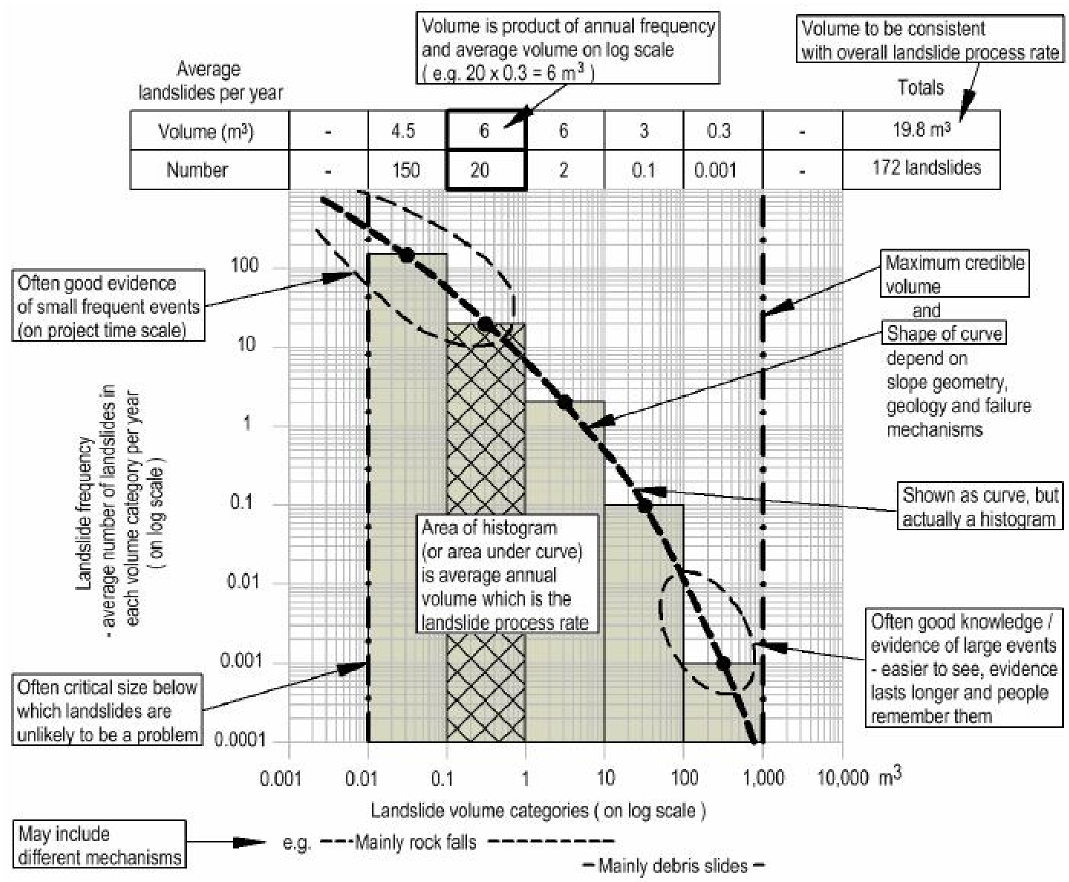

Figure 2-4 A generic landslide magnitude frequency model (Moon *et al.* 2005). Reproduced with permission of the authors.

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 2-5.

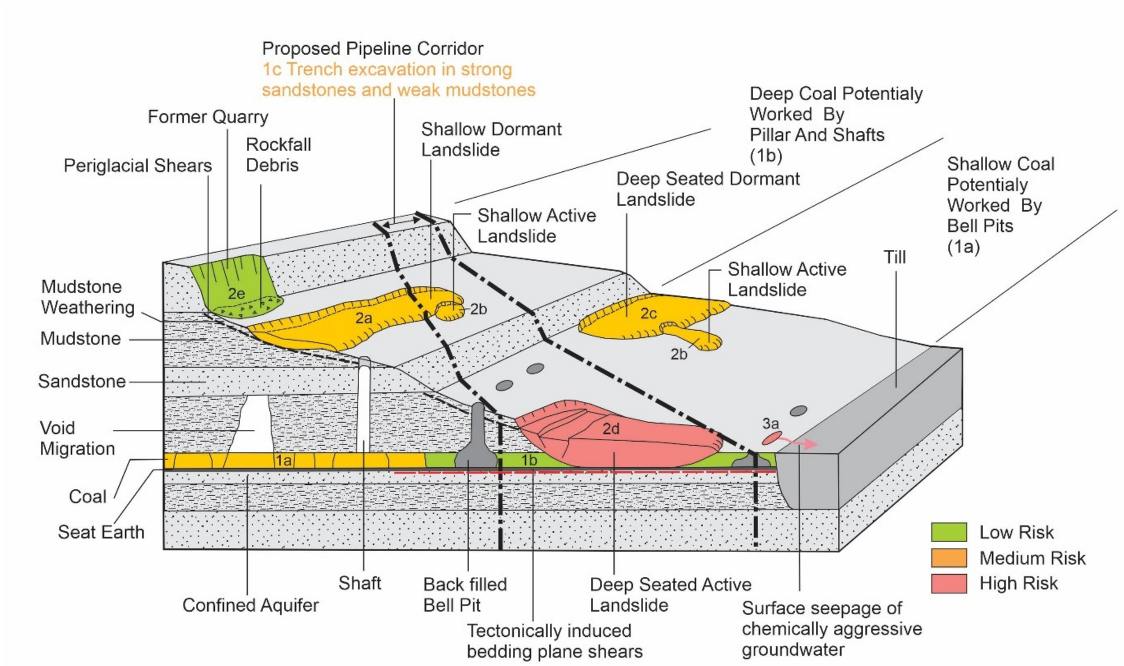

Figure 2-5 Visualisation following a desk study of the conceptual component of an EGM for a pipeline crossing unstable ground affected by mining and landslides (from Baynes *et al*. 2021).

2.2.3.4 Acquire observations of the project area throughout investigations

'Factual' 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.

Generally, it is useful to provide a geological interpretation in the log (as mandated in the Australian Standards, AS1726 2017), as this aids in the interpretation of the overall site conditions and hence adds value to the logs. 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 need to interpret what they are observing and need to decide what else or where else the conditions should be observed and measured, based on their previous observations and interpretation. Clearly, more experienced persons have an advantage. If the observer is provided with the EGM 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 revaluate 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.

2.2.3.5 Combining conceptual models and observational models into the EGM

No commentary.

2.2.3.6 Defining and characterizing engineering geological units

No commentary.

2.2.3.6.1 Geotechnical complexity

No commentary.

2.2.3.6.2 Engineering characterisation

No commentary.

2.2.3.6.3 Zoning

No commentary.

2.2.3.7 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) includes geology and presentation and evaluation of test results.

(2) The Geotechnical Model (in EN 1997-1:2004) 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 factual and an interpretive report. The 'Factual Reports' are usually regarded as 'Rely Upon Data', whilst the 'Interpretive Reports' often 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 Factual Report

In some cases, owners choose to issue only 'factual' 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 factual 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.

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 2-6. When developing digital-based maps, observed, projected and interpreted boundaries should be differentiated in a similar manner.

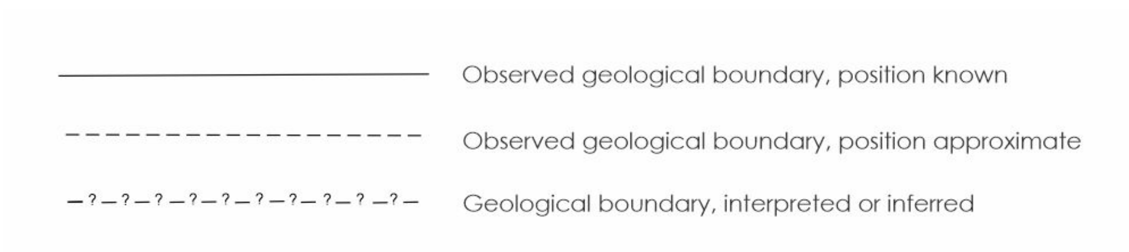

Figure 2-6 Geological linework conventions.

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. 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 2-7.

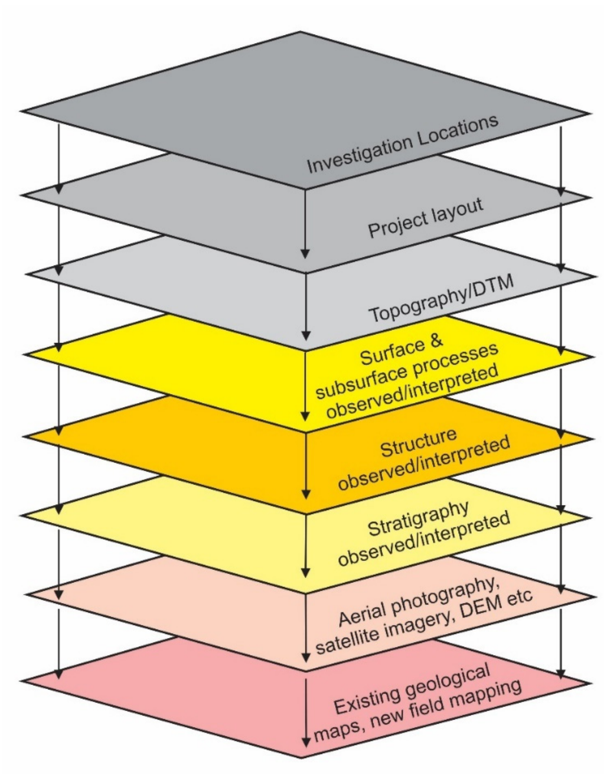

Figure 2-7 GIS architecture for an EGM.

2.3.4.4.2 2D sections

In addition, 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 factual information available to support the interpretation of the engineering geological units. Section locations may be chosen by designers to explore 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, 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, response to loading by a foundation), as well as the area of ground that could affect the project, (for example, a landslide from offsite impacting on the project). These will 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 defects, 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 interpretations of boundaries to 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 - that 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 2-8.

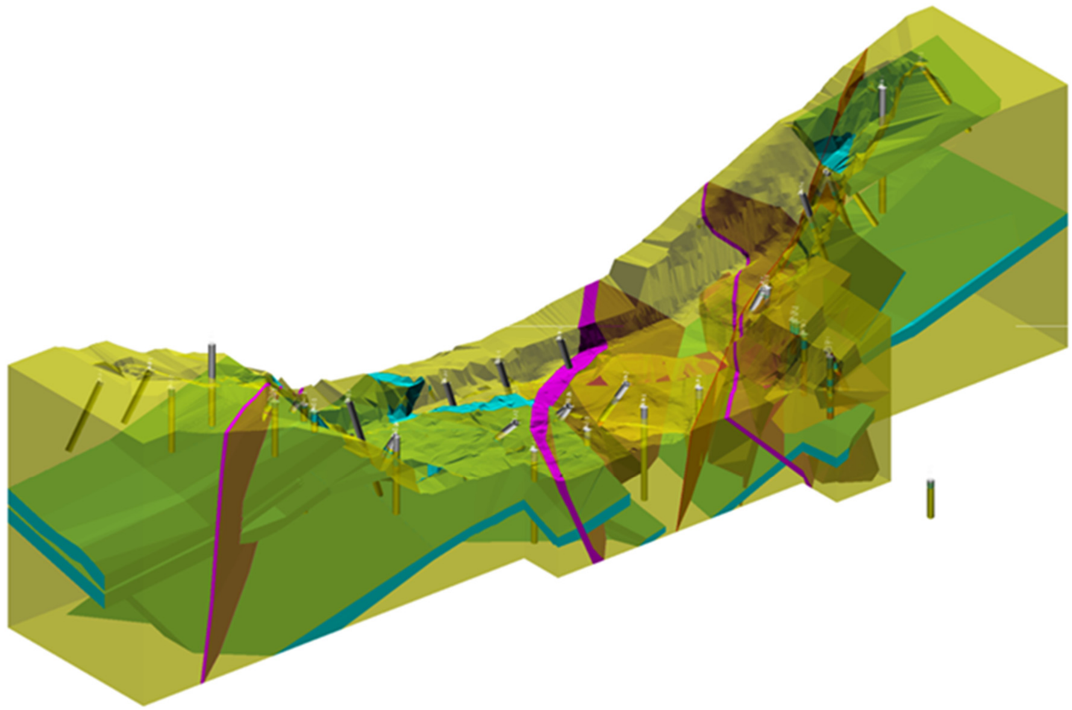

Figure 2-8 Explicit visualisation of the foundation geology of a concrete gravity dam including gently dipping andesites and fault zones intruded by late stage felsite dykes (image provided by Richard Brehauss and reproduced with his permission).

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 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 2-9.

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.

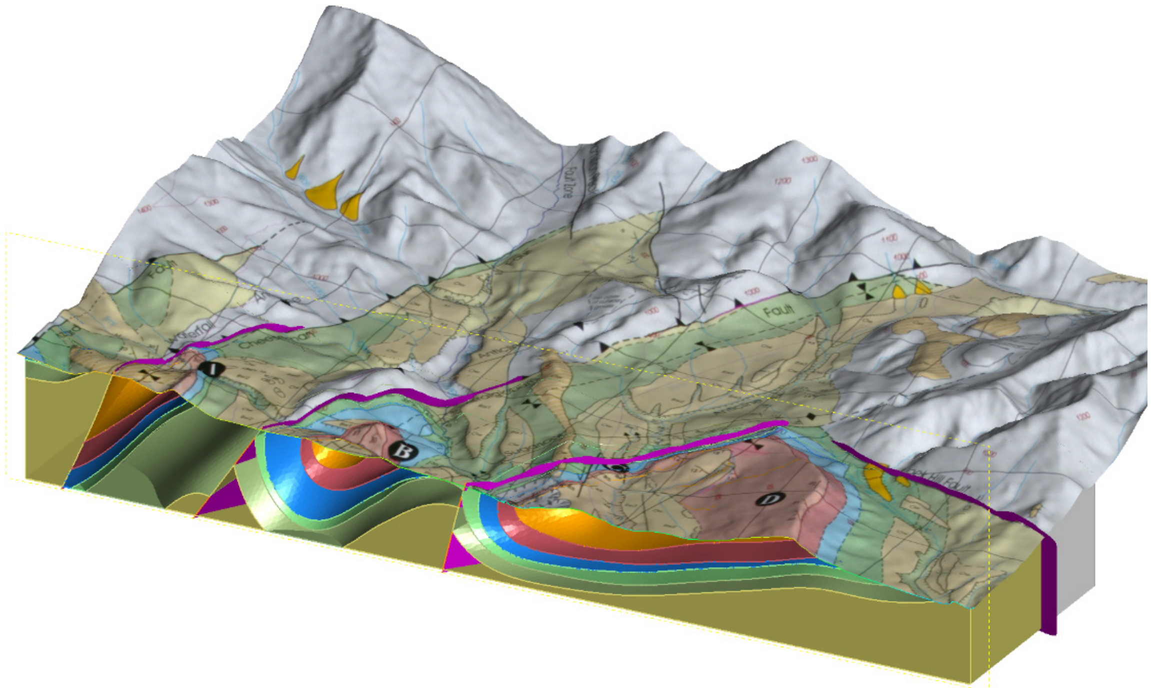

Figure 2-9 Implicit model developed from surface observations using algorithms to project sub-surface boundaries (image provided by Pat McLarin and reproduced with his permission).

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 • The 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 factual geotechnical 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, factual 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 factual data are obtained.

During 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 factual 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 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 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 2-10).

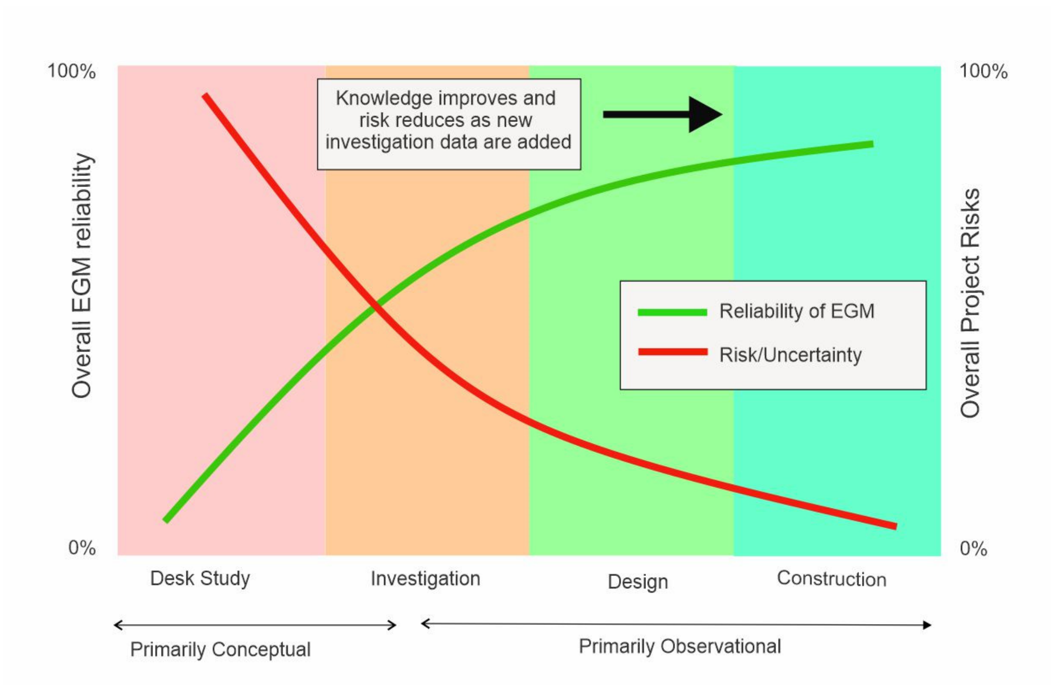

Figure 2-10 Idealised improvements in EGM reliability as project progresses.

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 2-11) 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.

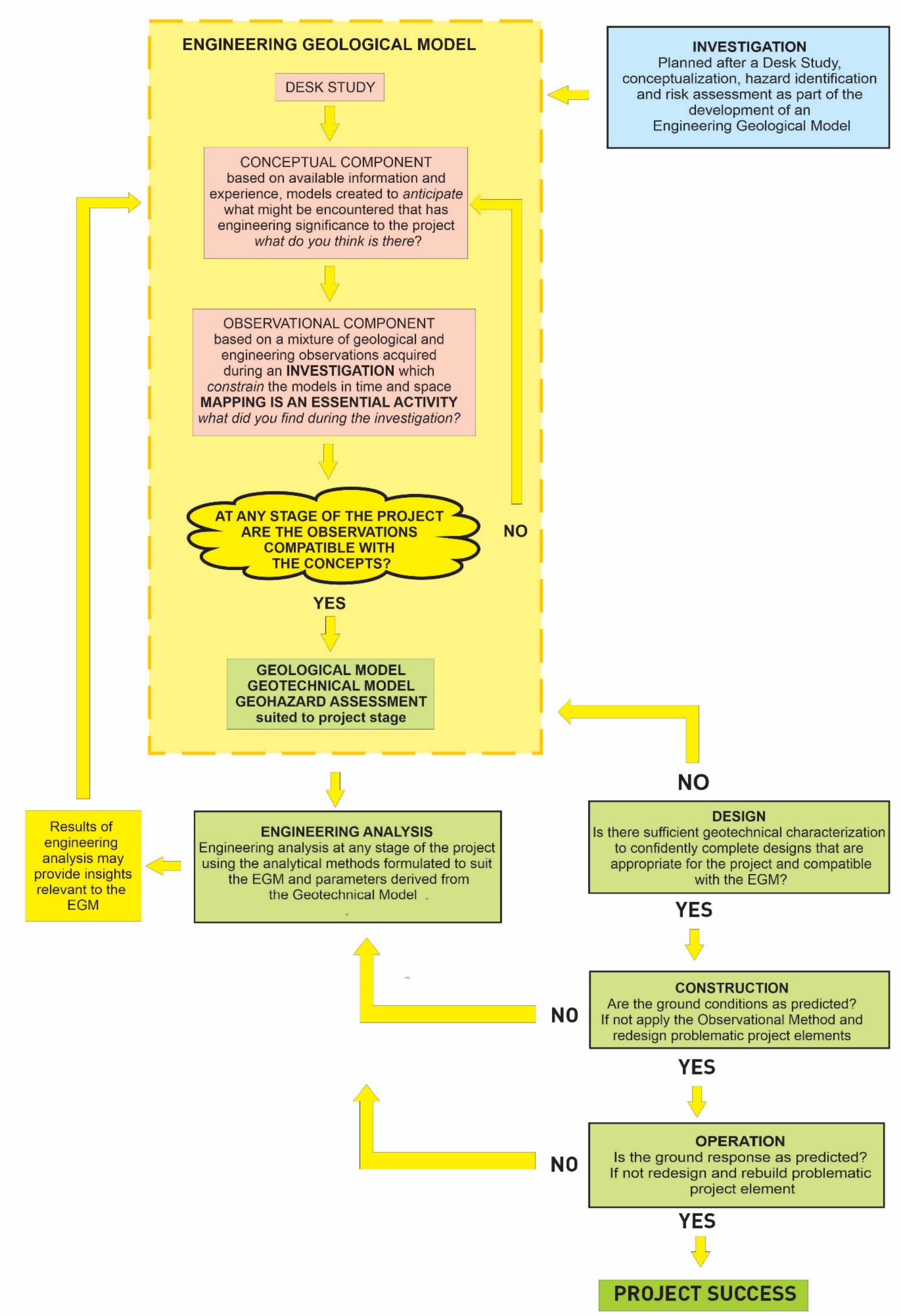

Figure 2-11 Feedback loops to progressively upgrade the EGM during the project life cycle.

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.

However, the following factors are also important:

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

- The geotechnical complexity.

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 wrong or inaccurate but 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 2-12 shows a reliability diagram in the form of a heat map as an example of how to graphically communicate uncertainty in the observations.

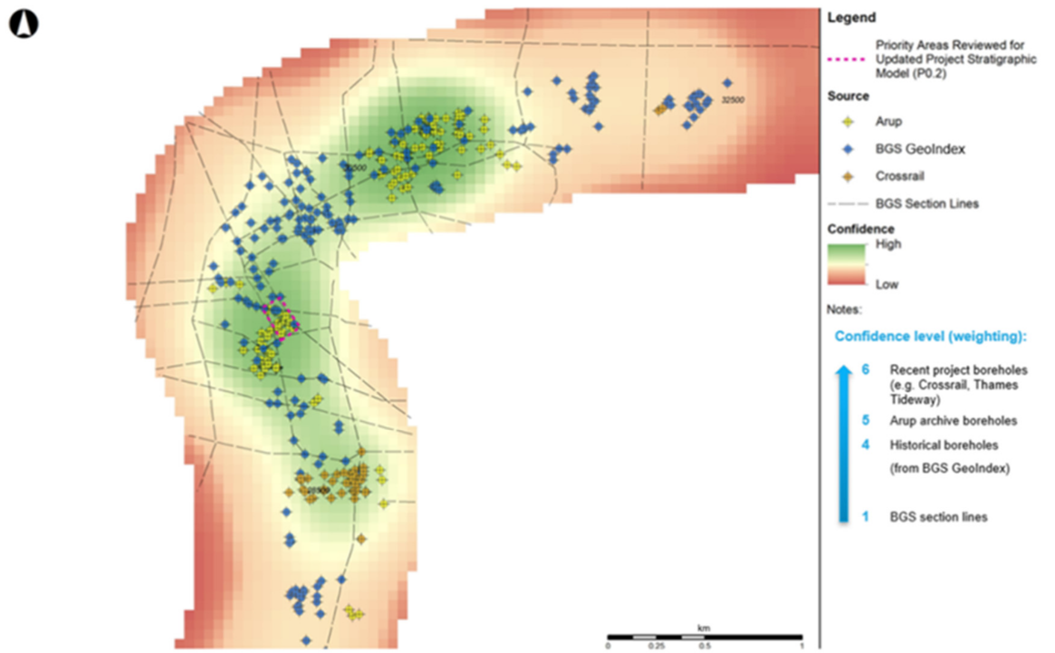

Figure 2-12 Confidence heat map for strata levels (from Ting *et al.* 2020).

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 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 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 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 Model with confidence.

  The key questions at this step include:

  - o What are the engineering geological controls on design as informed by the EGM prior to commencement of the analysis?
  - o How do the analytical results inform the understanding of mechanisms and ground behaviour and is this consistent with the conceptual understanding?
  - o 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 2-13 provides a generic process diagram for using the EGM knowledge framework to plan and execute site investigations.

2.6.4 EGM in analysis and design

2.6.4.1 EGM inputs to design

As the EGM is gradually refined during investigations, the observations acquired become increasingly compatible with the concepts, the quality of the understanding improves, uncertainty is reduced and for any stage of a project a point is reached where design can confidently proceed. At that stage an effective EGM contributes to:

- Developing a framework for the assessment and selection of appropriate geotechnical parameters for each engineering geological unit.

- Ensuring that any simplifications to the EGM that are required for geotechnical analysis are reasonable and robust.
- Choosing the most suitable analytical models for design. The level of analysis possible will increase in sophistication in relation to the EGM quality and confidence.
- A geotechnical risk assessment for the various engineering components of the project.
- The EGM also can be used as a basis for an initial assessment of constructability and associated construction techniques that can be employed, as well as a basis for preliminary cost estimation for the scope of works being considered (Engineer's Estimate).

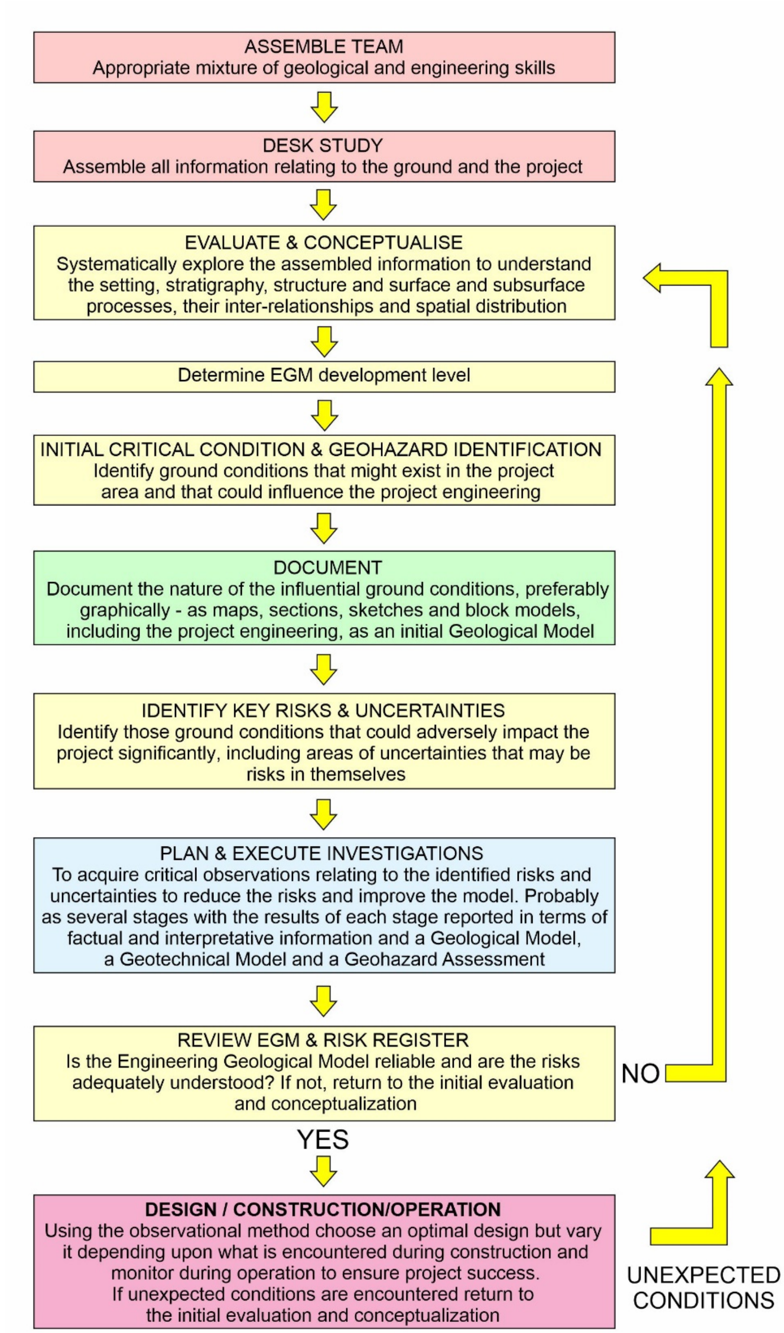

Figure 2-13 EGM components and site investigation (after Baynes *et al.* 2021).

2.6.4.2 Creating models for analysis

Simplified representations of both the distribution of the engineering geological units and their engineering characteristics have to be exported from the EGM knowledge framework to provide information on which to develop analytical models. Typically, these have comprised 2D sections but increasingly these are required in 3D. The analytical models have to be suited to the software being used and usually require considerable simplification of both the Geological Model and the Geotechnical Model and, therefore, significant judgment is required to ensure that representative and appropriate ground conditions, including geotechnical parameters and boundaries, are adopted.

2.6.4.3 Over-emphasis on digital models for design

Sophisticated 3D digital models of the engineering geological conditions that are not based on a reliable EGM can give a misleading impression of improved understanding. The apparently common tendency of undertaking more and more sophistication in digital modelling but without acquiring additional field-based verification data due to inexperience, lack of budget or lack of time (or a combination of all) should be recognised by designers, constructors and owners and avoided (Figure 2-14).

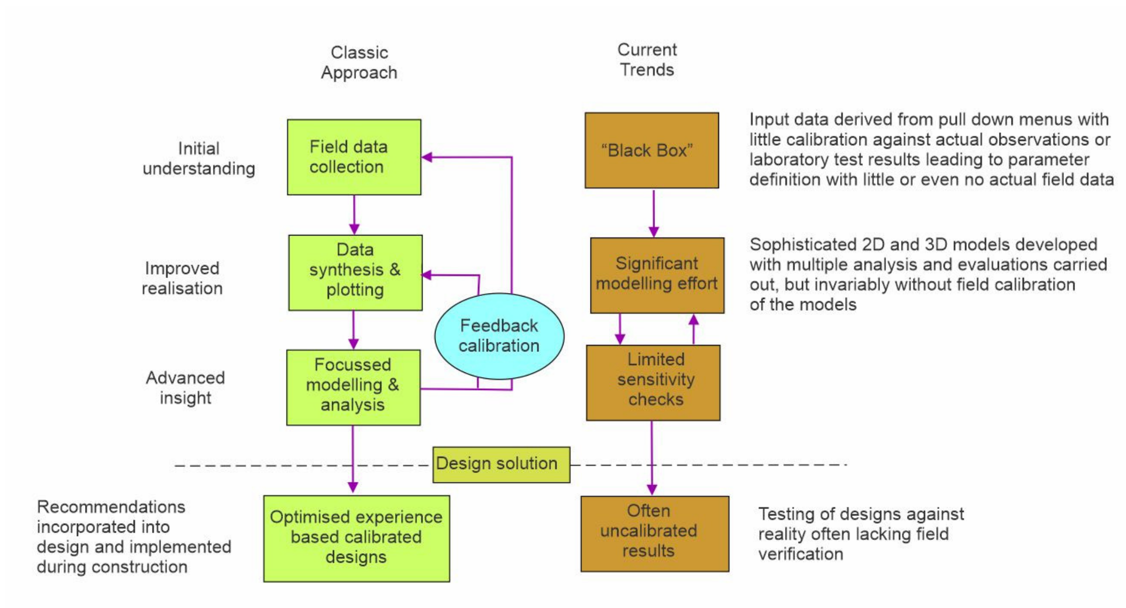

Figure 2-14 Comparison of the classic approach versus current design practice (after Carter 2015).

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

3 EXAMPLES

3.1 APPLICATION AND OUTPUTS OF EGMS

This section provides examples of EGM applications and outputs for a variety of key project types and reflects the diversity of approaches adopted by practitioners. It is important to note that these examples were provided by individual practitioners before the finalisation of the Guidelines and, as such, they may not follow the EGM development strategy laid out in this document. Some of the terminology used may differ from that recommended in the Guidelines. However, it was considered that the individual case studies provide invaluable examples of the incorporation of the EGM approach for different project types. It is intended to progressively upgrade the examples provided in subsequent revisions of the Guidelines.

3.2 EGMS FOR SMALL PROJECTS

Ian Shipway

The potential for ground-related risks to large infrastructure projects is generally recognised and the scopes of work for investigation and EGM development often reflect this understanding. However, the requirement to consider an EGM for small structures, and sometimes smaller components of large projects, is often neglected during the planning stages. Types of smaller projects where the use of an EGM in the design process is often initially overlooked include:

- Small buildings or other structures with lower capital cost.
- Small excavations such as isolated road cuts or fill embankments.
- Relatively minor parts of large infrastructure projects, where there may be (or may not be) a large over-arching EGM but the engineering geological detail for something like a specific bridge abutment may not have been considered.
- Temporary works for large projects, where the investigation has focussed on the requirements of the permanent works structures but has not considered minor components such as crane pads or temporary excavations.

In all of these situations the development of an EGM may not be initially contemplated until some problem with the engineering or construction arises because of lack of knowledge of the ground conditions, or some form of cost constraint on progress becomes apparent.

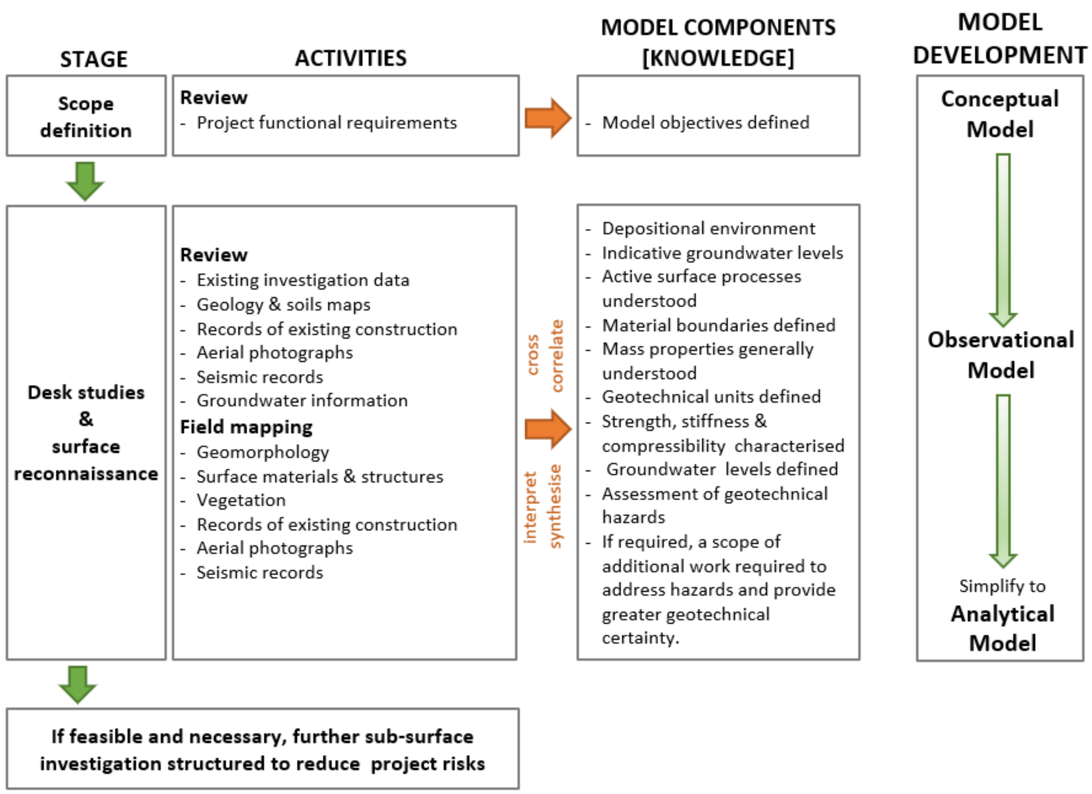


Figure 3.2-1 Outline of the critical initial tasks which should be conducted

The process of model development for a small project with common 'real-world' budget constraints or where the need to develop an EGM has not been recognised until after broader investigation has been conducted should be as shown in Figure 3.2-1. Essentially, adopting the process outlined may allow the timely development of a practical, useful model with a truncated scope of work.

Regardless of whether EGM development commences in conjunction with the initial site investigation, or at some later stage, it is the early steps of desk study and data review that are critical to the development of a practical EGM for small projects.

Figure 3.2-2 shows a typical small temporary works project where the need for some form of model was not understood - construction of a bridge abutment required a piling platform built next to a river to support a crane while it was pitching piles. No specific investigation for the piling platform was conducted. However, there was information from a detailed site investigation that was conducted to provide information for pile design of the bridge.

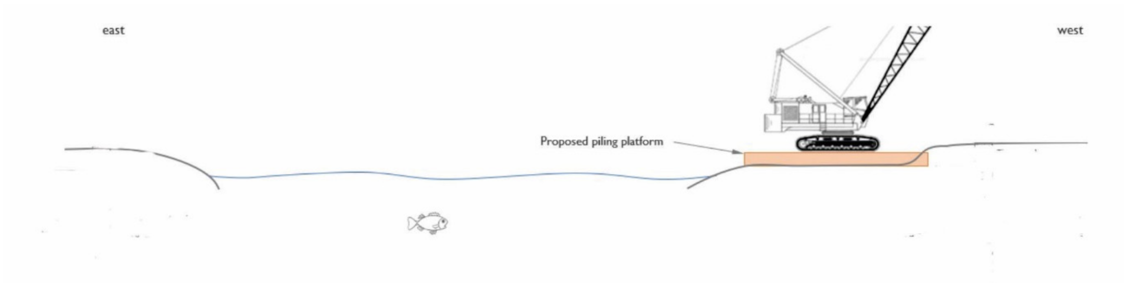


Figure 3.2-2 Sketch cross section before the development of an EGM for the temporary works.

Application of the process of EGM development in Figure 3.2.1, with an emphasis on acquiring the desk study information, allowed a more detailed cross section to be prepared as shown in Figure 3.2.3. The improved model anticipates the presence of an alluvial layer with potentially low strength and stiffness that may significantly affect the performance of the piling platform and identifies some specific geotechnical risks.

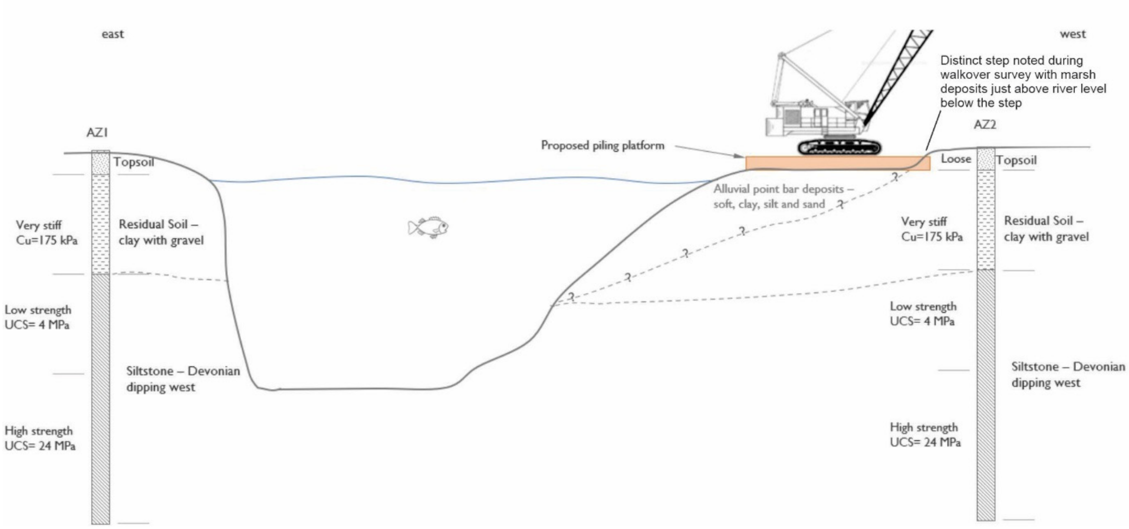


Figure 3.2-3 Site cross section including anticipated conditions and potential risks based on the completed simplified specific EGM for the temporary works.

With the improved awareness of the geotechnical risks, the designer can choose to:

- conduct more investigation to refine the EGM, or
- adopt the model as is and engineer around the risks inherent in the soft alluvial layer.

3.3 EGMS FOR ROCK ENGINEERING PROJECTS

Mark Eggers

Model objectives and purpose

A primary objective of the EGM for rock engineering projects is to understand the geological controls on rock behaviour when it is stressed by surface or underground excavation and external forces such as seismic loads. The purpose of this geological approach to rock engineering is to enable more accurate and reliable prediction of stability conditions and to facilitate engineering design, construction and operation of the asset.

It is important that the engineering end use and design objectives are clearly defined early in the design process. These decisions define how the model will be built, including assessing what are the key engineering elements to be designed. For example, in tunnel engineering the model objectives could include elements such as:

- Excavatability
- Stability and support design
- Dewatering and settlement
- Groundwater inflow and grouting
- Material handling, reuse and disposal.

In rock slope engineering the model may be asked to address design elements like:

- Production blasting, final limits blasting and excavatability
- Slope design parameters
- Stabilisation including reinforcement, unloading, protection measures
- Slope depressurisation of groundwater
- Slope movement monitoring and ground control management procedures.

Distinguishing elements of the rock engineering EGM

A particular focus of the EGM for rock engineering is the structural geology that is perhaps an important differentiator of this type of model compared with EGMs developed for soil engineering. In most engineering projects the *in-situ* and induced stresses are less than the intact strength of rock, in which case behaviour of the rock is dominantly controlled by discontinuities in the rock mass. As such, structural geology and related data interpretation are important skills required for building the EGM in rock engineering.

There are always exceptions to the rule, such as projects at greater depths and at locations where there is high stress concentration. Examples include deep underground mines or deep underground caverns for hydroelectric pumped storage schemes. In these circumstances the influence of structure can be reduced.

There is a trend in recent practice to concentrate the model development towards rock mass classification for assessment of rock mass shear strengths and use in evaluating empirical design parameters. Examples are RMR (Rock Mass Rating) and GSI (Geological Strength Index) for rock mass shear strengths and Q-system for underground support recommendations. The tendency for placing strong attention on rock mass classification can sometimes take the focus away from the main elements of the model that are driving rock behaviours and failure mechanisms, in particular structure and groundwater. The role of the EGM is to ensure all the main geological controls on rock behaviour and performance are adequately identified and evaluated to inform analysis and design.

Stages of model development for rock engineering projects

The relationship between different types of models in rock engineering projects, the project stages they are undertaken, the data sources used and activities carried out to compile each model is summarised in Figure 3.3-1. This chart forms a generalised work process diagram for assembling and interpreting an EGM for rock engineering projects.

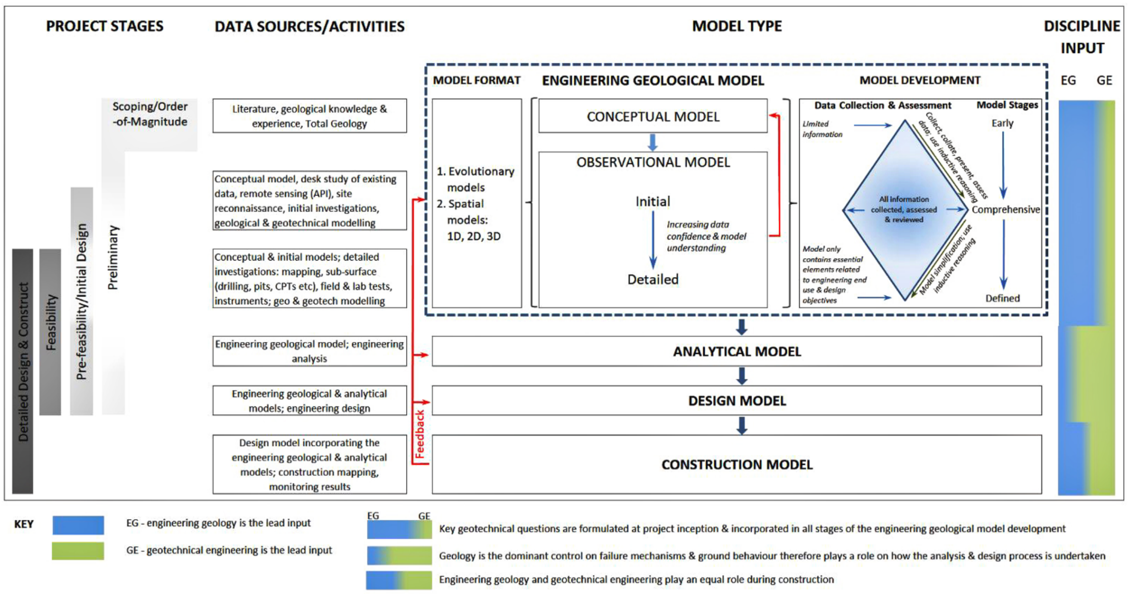


Figure 3.3-1 Work process diagram for EGM development in rock engineering (from Eggers & Bertuzzi 2020).

Modelling starts with conceptualization that is undertaken at the beginning of the project. It normally forms part of Scoping, Order-of-Magnitude or Preliminary studies based on a desk study of the literature, geological knowledge and experience of the project area supported by the concept of Total Geology. This is when the engineering objectives are established for compilation of the key geotechnical questions that must be addressed by the model and design.

For rock engineering projects, conceptualization is particularly critical to success of the overall modelling process. Ultimately, this early step allows generation of hypothetical structural and geological models (for example, rock alteration in mineral deposits) that are developed at the project scale based on the global and regional-to-district scale tectonic setting. The hypothetical models provide the framework in which future investigation data and ideas are tested and revised.

Development of the model can be represented by a diamond shape (Figure 3.3-1) that denotes the amount of information that is used or contained in the model at each stage (Sullivan 2010). At the early stages during conceptualisation and initial building of the observation model data is limited. Once the investigation is complete there is a comprehensive collection of information at the centre of the diamond. This could comprise engineering geological mapping and diamond core drill data including geotechnical logging, structural logging of oriented core, borehole imaging (optical and acoustic televiewers) and so on. The next step in the work process involves collation, presentation and interpretation of the data to refine the model. This is a simplification process to focus the model on the key geotechnical questions to be addressed by the engineering design.

This process may be cycled two or three times as the project goes through pre-feasibility, feasibility and detailed design stages. At each stage the model is refined to the specific geotechnical questions required for increasingly detailed engineering design including updating of the conceptualisation and hypothetical models underpinning structural, rock mass and hydrogeological interpretation of the data.

While the geologist develops the engineering geological model, the engineer plays a key part in the early stages when helping to formulate the geotechnical questions that the model should address. During analysis and design the geologist should maintain an involvement to ensure the geological controls on ground behaviour are adequately captured in the analysis and design. Construction is a shared responsibility between the geologist and engineer.

Components of the rock engineering EGM

What does an EGM for a rock engineering project look like? The main components of the model are summarised in Figure 3.3-2. Each of these parts are formulated during different stages of the model development that is shown in Figure 3.3-2 by relating the components to the model to the work process diagram presented in Figure 3.3-1.

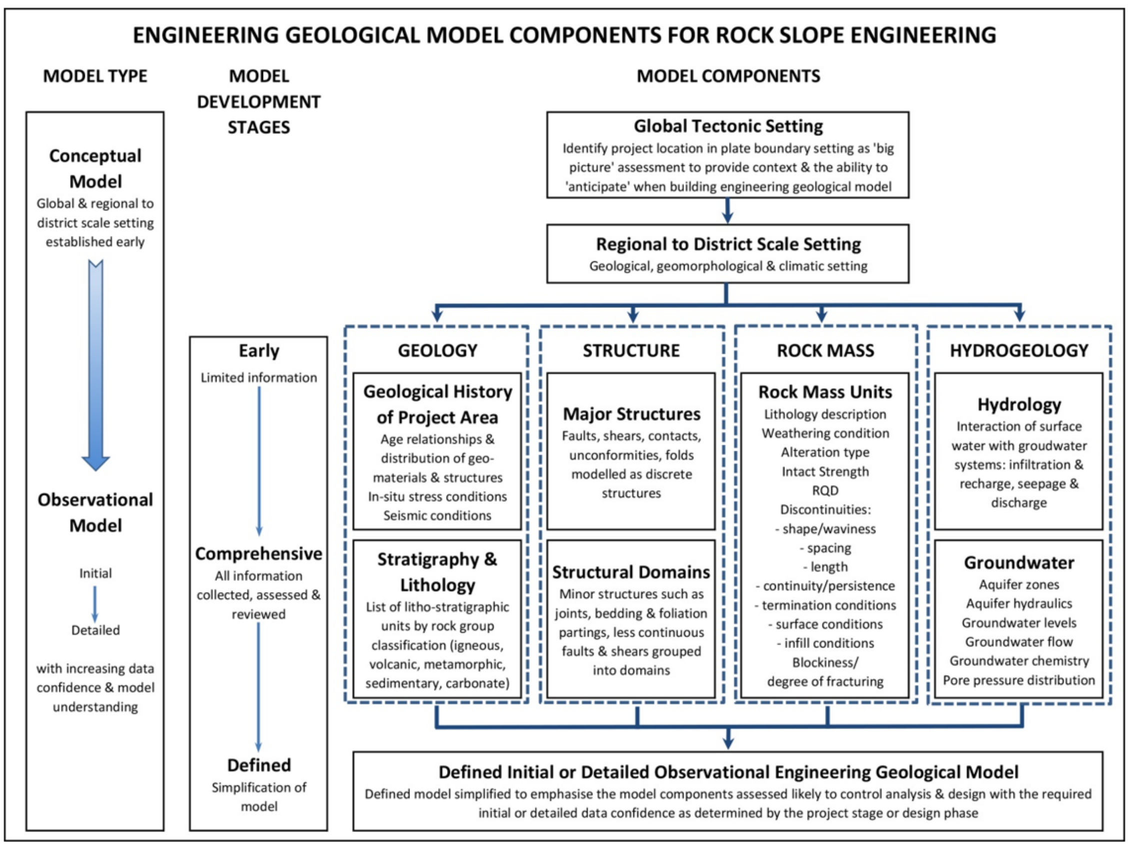


Figure 3.3-2 Components of the EGM in rock engineering (from Eggers & Bertuzzi (2020).

During conceptualization the global tectonic and regional to district scale geological setting is established. It is important this 'big picture' is established early in the modelling process because it provides a powerful tool to help anticipate the geological conditions expected at the project scale. The strength of this approach is the 'big picture' understanding helps consider the gaps and assess the uncertainties that are inevitable due to the limited 'sampling' of the rock mass that can be achieved by an investigation programme. Established structural and geological concepts and hypothetical models can be used to test the data collected on the basis of this 'big picture' knowledge when building the observational model.

The main components of the EGM can be labelled as follows: geology, structure, rock mass and hydrogeology. Figure 3.3-2 lists the different elements and features to be observed, recorded and interpreted under each component.

With regard to the geology component, the EGM should incorporate:

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

Format of main components

Each main component of the model can be assessed and described using the following steps, as illustrated in Figure 3.3-3.

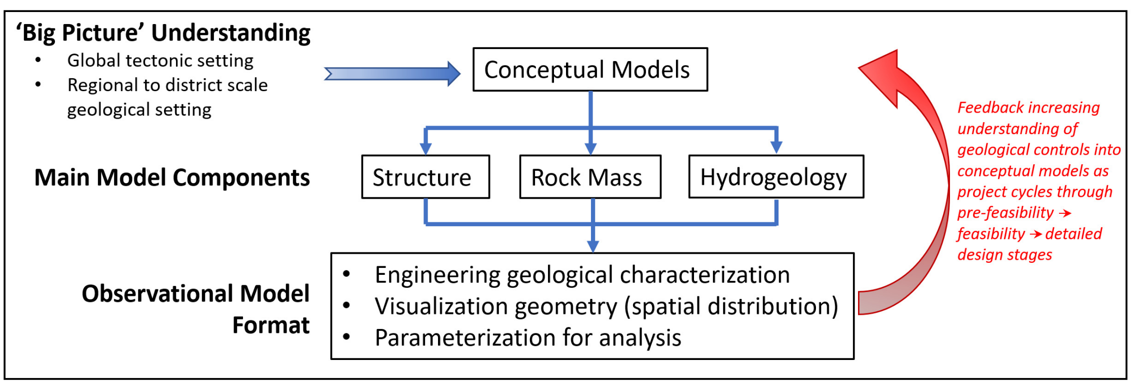


Figure 3.3-3 Format used to assess and describe the main EGM components

1. Assess the ***geological factors*** which control or influence the distribution and change in condition of the model feature: for example, impact of lithology and weathering on fault condition, differentiation of rock mass units by lithology, degree of weathering or alteration history. These factors are based on hypothetical or conceptual models formulated during conceptualisation from the 'big picture' geological understanding of the project. As the project cycles through the pre-feasibility-feasibility-detailed design study stages, increasing knowledge of the geological controls gained from the observational modelling are fed back into the conceptual models to better inform the next stage of project development.
2. ***Engineering geological characterisation*** of structure, rock mass units and hydrogeological units using appropriate classification and description systems. In some instances, project

specific systems can be devised to record and describe elements of the rock mass that are distinctive to the project geology. For example:

- Different types of brecciated rock in porphyry copper deposits to capture the key elements of the clast-matrix textures that will control ground behaviour of the rock mass
- Different styles of fault damage in major structures that influences shear strength properties.

3. ***Visualisation geometry*** (spatial distribution) comprising boundaries between structural domains, rock mass units and hydrogeological units, and discrete modelling of major structures. The boundaries and major structures can be presented in 1D (for example, borehole logs), 2D (plans and cross sections) or 3D (wireframes or block models)
4. ***Parameterisation*** that incorporates quantification of the physical properties such as strength, stiffness and permeability of intact rock, structure and rock mass ready for numerical analysis. This is based on characterisation of structure and rock mass units together with compilation of laboratory test results.

Content of model components

The notes that follow provide some guidance on the information contained in each main component of a typical rock engineering EGM.

Geological Structure

The structural component of the EGM is normally divided into two scales:

1. Large structures, that have continuity at approximately the same scale as the project; as such, these normally comprise faults and shears, unconformities and geological contacts.
2. Medium to small scale structures, represented in the model as domains.

Data sources common to both large and medium to small scale structures for engineering geological characterisation include:

- Mapping of exposures and outcrops
- Geotechnical logging of borehole core
- Structural logging of oriented borehole core
- Interpretation of borehole images from optical or acoustic televiewers.

Use of the stereographic projection to present and interpret the structural orientation data are key skills when building the structural geological model.

The ***large structures model*** will typically contain the following information:

- In addition to outcrop mapping and borehole-based data, ***lineament interpretation*** from aerial photographs and hillshade modelling of Lidar data forms important data source for the large structure model.
- Evaluation of a ***hierarchy or order of structures*** assists with understanding which defects will control stability at different slope or tunnel scales. In a structurally complex rock mass, a hierarchy scheme more sophisticated than differentiating between 'major' and 'minor' structures may be required to capture all the elements important for structural modelling. For scoping to feasibility studies the available data are dominantly from boreholes for a majority of projects. Table 3.3-1 presents a scheme that assists with interpretation of major structures from borehole logs, core photographs and downhole images. Similar systems can be devised based on mapping data or lineament analysis, typically using mapped or visible length and persistence as one characteristic to help judge the order.

Table 3.3-1 Example of a hierarchy of structures based on borehole data (Eggers 2016)

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

- ***Fault classification and confidence rating***. Interpretation of the structural model is often based on a number of data sources, principally evaluation of borehole intersections supported by an air photo and/or a Lidar lineament study and sometimes with the availability of surface exposures to map. The system presented in Table 3.3-2 enables all these data sources to be brought together to classify each structure. The fault classification is used to rate each structure for the level of confidence in terms of accuracy of prediction as shown in Table 3.3-3. The confidence rating together with the hierarchy evaluation contributes directly to knowledge of which structures can be relied on for stability analysis and at what scale the structure may impact on stability conditions.

Table 3.3-2 Example of a classification of fault data sources (Eggers 2016)

Airphoto/Lidar lineament	Drillhole intersection	Surface exposure
Y — with	1 — with	y — with
N — none	0 — without	n — none

Table 3.3-3 Example of a fault confidence rating system (Eggers 2016)

Rating no.	Classification	Rating descriptor
1	Y1y	High
2	Y0y, Y1n, N1y	Medium
3	Y0n, N1n, N0y	Low

- ***Spatial distribution/geometry***. Large structures are normally modelled discretely as specific features in the EGM. In a digital 3D model they can be incorporated as wireframe surfaces or as a block model if the structure is to be represented with a defined width, as informed by the engineering geological characterisation.
- ***Shear strength properties*** are evaluated from the engineering geological characterisation and laboratory test results. They also may be estimated from back analysis of past instability. Fault zone materials associated with large structures often comprise engineering soils. Testing of these materials may comprise triaxial shear strength testing of intact samples derived from cored drilling.

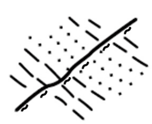
The ***structural domain model*** is composed of data from medium to small scale structures. Features and elements of importance to the structural domain model are summarised as follows:

- In the structural domain model it is important to clearly differentiate between internal structure, that forms a fabric in the rock mass, and true discontinuities.
- The process of formulating the structural domain model comprises:
    - Assess change in structural patterns across the site from each of the available data sources, that is, mapping, structural logging of oriented core and/or interpretation of borehole imaging (ATV, OTV).

  - Assess large structure controls on domain boundaries such as faults and shears, litho-stratigraphical contacts, unconformities and so on.
  - A model can be presented as a plan showing the structural domain boundaries with summary stereoplots showing the structural patterns of each domain.
- Engineering geological characterisation of structure should be based on discontinuity type, separated by domains, and discontinuity sets if there are sufficient data. The data from mapping or logging can often be efficiently presented as summary data histogram sheets with all the described characteristics presented on one sheet per discontinuity set or discontinuity type.
- Shear strengths of discontinuities is typically based on direct shear testing with results separated on a plot of shear stress versus normal stress for each discontinuity type with test results differentiated by discontinuity sample condition from logging, including discontinuity shape, roughness, infill type and width.

Be aware that the same type of geological structure can form both a fabric in the rock and discontinuity structures that operate at different scales in the rock mass. An example is foliation in a shale as explained in Table 3.3-4. The same concept applies for bedding structure in sedimentary rocks that can form a fabric and a series of different discontinuity structures such as partings, bedding shears and bedding parallel fault zones.

Table 3.3-4 Different types of foliation structure

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

Rock mass

These examples illustrate the importance of clearly defining and describing the different type of structures that is present in the project rock mass. Discontinuity type carries implications towards size (length, persistence), frequency (spacing) and shear strength that are all important characteristics to understand when modelling the structure.

The key to compilation of the rock mass component of the EGM is evaluation of the geological controls on changes in rock mass condition across the project site. Use of conceptual models formulated during assembly of the project geological setting are central to this step, that should include an understanding of geological history of the project and district. Examples of geological controls on the definition of rock mass units include:

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

It is important to remember that, for most projects, there are usually several different geo-controls on the type and distribution of rock mass units. For example, a typical set of controls is a combination of lithology and weathering. As the complexity of the geological history increases, the number of geo-controls on rock mass conditions usually increases.

An example of a rock mass model for a porphyry copper deposit in southeast Asia is shown in Table 3.3-5. In this example the rock type is the same across the project comprising an andesite on the flanks of an ancient stratovolcano.

Table 3.3-5 – Example of a rock mass model for a porphyry copper project (Eggers 2016)

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

The main differentiator in rock mass condition in this project is high sulphidation hypogene alteration, late stage supergene alteration, hydrothermal brecciation and faulting. The brecciation history for this project is complex, comprising:

- early and locally developed autoclastic flow breccias and intrusion carapace breccias
- spatially restricted intermediate stage diatreme breccias
- ubiquitous high sulphidation hydrothermal breccias, and
- fault breccias.

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

The rock mass model can be formulated as follows:

- Rock mass data histogram sheets from borehole logging and/or outcrop mapping that summarises the main characteristics for each rock mass unit.
- Digital model geometry can be presented as wireframe boundaries between rock mass units or a block model of the rock mass. Due to the typical low level of 'sampling' of the rock mass with widely spaced geotechnical boreholes, digital modelling of rock mass boundary surfaces often can be based on selected elements of the geological model, as a proxy based on the conceptual models developed from the 'big picture' understanding and the results of the engineering geological characterisation studies.

  Some caution is required when adopting geological proxies for modelling rock mass units for mine design studies. It is normally not appropriate to just adopt the resource geological model as the basis for assessing rock mass units. The resource model is primarily compiled to explain distribution of mineralisation grade. In contrast, the EGM is formulated to explain change in engineering geological character, that can be somewhat different to the form and function of the resource model.
- Parameterisation is based on a mix of engineering geological characterisation and laboratory testing. The rock mass classifications RMR and GSI are often used to estimate rock mass shear strengths.

A trend in recent times is for model development to be substantially limited to application of RMR and GSI for the purpose of estimating rock mass shear strengths. The 'recipe approach' provided by these classification systems is seen to provide a quick and easy method of modelling the rock mass. The danger of this approach is that the key geological elements of the rock mass that will likely control ground behaviour are not correctly recognised. The lack of a 'big picture' understanding of the project does not provide the conceptual knowledge to test the data collected during the investigations. The misidentification of critical failure mechanisms in analysis due to lack of adequate engineering geological modelling represents a geotechnical risk to engineering design.

Hydrogeology

Groundwater and surface water interaction with groundwater are important parts of the EGM for rock engineering. Key objectives of the groundwater model are to assess dewatering and settlement, inflow and grouting for underground developments and deep excavations and slope depressurisation for rock slopes and surface works.

There can be substantial advantages in integrating the geotechnical and hydrogeological investigations for a project, rather than treat them as stand-alone programmes. This includes sharing development of the 'big picture' understanding during conceptualisation and interpretation of hydrogeological units that is often a variant of the rock mass model. The larger structure model is equally important to the hydrogeology as it is to the geotechnical assessment.

Information of development of the hydrogeological model is provided in Section 3.6; see also Preene (2020).

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3.4 ROCK MASS MODELS FOR DESIGN OF EXCAVATIONS IN STRUCTURALLY CONTROLLED ROCK MASSES

Robert MacKean

Introduction

It is widely acknowledged that if geological structures dictate mechanisms of rock mass deformation, then the geological structure must be considered in detail and explicitly (Brown 2008, Hoek *et al.* 2013). Only then can stability mechanisms and stability levels be understood and appropriate engineering measures designed, when required, to enhance the natural state. This short overview aims to describe how geological structure can be incorporated into a design process, via use of a specific kind of EGM, called a Rock Mass Model (RMM).

Context established by a broader EGM and associated studies is essential in rock engineering design and as a prerequisite for an RMM. Such studies, described in detail elsewhere in this document, would normally include an understanding of regional geological history, including structure, climate and stress fields, definition of joint sets, subdivisions according to structural and lithological domains and other factors such as weathering, alteration and time dependent factors such as moisture sensitivity, solution, tectonics, loading or unloading and groundwater. These are all things that an engineering geologist must consider, depending upon the geological setting and engineering requirements.

Surprisingly, in current rock engineering practice, it is common for there to be little explicit representation of geological structure. Instead, 'global' (generalised) strength parameters, assumed to represent the contribution of both the rock material and discontinuities, are derived, and often used for continuum analyses. Without explicit reference to the controlling geological structure, such analyses are unable to simulate the influence of anisotropy or the particular rock mechanical responses and associated failure mechanisms of discontinuous rock masses, or, in many circumstances, provide any reliable basis for design.

Design conclusions from such analyses, including predictions of a uniform distribution of favourable ground loading on to a lining, can be highly misleading (Barton 2016) and several notable collapses have resulted, despite analyses indicating structural design code compliance.

As a solution, it is proposed that geological structure should be represented routinely as a RMM and that an RMM should be considered a requirement for best practice rock engineering evaluation and design. An RMM, acting as a detailed cross-sectional (or 3D) representation of the geological structure, should be developed in the context of an EGM, for any rock engineering project, to ensure the essential framework for characterisation, evaluation and analysis is provided.

RMMs aid combination of geological data, including structure, with rock mechanics theory to provide an interpretative and predictive capability for rock engineering practice.

What are Rock Mass Models and what is their purpose?

An RMM should aim to be a semi-deterministic model, using, when available, measurement from outcrop, boreholes and underground headings that, as far as is possible, places each discontinuity in its correct position in the model relative to others. This process is unlike statistically derived computational DFNs (Discrete Fracture Networks), that typically adopt a probabilistic approach.

The challenges of defining and identifying discontinuities in the field is not addressed here but reference is made to a useful summary by Hencher (2013). The paper also addresses the difficulties with accepting surface outcrop as a reliable analogue of conditions at depth.

An example of a RMM for a cavern project in Carboniferous Limestone, based on interpretation, is shown in Figure 3.4-1.

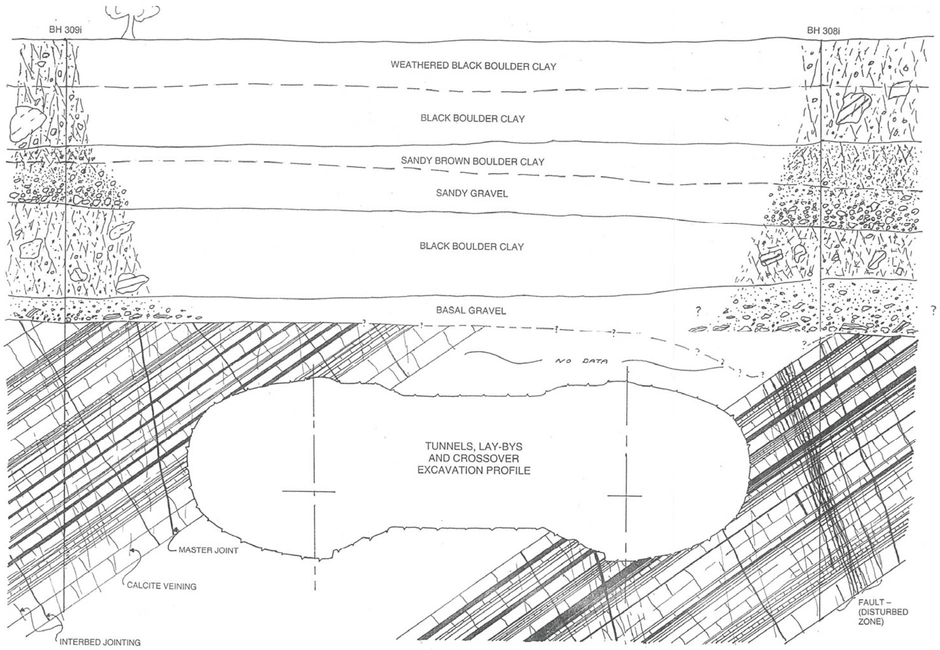


Figure 3.4-1 Example of a scaled rock mass model for a Carboniferous Limestone based on interpretation of borehole data for investigating feasibility of cavern construction on the Dublin Port Tunnel (hand sketch by Robert MacKean)

In the context of a broad EGM, an RMM depicts in detail the geological structure and distribution of rock materials in 2D or 3D, providing a framework to which parameters can be assigned and the principal controls of rock mass response identified. RMMs contribute at all stages of evaluation or design and their purpose is wide and varied, including:

- Siting studies, focusing on principal lithology and major geological structure in terms of orientation and frequency.
- Location specific characterisation and synthesis of host geology at depth.
- A visual representation of actual geological structure in the context of an engineering scheme (such as slopes, tunnels, caverns, foundations including dams).
- Presentation of a specific rock mass condition as a basis for classification (Q, RMR etc.) -that is, the classification becomes an *output* of the geological and rock mass modelling process.
- Informing judgement or empirically-based engineering evaluation of intrinsic stability state and conceptual layout of required engineering measures.
- A framework for geomechanical characterisation of all components of the rock mass.
- A basis for subsequent Distinct Element numerical analysis, engineering evaluation and rock engineering design.
- A framework for hydrogeological characterisation, flow predictions and a basis for mitigation design including grouting.

Either conceptually or as input to numerical analysis, RMMs enable appreciation of realistic rock mass response. This understanding of deformation mechanisms informs selection of excavation method, geometry, sequencing, ground treatment, groundwater control, overbreak prediction and methods of support such that they are suitable for the geological environment.

The Importance of Scale

The concept of scale is important in recognising when geological structure (and associated properties), as depicted in an RMM, must be considered explicitly in rock engineering.

Traditionally in rock mechanics, understanding the scale of the task in terms of the volume of rock mobilised (stressed) by the engineering scheme, compared with the spacing and position of controlling geological structure, helped define the appropriate rock strength to use in analysis (Hoek 1981, Wyllie & Mah 2004). For example, the stability of an individual bench in a cut slope might be controlled by the shear strength of a single persistent joint, whereas on a larger scale, such as the stability of a higher slopes, the 'global' strength characteristics that encompass the entire rock mass in terms of materials and discontinuities might be applicable. A more recent presentation of this concept (Figure 3.4.-2) clarifies the restrictions on applying global shear strengths (such as GSI), to rock masses that are homogeneous and lack anisotropy. In this respect Hoek *et al.* (2013) stated the following important clarification: *"A fundamental assumption of the Hoek-Brown criterion for the estimation of the mechanical properties of rock masses is that the deformation and the peak strength are controlled by sliding and rotation of intact blocks of rock defined by intersecting discontinuity systems. It is assumed that there are several discontinuity sets and that they are sufficiently closely spaced, relative to the size of the structure under consideration, that the rock mass can be considered homogeneous and isotropic". (emphasis added).*

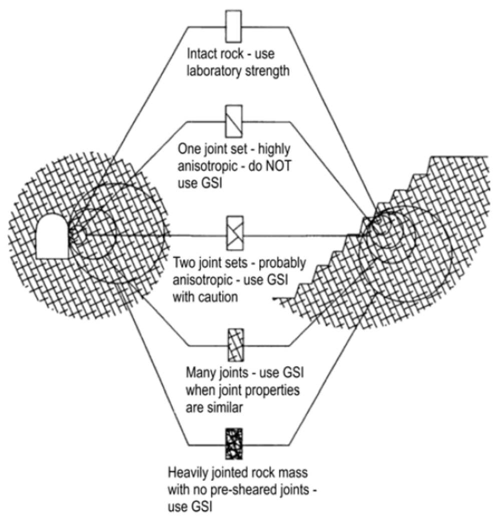
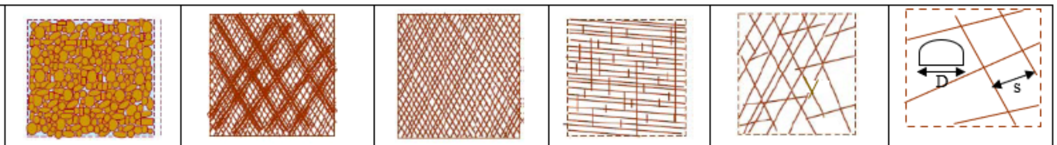


Figure 3.4-2 Limitations on the use of Geological Strength Index (GSI) depending on scale (Hoek *et al.* 2013).

It is notable that the scale transition from intact rock to heavily jointed rock, as depicted in Figure 3.4.-2, involves both a larger number of joint sets and joints, such that eventually "*the rock mass can be considered homogeneous and isotropic*" (that is, in numerical modelling terms 'continuous', or sometimes regarded as reaching the Representative Elemental Volume, Hudson, 1989). Experience shows that rock masses often remain inhomogeneous and anisotropic even at large scales, on account of the influence of discrete major geological structures. This further limits the application of GSI for deriving global shear strength parameters and emphasises the importance of a representative RMM in aiding rock mechanical understanding.

A similar approach, that assesses the influence of 'scale' for underground projects, was proposed by Bandis *et al.* (2011). This scheme related the span of an opening to the spacing of the principal joint set, with the aim of identifying an appropriate method of characterisation and analysis (Figure 3.4-3). Figure 3.4-3 indicates 'continuums' (homogeneous and isotropic) to be end members, that are rare in nature.



Description of Rock Mass	Unlithified granular material	Tectonically disturbed s < 0.05m D/s > 500	'Very closely' jointed s = 0.05-0.1m D/s = 100-500	Bedded s = 0.1-0.5m D/s = 20-100	'Widely' Jointed s = 0.5-2.0m D/s = 5-20	Intact massive s > 2m D/s < 5
Analysis	Continuum	Equivalent Continuum		Discontinuum		Continuum

Figure 3.4-3 Broad distinction of rock mass types illustrating changing form of analysis in the transition from intact rock, through jointed rock, to completely tectonised rock, all in relation to a 10m span tunnel (sketches are highly indicative). Adapted from Bandis *et al.* (2011).

An understanding of scale shows that geological structure tends to be the overriding influence in most situations involving engineering of rock masses. RMMs ensure recognition of geological structure and their adequate representation in the design process.

Development of a Rock Mass Model

Procedures for the development of RMMs will vary according to the scale of the model, the geological environment, the engineering challenge and the nature of available data. Further, the number of models needed to characterise the project will depend upon spatial variations that should be analysed and understood via the EGM preparation process. In this context, the identification of geological domains, within which the conditions can be represented by a single RMM, is an important step. In general, considerations for an individual RMM are set out in Figure 3.4-4.

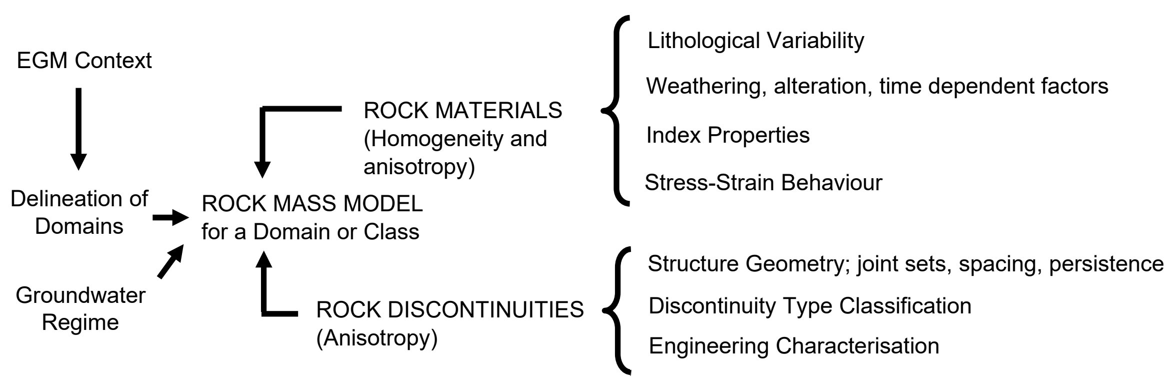
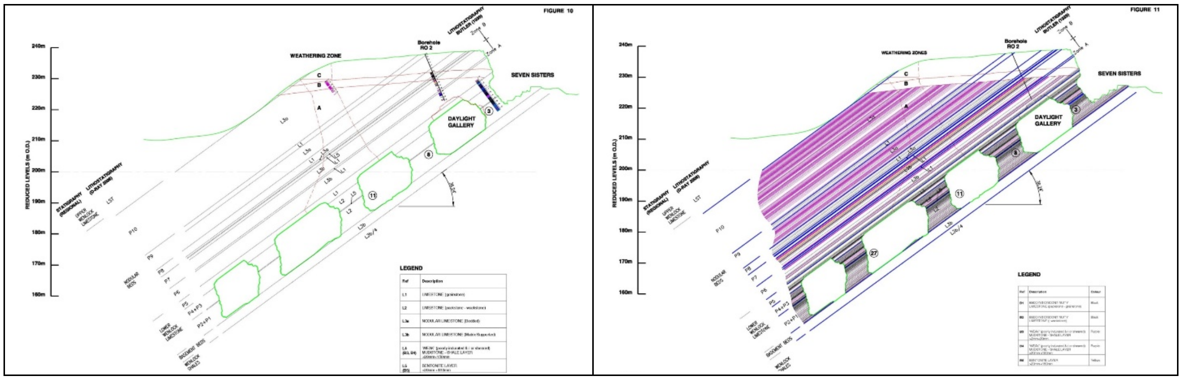


Figure 3.4-4 Key components of a Rock Mass Model (RMM).

An example of a semi-deterministic model development, relevant to a layered sedimentary rock mass, with highly persistent bedding-related structure, is work undertaken for stabilisation of a mine in Dudley (UK) (MacKean *et al.* 2015). In this example, detailed litho-stratigraphical sequencing for the Silurian rocks provided an initial framework for the model (Figure 3.4-5 left) and detail was provided via bed-by-bed logging in outcrop and core and correlated via marker horizons (Figure 3.4-5 right).



Left Hand Side – Cross section through mine workings based on 3D laser scan survey, showing lithostratigraphy.	Right Hand Side – Cross section through mine workings showing Bedding Discontinuity Model. Colours represent different geomechanical discontinuity types.

Figure 3.4-5 Wrens Nest Rock Mass Model development (from MacKean *et al.* 2015)

The rock layers in this example were composed of a wide range of carbonate lithologies and each type was characterised in terms of the geotechnical properties (including index properties, stress-strain behaviour and how these varied with the influence of weathering) consistent with typical geotechnical practice.

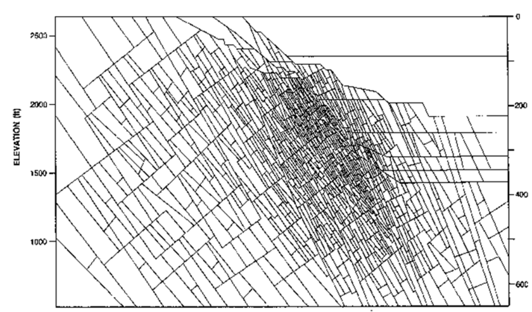


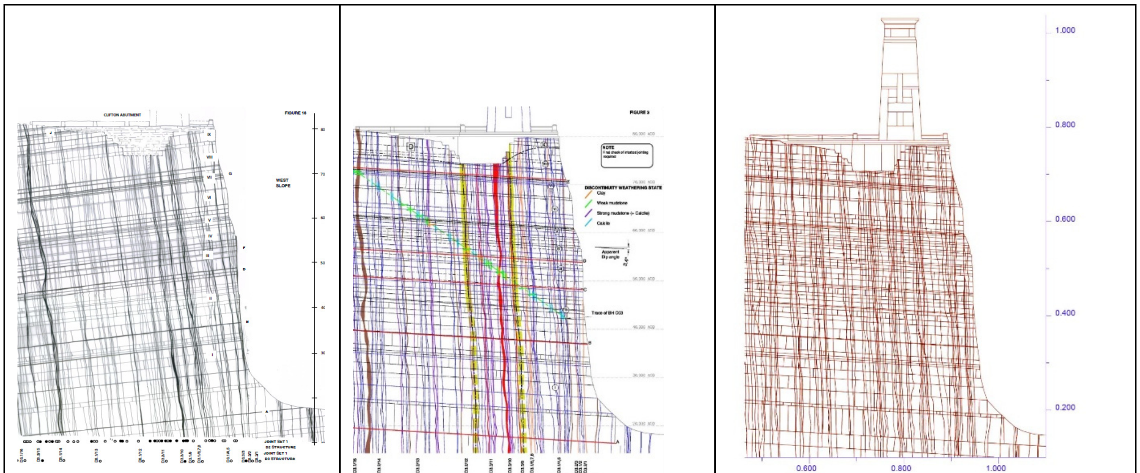
Figure 3.4-6 DEM for a high rock slope with model detail concentrated in areas of higher stress concentrations (From Sharp & MacKean 2000).

There may be examples where computing limitations dictate, to some extent, the level to which rock mass detail can be incorporated. In the example of very high slopes, computer power limitations have demanded a focus on larger scale, more widely spaced structure. A way around this is to provide more detail in areas of interest in the model (Figure 3.4-6). However, modern computing power allows fully detailed slope models at scales of at least up to 100m (Figure 3.4-7).

Discontinuity Types

Discontinuities will initially be defined according to orientation and assigned to a Joint Set, which has a characteristic range of strike and dip.

A second step, and a principal component of an RMM, is classification of discontinuity 'types'. 'Types' may be specific to a joint set. In the example from Dudley, six geomechanical bedding types were defined and characterised and every bedding discontinuity assigned to a 'type', the assigned types are evident as the different coloured lines in Figure 3.4-5 (right hand side). The types varied from clay layers to strong limestone – limestone bedding discontinuities. Similarly in the Clifton Suspension Bridge example (Figure 3.4-7 centre) four types of vertical structure were logged, a concentration of clay-filled structures being situated beneath and to the rear of the bridge tower (shown in red in the central diagram).



Original Sketch Based on Mapping	*CAD Drawn Updated Rock Mass Model (using borehole data)*	*UDEC Computer Model Representation of Geological Structure*

Figure 3.4-7 Clifton Suspension Bridge East Abutment – Rock Slope 70m high approximately. Supplied by Robert MacKean with permission of the CSB Trustees.

An example of discontinuity type classification for sub horizontal joints in tropically weathered granite is shown in Figure 3.4-8. When the type classification was applied to boreholes the discontinuity types defined a vertical but laterally variable distribution that led to a proposed cavern being repositioned, so as to avoid deeper weathering (Chui *et al.* 2011), thereby reducing risk and cost.

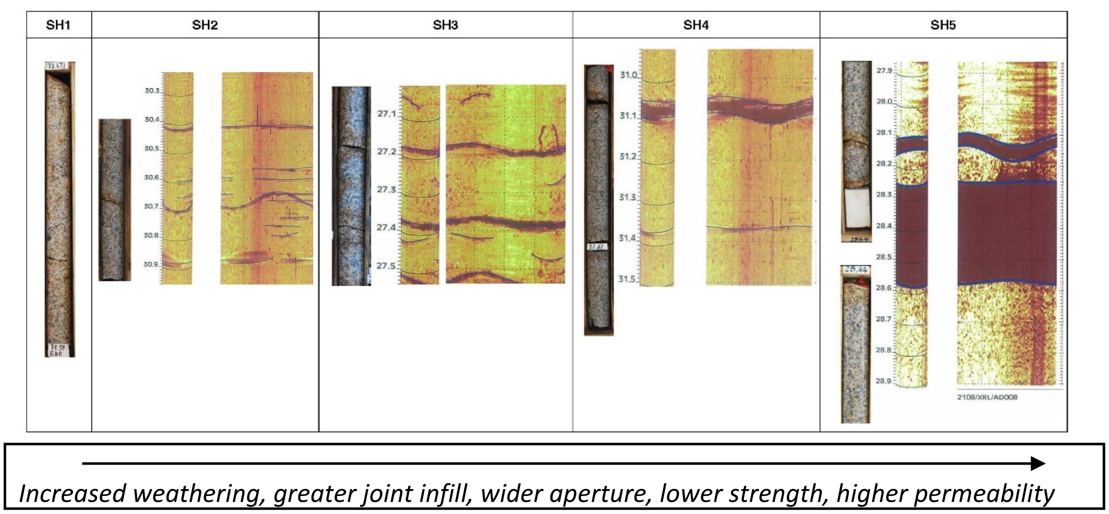


Figure 3.4-8 Illustration of discontinuity type classification for tropically weathered granites. Classification for sub-horizontal joints using example core photographs and associated downhole televiewer data (prepared by Robert MacKean).

Once the classification is established each 'type' can be characterised, based on their physical characteristics such as roughness, aperture, degree of alteration, infill and wall strength. These provide the basis for derivation of Joint Roughness Coefficient (JRC), Joint Compressive Strength (JCS) and residual friction, together with scale effects, all indices of the Barton-Bandis (BB) model for shear strength and stiffness modelling (Barton & Choubey (1977), Bandis *et al.* (1983) and Bandis (1990).

Integration of a Rock Mass Model into a Numerical Model

As described, physical properties of the discontinuity types can be used to define stress-strain relationships, suitable for use as constitutive models in subsequent numerical analysis. In the Dudley case example the 'BB' constitutive model was used within UDEC-BB. This allows for interactive stress and strain dependent discontinuity strength characterisation under effective stress conditions such that the full implications of stress history is simulated. The Dudley case study is shown in Figure 3.4-9 and a further example, from Dublin, is shown in Figure 3.4-10.

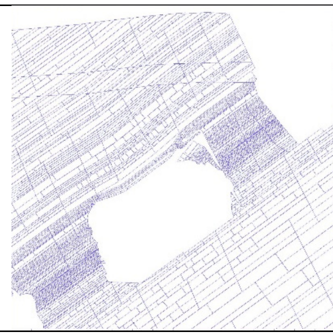
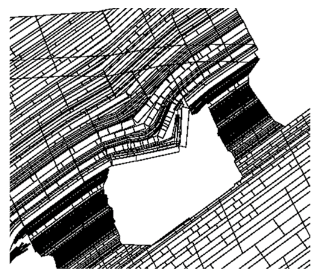
		
Left Hand Side – Rock Mass Model sketch used for preliminary engineering assessments	UDEC model with full RMM detail, result showing roof span deformation as well as haunch fallouts.	Right Hand Side –UDEC model with continued roof deformation and collapse

Figure 3.4-9 Wrens Nest mine stability evaluation (MacKean *et al.* 2015).

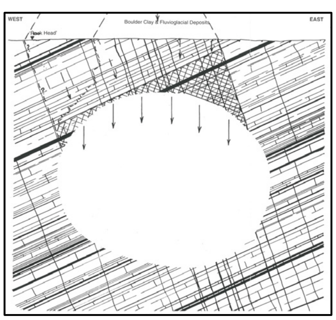
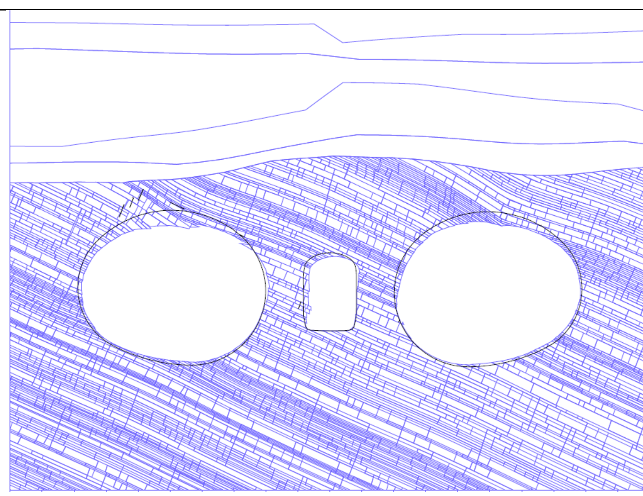
	
Left Hand Side – Rock Mass Model sketch used for preliminary engineering assessments	Right Hand Side – Distinct element model in UDEC with representation of full RMM detail and predicted deformation

Figure 3.4-10 DEM UDEC model for Dublin Port Tunnel cross over cavern design (Geo-Design 2002).

An example of DEM model output from the Clifton case study (Figure 3.4-11) is of stress distribution beneath the bridge tower that is seen to be concentrated in a narrow vertical zone beneath the tower (yellow and red colouring) on account of the distribution of weak, vertically orientated discontinuity types.

For a discontinuous rock mass, rock material strength and stiffness are important. However, the overriding control of rock mass response and behaviour is from the discontinuities and their strength and stiffness attributes. Prediction of overall response for discontinuous rock masses is, thus, a complex and interactive process, involving materials and discontinuities, and varies significantly with location, direction and stress state. This complexity has important consequences for the reliability of prediction and simulation via numerical modelling and for the understanding of rock mass response around an excavation and, thus, the fundamental importance of an RMM.

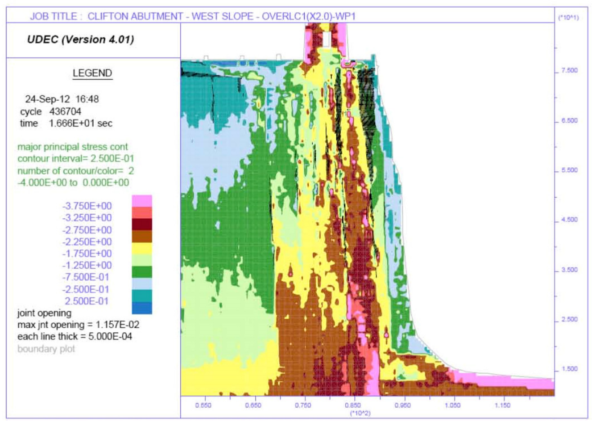


Figure 3.4-11 DEM UDEC model output for Clifton Suspension Bridge of major principal stress distribution under bridge loading (with permission of the CSB Trustees).

The alternative and contrasting use of rock mass classifications to derive input parameters for implicit continuum design analysis (via GSI, for example), without the context and justification of a comprehensive EGM and RMM, should not be acceptable best practice for civil engineering applications in discontinuous rock masses.

EGMs and RMMs should be regarded as an essential basis for stability state evaluation and appropriate analytical method selection.

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3.5 EGMS FOR SOIL ENGINEERING STUDIES

Ian Shipway

The development of an EGM for areas underlain by thick soil deposits presents a distinct set of requirements because of the potential for soil materials to change or be modified over relatively short periods of time by a range of surface processes. Soils in an engineering context, as opposed to rocks, are simply taken to be materials that can be disaggregated with gentle agitation in water. Therefore, they are subject to changes in form and characteristics through natural surface processes (actions of wind, water, ice, gravity, weathering) and anthropogenic actions both during and following their initial deposition. Consequently, the interpretation of the geomorphological context is critical in the early stages of EGM development and will usually provide insight into the most recent episodes of deposition and range of active surface processes. This leads to a broad classification of the surface soils into:

- Transported soils:
  - By water – river (alluvial), estuary, swamp, marine soils
  - By gravity – colluvial soils
  - By wind - aeolian soils
  - By volcanic activity - pyroclastic soils
  - By ice - glacial or periglacial soils
  - By human activity - anthropogenic soils.
- Soils developed *in situ*:
  - By chemical weathering
  - By physical weathering
  - By hydrothermal activity
  - By decomposition of organic materials (such as peat)

However, the current geomorphological conditions may be relatively featureless and may not reflect the complexity of deeper soil deposits formed by depositional processes that have varied through the Quaternary with dramatic changes in climate and associated changes in sea level. In active volcanic terrains, fluctuations in volcanic activity can also result in complex ground conditions. There may be layers of aeolian soil flanking deep alluvial deposits, or layers of ash (pyroclastic soil) sandwiched between residual soils derived from basalt. In these circumstances it is often necessary to rely on subsurface investigation techniques to develop the conceptual model and feed the results progressively back into the EGM (Figure 3.5-1).

Cone penetrometer tests and other methods that show a continuous profile of specific characteristics are fundamental tools in assessing broad definitions of layers within the soil sequence and the shape of the base of the soil strength materials that often represents the beginning of Quaternary deposition. Engineering in soils often require different skill sets, for example, knowledge of geomorphology, pedology and sedimentological logging rather than geotechnical logging.

Many geological aspects of the EGM knowledge framework are often progressed by developing an understanding of soil geotechnical behaviour. For example, the interpretation of the relative ages of layering within a soft alluvial clay profile is often critical in understanding the compressibility of the respective layers. Although the clay layers may appear similar in colour and other physical characteristics, there may be differences in measured or calculated properties that allow an assessment of the geological age of the soils, such as moisture content, consistency limits, shear strength, over-consolidation ratio etc.

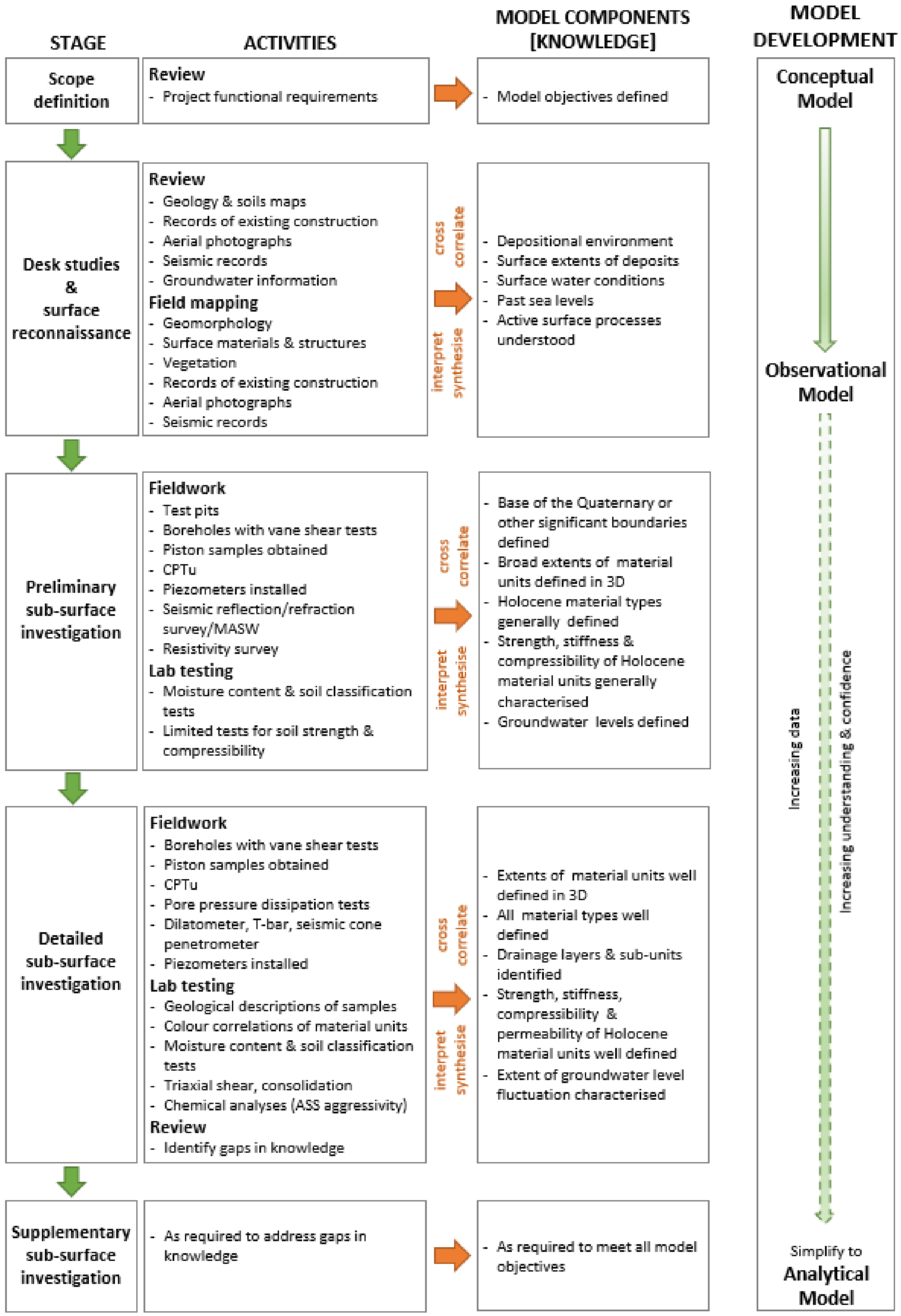

Figure 3.5-1 Developing an EGM for soil studies.

These values can be fed back into the model to support an interpretation of the stratigraphy that, in turn, can be used to identify engineering geological units through a zoning process and identify where material boundaries occur.

The identification of structures within soil (fissures, casts and other defects/discontinuities) can be very difficult and will often rely on the careful examination of soil samples from depth. However, once identified the type of structure identified can be a key element to better understanding the soil origin and, therefore, defining the model stratigraphy and engineering geological units.

Figure 3.5-2 shows extracts from the output of a preliminary EGM for a large building with multilevel basement that was to be constructed within a previously developed riverbank underlain by a Quaternary sequence of varying age and composition.

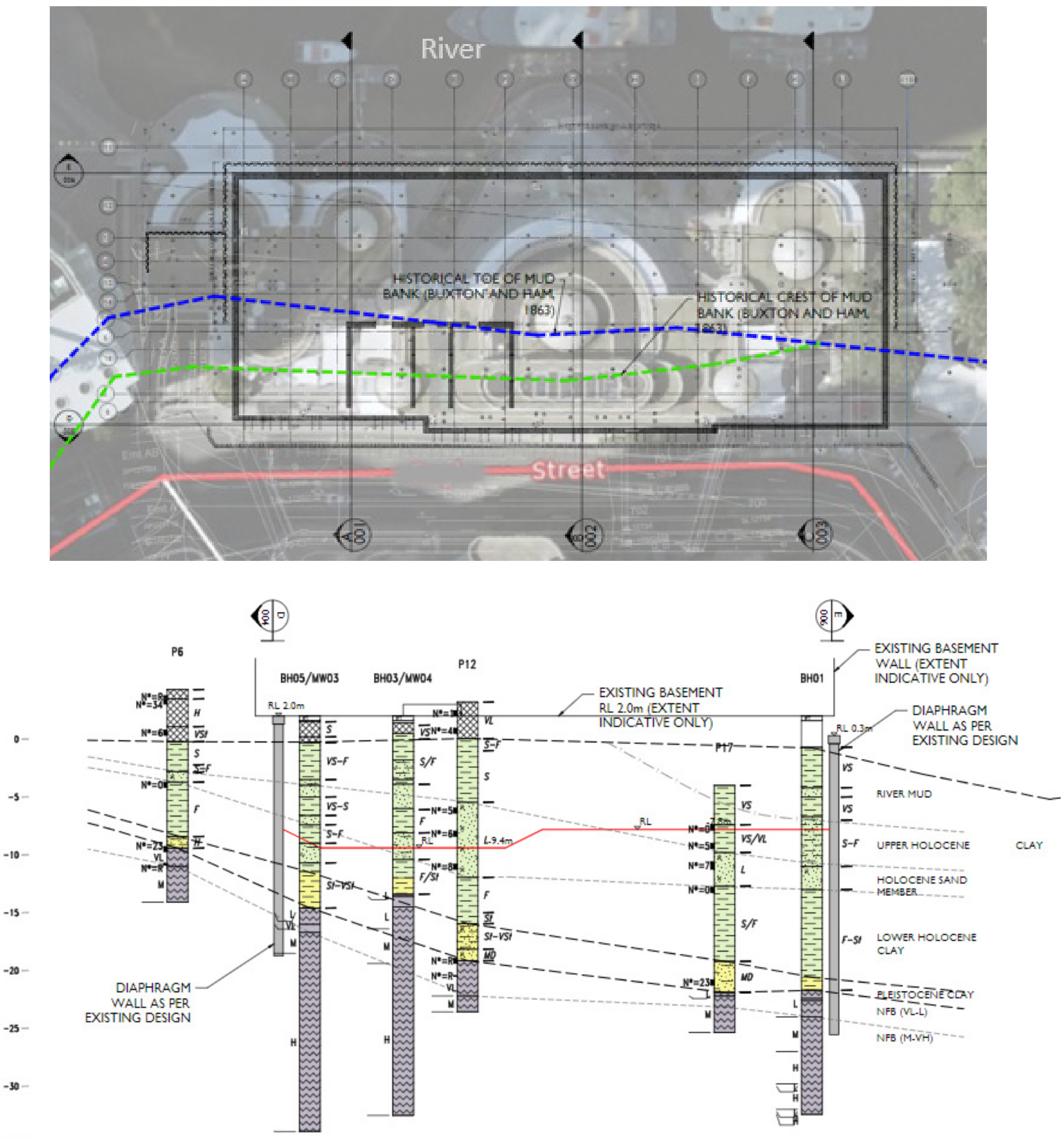

Figure 3.5-2 Plan and Cross Section extracted from an EGM for a building with basement over a riverbank area. The red line indicates the new basement level.

The entire model comprised:

- Data tables.
- Plans at several scales.
- A series of cross sections such as that shown in the figure.
- A basic 3D model showing broad relationships of major units.

As the site and those adjacent had been developed several times previously and were completely covered by fill or basements, surface geological observations were not possible. Historical maps showing the crest and toe of the former riverbank formed key model inputs that were used in conjunction with shear strength data to derive the sequence of Holocene layering depicted in the example cross section. Clues to the extents of some units were provided by simple hand penetrometer data given on borehole logs that were cross correlated with cone penetration tests (not shown).

3.6 EGMS FOR HYDROGEOLOGICAL STUDIES

Ann Williams

Relationship of the EGM to the Hydrogeological Model

A hydrogeological model is a representation of a groundwater flow system. Its purpose is to provide understanding (generally numerical) of groundwater flow, levels and pressures as well as recharge to the groundwater system and discharge from the groundwater system. The process of hydrogeological modelling can be summarised in a flow chart (Figure 3.6-1). Key components of the hydrogeological modelling process are:

- Planning
- Conceptualisation
- Modelling
- Reporting

The EGM is a critical input to the **conceptualisation** of the hydrogeological model. The conceptual hydrogeological model identifies the features that might influence groundwater behaviour in the status quo and post-problem stages.

Consequently, the EGM should provide a representation of the geology (from which the hydraulic properties of the soils and rocks represented in the model can be assessed or investigated), the topography (that might influence groundwater flow direction and surface water/ groundwater interactions), identify links to surface water systems (sources of recharge or discharge such as lakes, rivers or springs) and boundary conditions (for example, geological structures, major rivers or coastline). Human activities such as groundwater abstraction and/or stormwater recharge, should also be determined.

If the EGM is to be used as input to a hydrogeological model, then consideration should be given to its extent, so that it covers at least the likely hydraulic boundaries and extends sufficiently beyond the potential effects of the hydrogeological problem to be modelled. A collaboration between the engineering geologist and the hydrogeologist is recommended at the Planning stage to ensure that this is achieved.

EGMs are generally developed with a lot of detail at and near the proposed area of interest. When these models need to be used for hydrogeological assessments, the hydrogeological model needs to extend significantly greater distance away from the main area of interest, to avoid the influence of boundary conditions. If the EGMs are developed in such a way that these can be expanded easily or, with expansion in mind, with regards to the software model and understanding of larger scale geology, it is more helpful for hydrogeological modelling purpose.

The hydrogeologist might modify the EGM in development of the conceptual hydrogeological model to balance the complexity of available information with the ability to pragmatically model a problem that achieves the goals of the project. For example, different geological units might be combined in the hydrogeological model if they exhibit similar hydraulic properties. The goals and outcomes of the model would be established in the prior planning phase.

The hydrogeological model is used to assess the effects of a change in the existing environment on groundwater levels, flow volumes and directions, and water pressures. A change to the existing environment might be 'natural', for example, sea-level rise, increased rainfall or drought or, might be introduced, for example an excavation, dewatering, construction underground, loading compressible soils or abstraction wells. Such changes might result in raising or lowering groundwater level that might cause flooding, consolidation settlement, or saline intrusion; it might impact well yields and/or result in changes in groundwater flow directions. Changing the direction of flow might spread contaminants already residing in the ground.

Planning

The purpose of the Planning phase is to align understanding on how the EGM will be used and what outputs are sought from the hydrogeological model, as well as what can be achieved with the available resources and data. This will include understanding the level of confidence needed in the outputs (for example, a model with a lower level of confidence may be appropriate at earlier stages of a project or to focus the scoping of further investigations to achieve the project's goals), and the level of confidence in the inputs available (for example, groundwater level data recorded in a formed piezometer over a period of time will be more reliable than that obtained from a one-off reading during drilling). From a hydrogeological perspective, model output confidence includes the ability to calibrate the model to historical surface water and groundwater data.

It is useful to prepare a statement of limitations or exclusions as the model is prepared to avoid losing sight of the purpose for which it is being developed.

Conceptualisation

The conceptual hydrogeological model should identify and describe the processes that control or influence the movement and storage of groundwater. The area of the conceptual model should be large enough to cover all potential influences on the groundwater system and the extent of effects that might arise from the project to be considered. It should also be large enough to capture all of the groundwater flow processes controlling groundwater behaviour in the study area.

The conceptual model can be presented as a series of 2- and 3-D diagrams supported by a description of the key hydrogeological units, rainfall recharge, flow and discharge of groundwater (including a basic water balance) and how this might be influenced by seasonal variation and the project. The conceptual hydrogeological model should seek to explain the observed groundwater behaviour in the model area. Reports should include some basic semi-quantification so that it is possible, for example, to assess if it is reasonable that the model indicates that 90% of inflow comes from rainfall with the balance from intra-aquifer flow etc.

In summary, the conceptual groundwater model:

- Is a combination of the EGM and hydraulic influences – it sets the context for the assessment of effects on the groundwater system.
- Identifies key hydrogeological units and relative properties.
- Identifies key boundaries, sources and sinks.
- Identifies inferred interactions between units and between groundwater and surface water.

Depending on the project, the following aspects may need to be considered within the EGM:

Catchment

- Identify likely groundwater catchment boundaries.
- Regional scale sources of recharge and discharge.
- Review rainfall records to determine typical seasonal and annual variation.
- Regional scale groundwater flow direction/s.

Hydrogeological units and their properties

- Defined according to their likely hydrogeological behaviour.
- Hydrogeological parameters, accepted values and ranges (distinguish from values used in model calibration and verification).

Groundwater levels

- Plot the distribution of groundwater level data.
- Do groundwater levels vary (both in absolute level and in seasonal range) in the different units?
- Identify groundwater flow direction and gradients, and if these vary temporally.

Groundwater recharge and discharge

- Rainfall recharge (how much, how was this quantified? Spatial and temporal variations due to land use, soil cover and climate).
- Interactions with surface water bodies and the coast.
- Inter-aquifer flow (that is, exchange with other aquifers, for example, leakage from above or below).

Groundwater Quality

- Are there known water quality issues (for example, areas of introduced contamination or naturally high levels of a contaminant that might be relevant to the project?)
- Is there the risk of saline intrusion?

Groundwater Use

- Existing groundwater or surface water takes that might influence the status quo or be affected by the project.
- Abstraction and recharge systems (fresh water, recycled water [from heating and cooling systems] and storm or wastewater).

Hydrogeological Modelling

Hydrogeological models require an understanding of the past to simulate the present situation and allow assessment of future scenarios. Guidance on hydrogeological model development is provided in documents such as Harbaugh *et al.* (2000), Reilly & Harbaugh (2004) and Barnett *et al.* (2012). A high level overview only is provided here to give the developer of the EGM an understanding of the requirements of the hydrogeologist.

Data Inputs

Typical data inputs include:

- Ground investigations used in development of the EGM (geological data, groundwater level data in each unit, *in situ* permeability test results [packer tests, slug tests], pumping tests and results of trial excavation dewatering etc.)
- A review of published and unpublished literature to tabulate hydrogeological properties obtained from testing and modelling of similar, or the same, geological materials in the region.
- Plot groundwater level data obtained from other monitoring sites regionally (geological units screened, seasonal variation, correlation with rainfall, nature of aquifer [unconfined, confined, artesian, water table etc.])
- Topographical data, that may be used to develop a 3D ground surface plot in applications such as SURFER, assuming no 3D model has been generated.

- Ground surface imagery (google earth/drone footage/aerial photographs) to facilitate locating the modeller and recognising the significance of potential effects (for example, the extent of drawdown on streams or the coast, or beneath structures); this also assists in identifying the extent of developed and undeveloped land to allow selection of appropriate recharge domains.
- Historical rainfall data from which an appropriate level of rainfall recharge can be selected.
- Surface water investigations used in the assessment (river level and flow gauging data to identify where streams gain or lose water) to support model calibration.

Model Set-up

A number of decisions need to be made around how to best represent the conceptual model in a computer modelling environment. One of the first considerations is to determine whether the problem can be adequately modelled in 2D, or whether there are sufficient data, and the outcomes sought necessitate, a 3D model. In practice, multiple models may be developed to respond to a problem. These may include a surface water model, a 2D seepage model (for example, to examine, in detail, changes in flow around a structure), a 3D regional flow model to consider overall flow and aquifer behaviour, and 3D 'cut-out' models to examine a particular 3D problem within the context of the wider model. However, it is recommended that the simplest approach to modelling that will achieve the outcomes agreed at the planning stage, be applied. Simplicity aids model convergence and calibration, while limiting time to run each scenario and therefore the cost.

There are a number of commercially available software codes for groundwater modelling and these are set out in Table 4-1 of Barnett *et al.* (2012) along with advice on selection of an appropriate software package.

Once a decision has been made on the software and number, nature and purpose of models that will be built, the following need to be considered:

- Scale. The model should be bound by known head boundaries (for example, rivers, coastline) or be of sufficient extent that boundary assumptions do not influence model outcomes.
- Assessment of how the model can be best divided into a grid of calculation nodes; thin geological layers and large changes in parameter values over short distances may mean that the model does not 'converge' and will not run.
- Timeframes to be used in modelling.
- Consideration of how the geology has been defined and how surface water features are incorporated. It is simplest if these features can be taken into the hydrogeological model directly from the EGM.
- Calibration (quantitative and qualitative); a model that is 'calibrated' is required to address many hydrogeological problems. First, a qualitative calibration is carried out to check that key aspects of the conceptual model are respected (for example, to check that flow direction and discharge match observations). Then, a quantitative calibration is carried out by modifying model input data so that the model more closely matches observed heads and flows or concentrations for quality/plume modelling. Parameter adjustment can be done manually or automatically by using nonlinear regression statistical techniques, with the model being run many times in a 'trial and error' manner until a satisfactory calibration is achieved. The effort applied to achieving a 'good' calibration is dependent on the intended use of the model. Determining if the calibration is sufficient for the intended use of the model is important in evaluating whether the model has been constructed appropriately. A numerical value that indicates the closeness of fit between the modelled and observed data sets is often used (for example, the Scaled Root Mean Square error of < 10% is often considered a satisfactory fit).

- Model sensitivity to variations in parameter values (typically) but also grid size, boundary conditions and calibration criteria. Sensitivity analysis is the evaluation of model input parameters to see how much they affect model outputs, that are heads and flows or concentrations. The relative effect of the parameters gives a greater understanding of the simulated system and limitations of the model to assist decision-making and can be used to scope any further work. Further, the most sensitive parameters will be the most important parameters to be closely monitored during the project.
- Testing bias needs to be considered, that is, if your model is sensitive to horizontal 'k' of a fractured rock but all your sampling is of unfractured rock, then matching the observed values might not give you an upper bound. Conversely if all your observed values were biased to isolated fracture zones you might have overestimated.
- How the project or change to the environment is simulated, for example, introduction of a sheet-piled wall, a shaft or a tunnel. Is it introduced progressively or 'wished in place' in a single time step or series of steps? Is it introduced as a boundary? How is leakage considered etc.? Is dewatering via sump pumping, a single well or multiple well points?
- How boundary conditions can be used to represent the interactions between groundwater and adjoining surface water features. Also, it must consider how climatic conditions (rainfall and evaporation) and groundwater abstraction or recharge is to be included in the model and how the variations in hydrogeological properties of the system will be defined.
- How to account for conditions that cannot be quantified (for example, a very large number of small private wells for which yield is not available but cumulatively may be significant to the budget) or cannot be included in the groundwater flow model (for example, in-stream/surface water flow/stormwater runoff etc.)

Modelling Scenarios

Hydrogeological models are often developed to assess the effects of a change to the existing environment (for example, climate change, introduction of new wells to abstract groundwater, dewatering of a basement excavation, discharge of wastewater to land, construction of a tunnel etc.). This means that the status quo needs to be modelled and run out to the same future point as the change being assessed in a scenario run.

If a model is run to steady state (equilibrium) the model results indicate the final groundwater condition that occurs when all changes to the system have stabilised. This is likely to be an average condition that does not account for seasonal variation, temporal changes in flow rate etc. Alternatively, the model can be run in time stages (calculations are made in a sequence of time steps) into the future so the progressive change in groundwater conditions, and/or temporal variations in the longer term can be investigated.

Modelling scenarios typically consider:

- Potential impacts on groundwater levels, flow and flow directions.
- Groundwater inflows to excavations.
- Changes in flow volume and direction in and around underground structures.
- Changes in the rate of discharge of groundwater to streams and water bodies or changed interactions between groundwater and surface water.
- Potential for changes in flow directions, paths or gradients to alter contaminant flow paths, including saline intrusion.
- Extent of groundwater drawdown and the potential for consolidation settlement to occur.
- Potential for flooding as a result of impedance of groundwater flow.

- Potential for existing well users to be adversely affected.
- Change in aquifer budget and implications for well fields, environmental tolerance and/or longer term sustainability.
- Model limitations (uncertainty). Because we cannot construct a single 'true' model, simulated results are always uncertain.

Reporting

The whole of the modelling process should be documented in a report including the conceptualisation and model set-up, calibration and sensitivity analysis, predictive simulations modelled and uncertainty analysis. Reilly & Harbaugh (2004) recommended that the following should be described as a minimum:

- The objectives of the hydrogeological model.
- The EGM and the hydrogeological system under investigation, including all data sources considered and how they were evaluated and derived.
- The mathematical methods used and their appropriateness to the problem being solved.
- The boundary conditions used in the model simulations.
- The discretised network used (if one was used) and the rationale for its selection.
- The aquifer properties modelled.
- For steady state models, all of the inputs to the status quo model, including recharge from infiltration, river stage changes, leakage from other aquifers, and discharges via springs, evapotranspiration from groundwater etc.
- For transient models, the initial conditions that are used in the simulations.
- Calibration criteria, procedure and results.
- The limitations of the model's representation of the actual system and the likely impact they might have on the results and conclusions presented.

As a guide it is suggested that the level of documentation reported is sufficient that another modeller could set up and run their own model simulations.

Monitoring

Because the hydrogeological model is not a unique solution and provides only a reasonable indication of the effects of a project on the environment, it is recommended that reports identify an appropriate level of monitoring that might be installed to check that actual effects are similar to those predicted, or to allow mitigations to be implemented if they are not. Monitoring may include:

- Piezometers: specify type, locations, units screened or in which tip is installed, frequency of recording (record groundwater levels and/or pressures) and method of collection (manual measurement versus automated logging and telemetry).
- Surface water level and flow gauges to check effects on streams or other water bodies.
- Key water quality determinants to assess if the changes imposed result in altered groundwater chemistry.
- Settlement marks: on what (ground or structures) and where.

Mitigation

If the effects on groundwater are found to be greater than anticipated and potentially problematic then it may be desirable to initiate mitigation measures. It is best to consider and agree these prior to the need arising for their implementation as changes may continue to progress even after an activity has ceased. Typical mitigation measures might include:

- Monitor and respond.
- Construction management (for example, reduce length and/or duration of open excavation).
- Design strategies (for example, increase the depth of sheet-piles to increase groundwater cut-off and reduce drawdown effects).
- Active mitigation (for example, temporary sheet-piles, recharge etc).

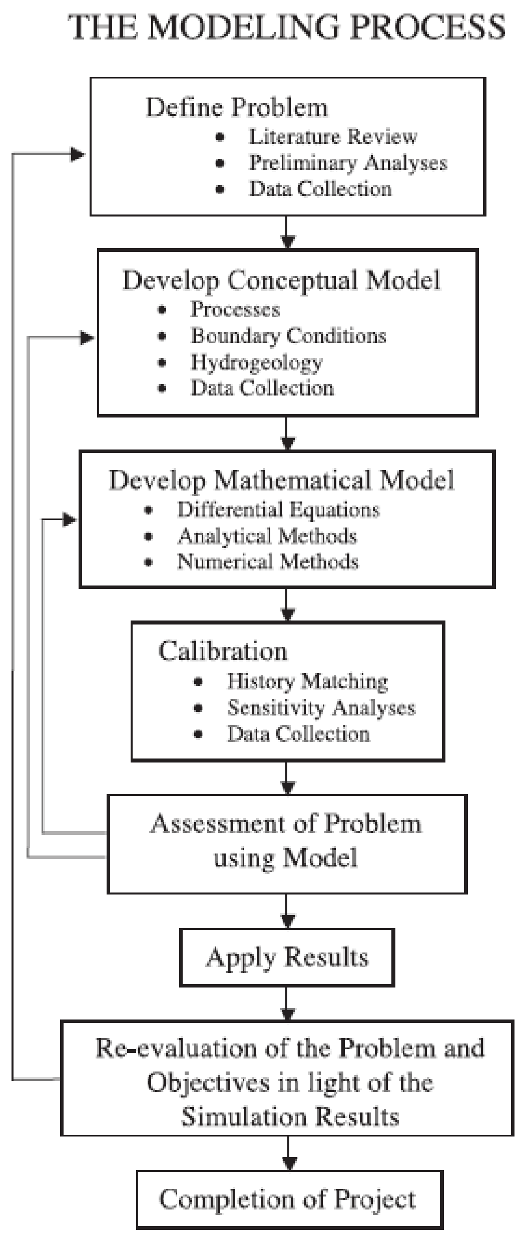

Figure 3.6-1 Standard groundwater modelling protocol after Reilly (2001)
Credit: U.S. Geological Survey

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3.7 EGMS FOR LANDSLIDE STUDIES

Steve Parry

The key objective of an EGM for a landslide hazard assessment is to understand the engineering geological and geomorphological controls on instability and how those might impact the project. In particular, the EGM should identify potential landslide types, that is, not only what has occurred but what could occur, as well as their likely magnitudes and frequency. Depending on the landslide types, the EGM will need to consider a variety of factors, from discontinuity controls on block size for rock fall to potential rates of entrainment for debris flows.

The initial stage of any study should be the development of a primarily conceptual model focusing on hazard. This Conceptual Hazard Model (CHM) is likely to be a combination of limited observational data within a conceptual framework. Depending on the type and magnitude of previous landslides, field evidence may no longer be easily observed. Consequently, the conceptual component, based on knowledge and experience of landslides in similar terrain, is critical to ensure all potential hazards are evaluated.

The aim of the CHM is to evaluate (Lee & Jones 2014):

- What could happen – what are the potential landslide types?
- Where could it happen – the susceptibility for each landslide type.
- Why might such events occur – likely triggers.
- When might such events occur – frequency of occurrence and likelihood of runout.
- What will be the impact of such events – the possible consequences of the landslide.

Visualisations of the CHM allows the explanation of complex, often interacting, processes to non-specialists (Figure 3.7-1).

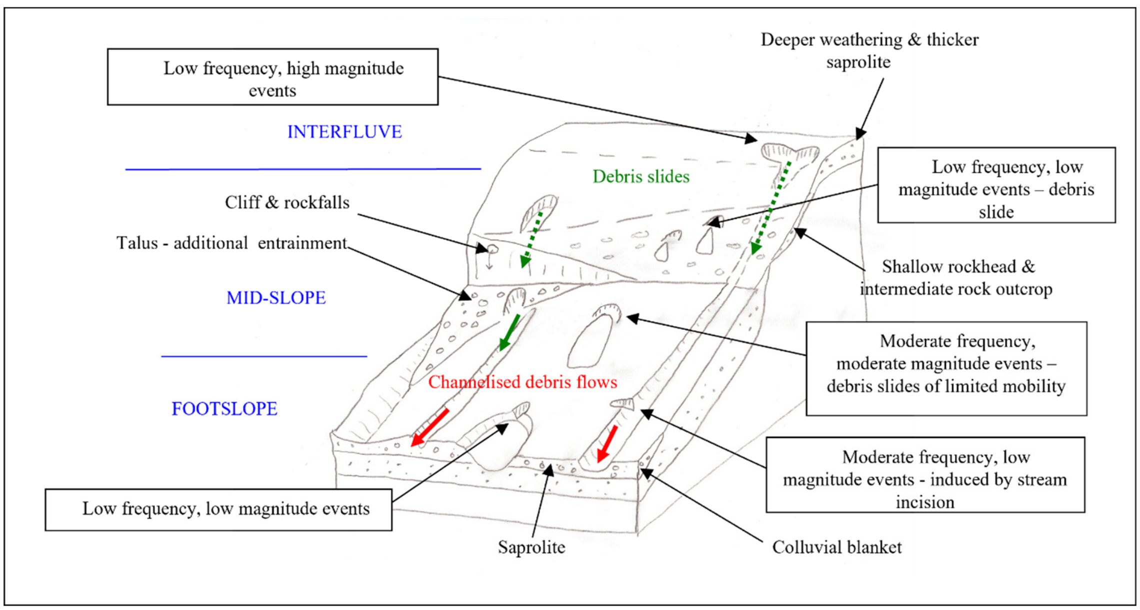

Figure 3.7-1 Example of the visualisation of a CHM for communication purposes (from Parry & Ng 2010)

The initial CHM should be re-evaluated following any initial engineering geological/geomorphological mapping from remote sensing data. Whist mapping is observational in nature, it provides a fundamental insight into the geomorphological setting. In parallel with the mapping, an initial landslide inventory is developed. The mapping and inventory provide the feedback loops against which the CHM can be evaluated. The CHM provides targets for subsequent detailed field mapping and supports the early development of uncertainty and risk registers for the project that should be updated throughout the various stages of the study (Figure 3.7.-2).

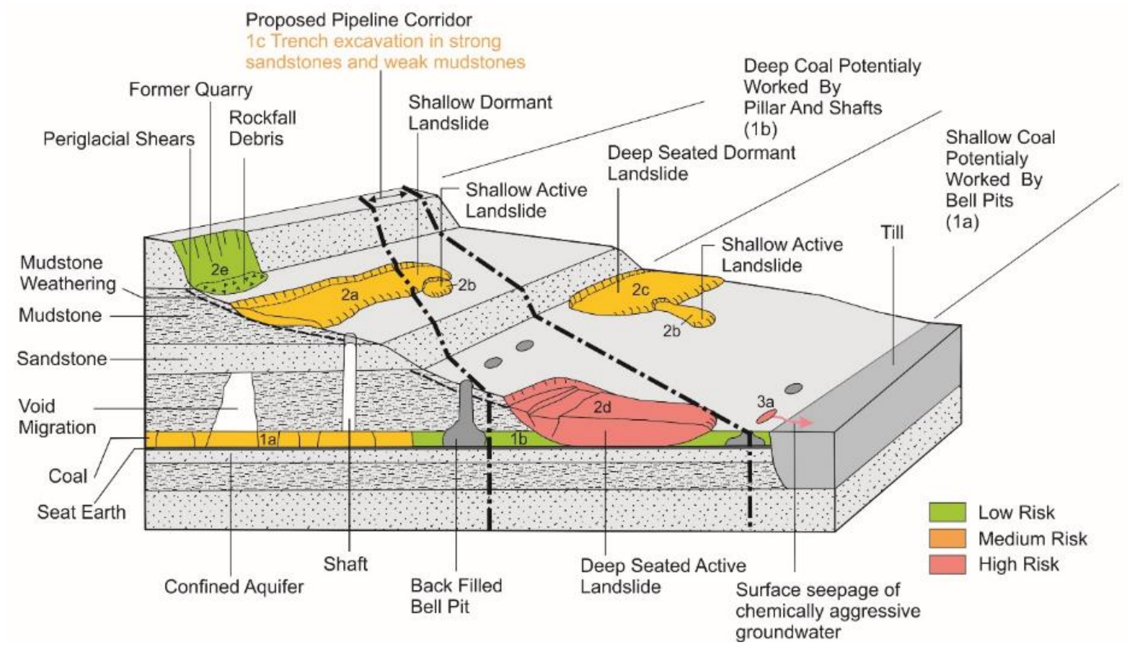

Figure 3.7-2 Example of the visualisation of possible ground risk, including landslides, developed from a conceptual model (from Baynes *et al.* 2021).

Given the nature, scale and often remote locations of such studies ground investigations are often limited and there should be considerable emphasis on detailed engineering geological and engineering geomorphological field mapping, (Figure 3.7.-3).

The field mapping should only be undertaken once the desk study, including mapping from remote sensing, has been completed and a CHM developed. The purpose of the field mapping is to evaluate and test the EGM. In particular to:

- evaluate observations and validate interpretation from the remote sensing interpretation, in particular, the landslide inventory;
- augment existing evidence with respect to the geomorphological processes that control the location, magnitude and frequency of landslides;
- evaluate and revise the CHM and to generate a series of observational models, including material descriptions and an evaluation of geomorphological processes; and to finalise any ground investigation design.

Ground investigation may be required to complement the field mapping. However, the cost can be expensive, particularly in remote locations. Consequently, each investigation station must be carefully selected based on the EGM to maximize the information it will provide. The EGM also allows the early evaluation of possible remedial solutions and, where applicable, the ground investigation should gather data to support the design of those solutions.

Given the spatial and often subtle variations in superficial deposits, trial pits and trenches are invaluable. However, if the ground investigation stations are only logged to National Standards, textural variations may not be described and lithofacies and environments of deposition of superficial deposits not recorded. This makes any subsequent interpretation problematic, for example, distinguishing debris flow from debris flood deposits. Consequently, alternative approaches such as sedimentological rather than geotechnical logs should be used; for example, within debris fans, pedological logs provide more appropriate descriptions (Sewell *et al.* 2015).

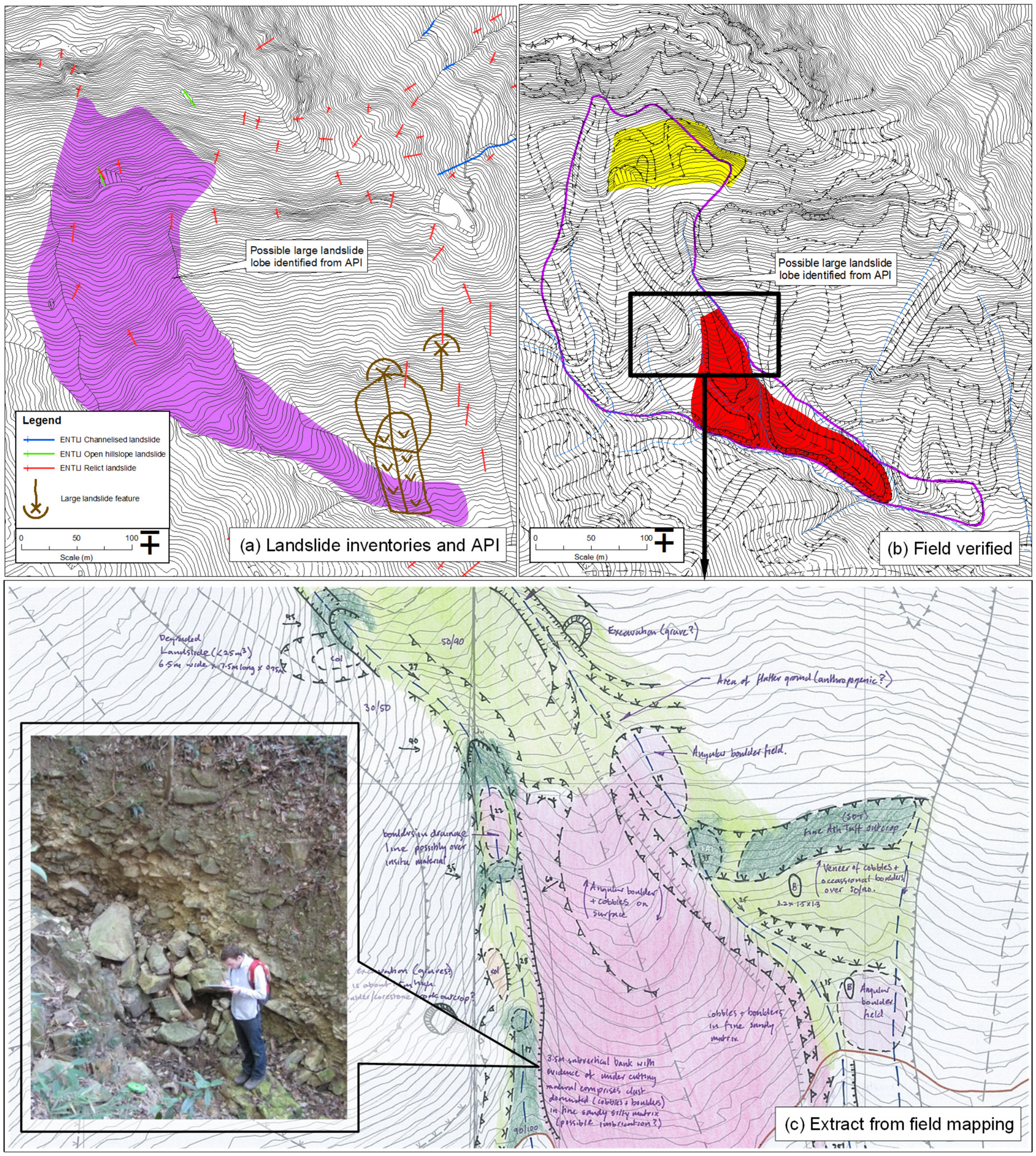

Figure 3.7-3 Mapping in Hong Kong, (a) Landslides in existing inventories and a possible additional large, degraded landslide debris lobe identified from aerial photograph interpretation. (b) & (c) Field mapping indicated that the lobe is derived from multiple events. For example, the feature identified in red consists of a distinct deposit comprising angular to sub-angular, slightly to moderately decomposed, clast-supported cobbles and boulders. A depression (yellow) is evident above this lobe. The field evidence suggests that the lobe may represent debris from a large rock avalanche. From: Geomorphological Mapping: Methods and Applications Developments in Earth Surface Processes, Chapter 15 The Application of Geomorphological Mapping in the Assessment of Landslide Hazard in Hong Kong. Parry 2011, © 2011 Elsevier.

The observational data obtained during the field mapping and ground investigation is compared with the CHM and the initial Geological Model. A key aim is to identify reference ground conditions (Baynes *et al*. 2005) within similar geomorphological settings (Terrain Units), focusing on the thickness and type of superficial deposits, the depth of weathering, areas of rock outcrop and structural domains with respect to controls on instability. Each terrain unit is evaluated against the landslide inventory and an assessment made of landslide type, magnitude and frequency with respect to each unit. Figure 3.7.-4 shows the terrain units derived for a site in Hong Kong.

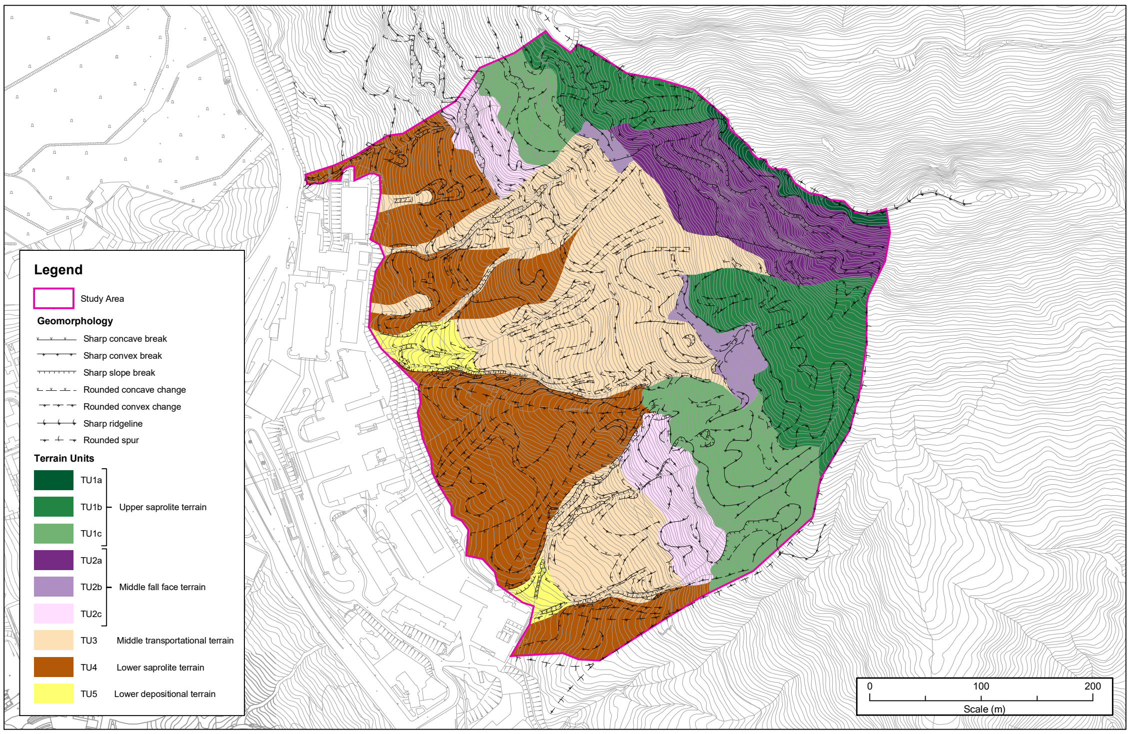

Figure 3.7-4 Terrain units developed from the EGM (Parry 2011). From: Geomorphological Mapping: Methods and Applications Developments in Earth Surface Processes, Chapter 15 The Application of Geomorphological Mapping in the Assessment of Landslide Hazard in Hong Kong. Parry 2011, © 2011 Elsevier.

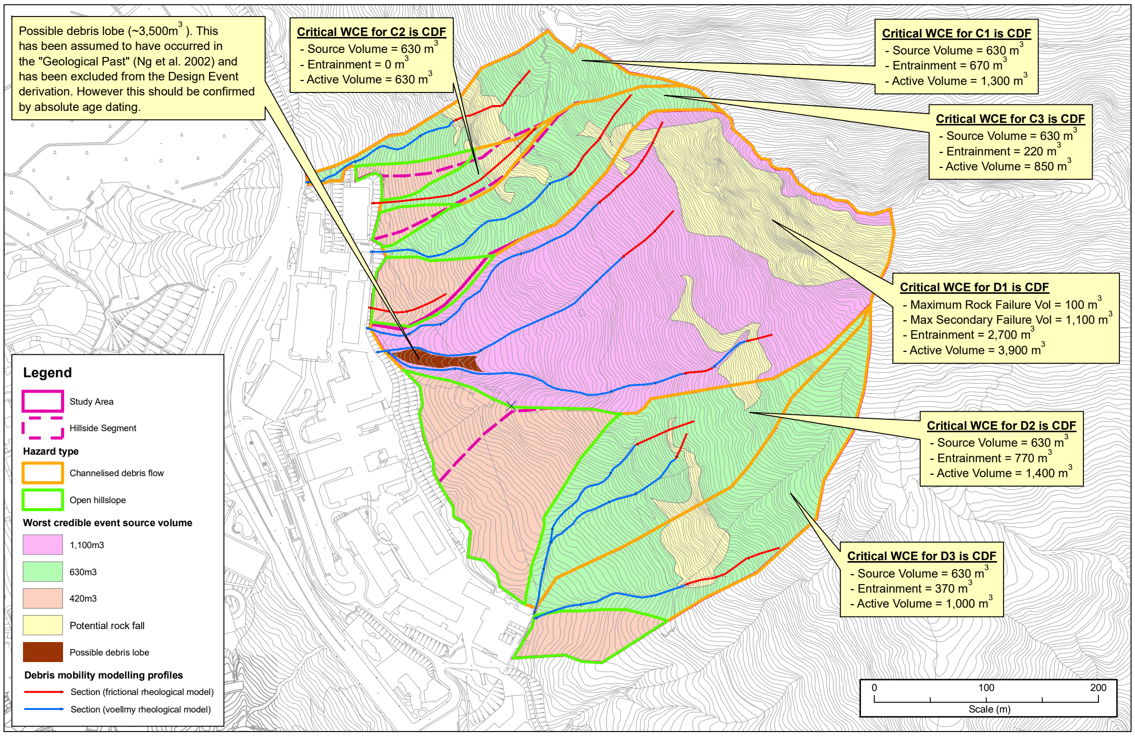

Figure 3.7-5 Design events derived from the EGM (Parry 2011). From: Geomorphological Mapping: Methods and Applications Developments in Earth Surface Processes, Chapter 15 The Application of Geomorphological Mapping in the Assessment of Landslide Hazard in Hong Kong. Parry 2011, © 2011 Elsevier.

In addition to establishing the likely magnitude and frequency of each landslide type, controls on landslide run out need to be evaluated. In particular, the potential for the development of more mobile flow type landslides and any subsequent entrainment. This is primarily based on evidence from mapping such as previous events and the presence of geomorphological conditions that would be conducive to such an event. Figure 3.7.-5 shows the derivation of ’design events’ for each terrain unit.

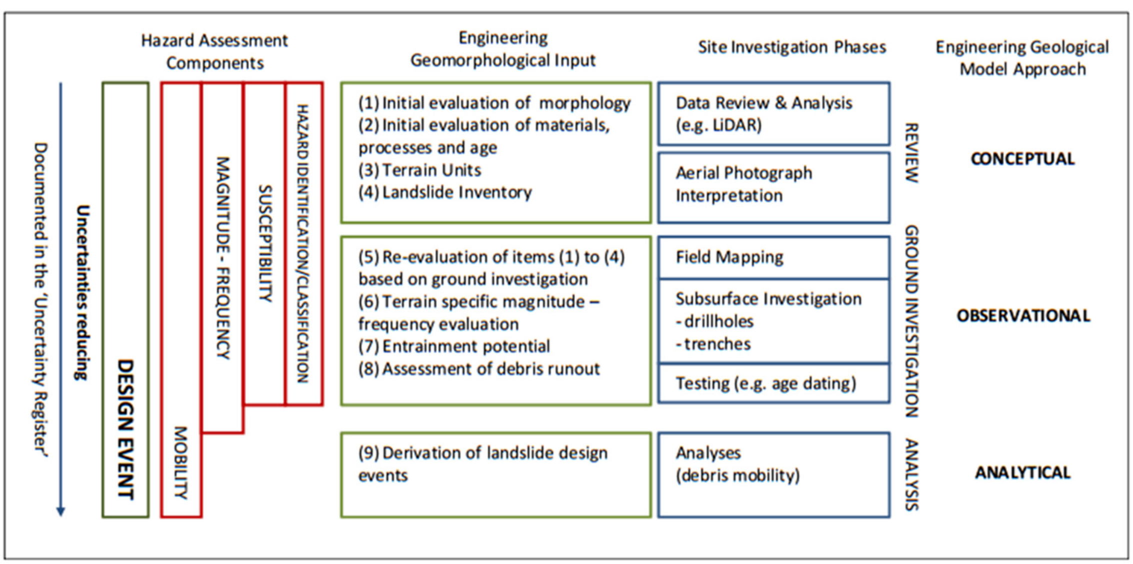

Figure 3.7-6 Use of EGMs in Landslide Hazard and Risk Assessments From: Proceedings of the 11th International Symposium on Landslides (ISL) and the 2nd North American Symposium on Landslides, Engineering geomorphological mapping for landslide hazard assessments in Hong Kong, Parry & Hart 2012. © 2012 CRC Press by Imprint. Reproduced by permission of Taylor & Francis Group.

In summary, an EGM allows for the logical evaluation of landslide hazard (and subsequent risk) (Figure 3.7.-6) with outputs including conceptual hazard models, engineering geological/geomorphological mapping, landslide inventories, potential landslide types and their associated magnitude and frequency, entrainment rates, run out potential and the derivation of appropriate parameters for any analytical modelling, for example, debris mobility modelling and potential impact velocities.

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3.8 EGMS FOR CONTAMINATED LAND

Judith Nathanail & Paul Nathanail

The ground can be a source of natural or anthropogenic contamination, a pathway transmitting contaminants, a barrier to such transmission or a receptor that could be negatively impacted by contaminants (Table 3.8-1).

Table 3.8-1 Geology as source pathway/ barrier and receptor. © Land Quality Management Ltd reproduced with permission.

CSM component	Examples of geology acting as this component
Source/contaminant	Arsenic, lead, nickel, sulphates
Pathways	Sand, sandstone, chalk, fissured mudstone, buried channel, localised higher permeability zones, fault (zone of higher permeability)
Barriers	Clay, mudstone, fault (low permeability due to gouge)
Receptors	Chalk, sandstone, smaller aquifers which may provide water for local supply of feed surface water

In risk-based contaminated land management, within a specific legal context, contaminant linkages connecting sources of contaminants, pathways and receptors must be identified. The Conceptual Site Model (CSM) is the central tool used to depict contaminant linkages and hence help evaluate and manage risk from contamination.

A CSM is a "*synthesis of all information about a potentially contaminated site relevant to the task in hand with interpretation as necessary and recognition of uncertainties*" (ISO 21365, 2020). It is used to inform decisions about the need for action to manage risks posed by land contamination to receptors such as human health, surface and ground water, ecosystems, buildings, livestock and crops that are defined by relevant laws.

The level of engineering geological detail in a CSM ranges from simple and abstract to highly detailed – from generic to observational, and occasionally evolutionary. The CSM highlights key aspects of the geology of a site to understand the scale, nature and legal significance of potential risks from contaminated soil, water and gas or vapours.

Extraneous information can obscure understanding of contaminant linkages. Whilst detailed geological cross sections may have been created during a project, in a CSM the geology is depicted in terms of it being a source, pathway/barrier or receptor. The CSM summarises and communicates the key information relevant to evaluating risks from contamination that could be, or has been shown to be, present at a site (Table 3.8-2).

CSMs typically comprise a plan (Figure 3.8-1) and cross section (Figure 3.8-2) showing the key source, pathway/barrier and receptor features on the site and surrounding area together with a table or network diagram (Figure 3.8-3) showing the topological contaminant linkages known or suspected to be present and supporting text (Table 3.8-2). A CSM helps and captures understanding of the risk from contamination at a site expressed as contaminant linkages.

Table 3.8-2 Information to include in a CSM. © Land Quality Management Ltd reproduced with permission.

Information	Comment
Legal context	Establishes receptors of concern and level of risk triggering action
Current/planned use of site and vicinity	Establishes likely nature and behaviour of people on and in vicinity of the site
Risk management stage	1. Preliminary or quantitative (generic or detailed) risk assessment; 2. Remediation options appraisal; 3. Remediation design, implementation or verification
Historical land use on site and in vicinity	Establishes potential for historical contamination
Environmental setting	Establishes nature of the ground and potential environmental receptors
Site geology, including engineering geology, geochemistry, geomicrobiology, hydrogeology, seismicity, ongoing processes	Geology as a source of contamination, pathway/barrier to migration or receptor (as groundwater); engineering geology can influence contaminant transmission and sustainable remediation strategy
Actual/potential contamination	Composition, scale, distribution, fate & transport, toxicity
Nature and location of contaminant sources, pathways/barriers and relevant receptors	Each component is needed if there is to be a risk
Contaminant linkages of connected sources, pathways and receptors	Linkages drive the risk
Assumptions and uncertainties	If these drive the decision, they should be reduced by gathering further information

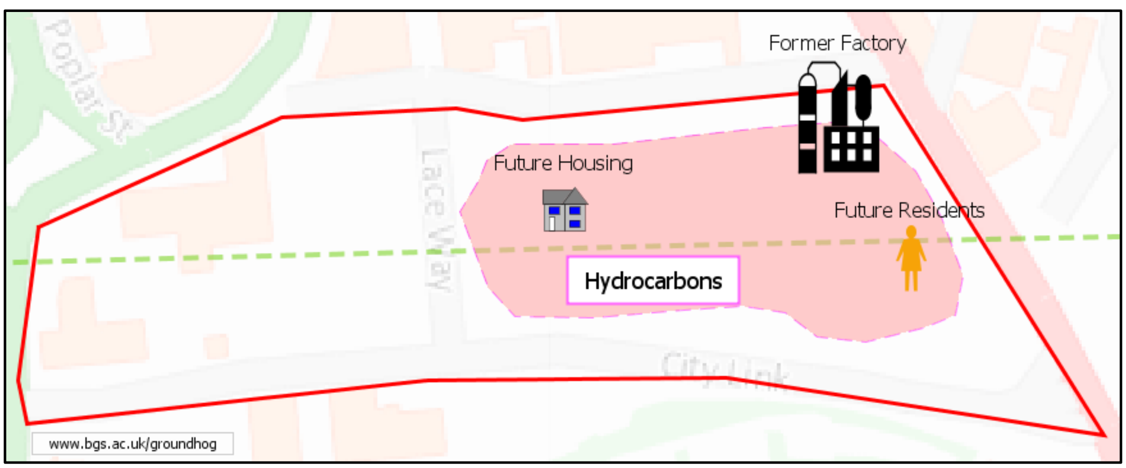

Figure 3.8-1 CSM at PRA (Preliminary Risk Assessment) – Plan view – shows location of sources and receptors; dashed green line indicates cross section in Figure 3.8-2. © Land Quality Management Ltd reproduced with permission.

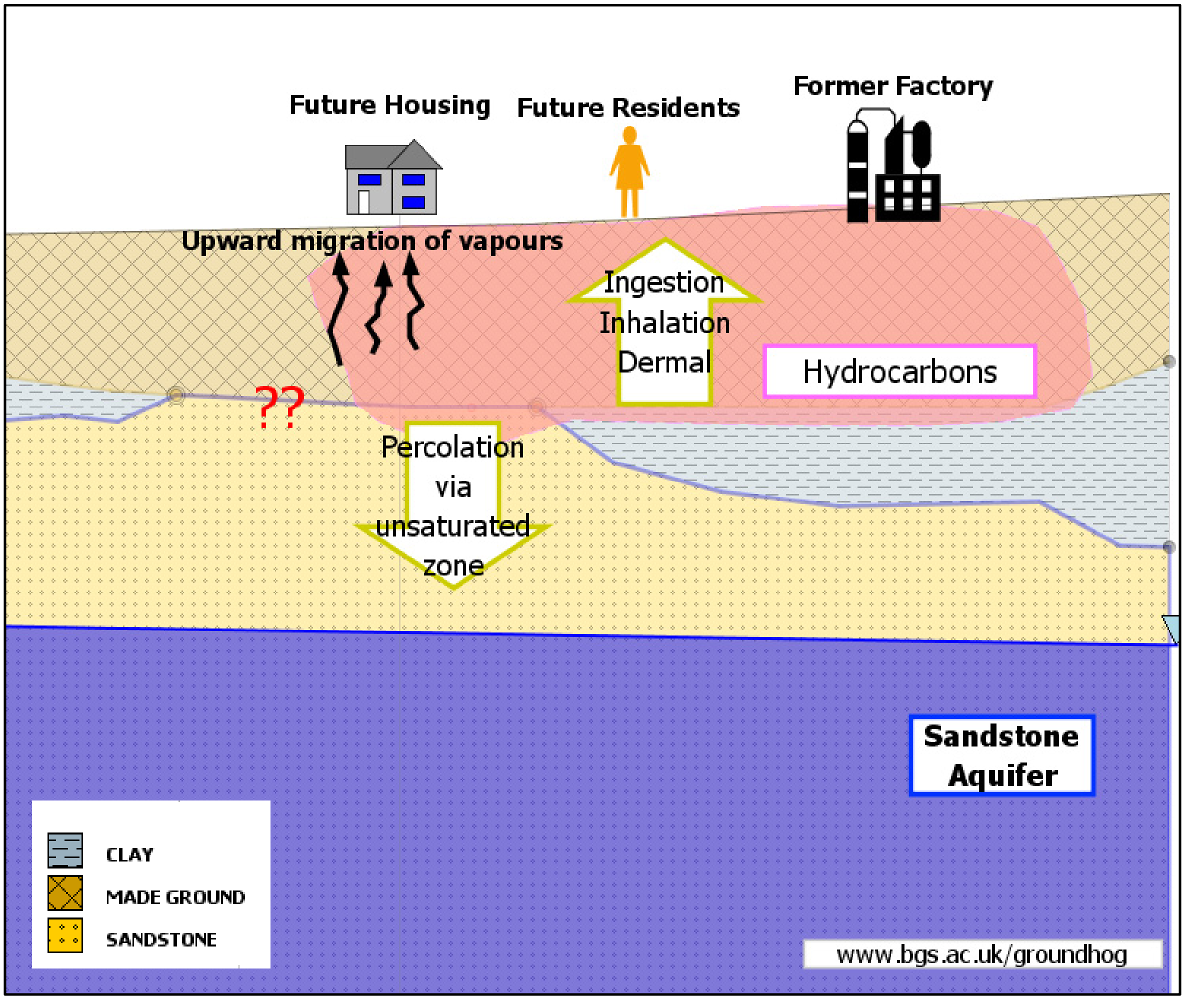

Figure 3.8-2 CSM at PRA – Cross Section – shows sources, pathways and receptors in relation to geology. In this example the continuity of the clay layer is uncertain. © Land Quality Management Ltd reproduced with permission.

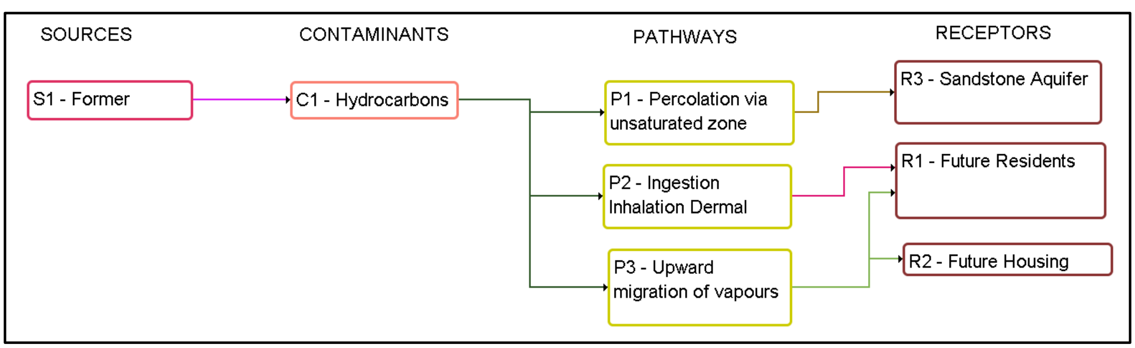

Figure 3.8-3 CSM at PRA – Network Diagram – shows potential contaminant linkages.

The CSM is used to determine the need for further information to reduce critical uncertainty, evaluate risk and need for remediation, identify feasible remediation strategies and demonstrate remediation has successfully broken all contaminant linkages (Table 3.8-3).

Table 3.8-3 Uses of a CSM in risk based contaminated land management© Land Quality Management Ltd reproduced with permission.

Stage	Use
Preliminary risk assessment	Deciding whether to conduct intrusive site investigation to characterise contamination or inform a quantitative risk assessment
	Identifying the likely location of potential contamination hazards at a site.
	Qualitative evaluation of potential contaminant linkages at a site
	Designing a soil, ground gas and groundwater sampling and analytical strategy
Quantitative risk assessment	Selecting risk assessment and generic or site specific assessment criteria
	Interpreting monitoring results
Remediation options appraisal	Choosing the remediation strategy
Remediation design	Greening and value engineering the selected remediation strategy
Remediation verification	Demonstrating remediation has been effective in breaking all contaminant linkages
Throughout	Predicting impact of future events such as climate change or changes in land use
All stages	Communicating with stakeholders at all stages of land contamination risk management

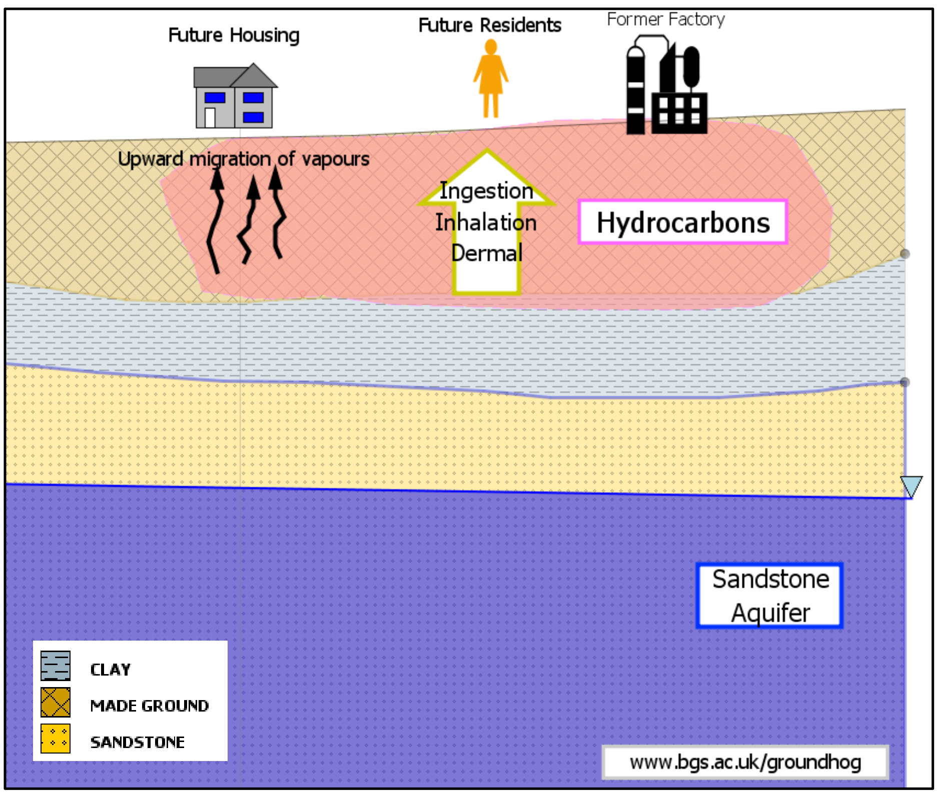

Figure 3.8-4 - CSM based on results of intrusive site investigation and QRA – Cross Section. In this example, the site investigation proved the clay layer is continuous. © Land Quality Management Ltd reproduced with permission.

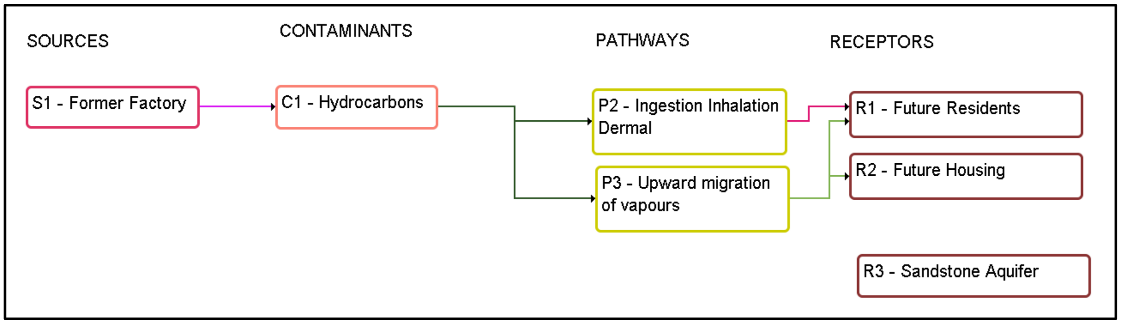

Figure 3.8-5 CSM based on results of intrusive site investigation and developed during QRA – network diagram - In this example the linkage involving the Sandstone Aquifer is no longer present but risks to future residents and future housing remain. © Land Quality Management Ltd reproduced with permission.

Figure 3.8-4 and Figure 3.8-5 show how the CSM is updated with information from the site investigation and risk assessment, addressing some of the uncertainties in the PRA (in this example the plan view is effectively the same as the plan view at PRA, so has not been repeated).

The CSM succinctly summarises the site features relevant to land contamination risk management: contaminant sources, pathways/barriers and receptors, connected in contaminant linkages.

The CSM helps evaluate, communicate and manage risks from land affected by contamination. It is a testable approximation of environmental conditions and processes on a site and its vicinity. A CSM captures what is known and what is unknown or uncertain. It is updated as more information becomes available. Properly used, the CSM should drive the risk assessment and inform the remediation. The end point of land contamination risk management is a CSM showing that all contaminant linkages are demonstrably broken (Figures 3.8-6, 3.8-7 and 3.8-8)

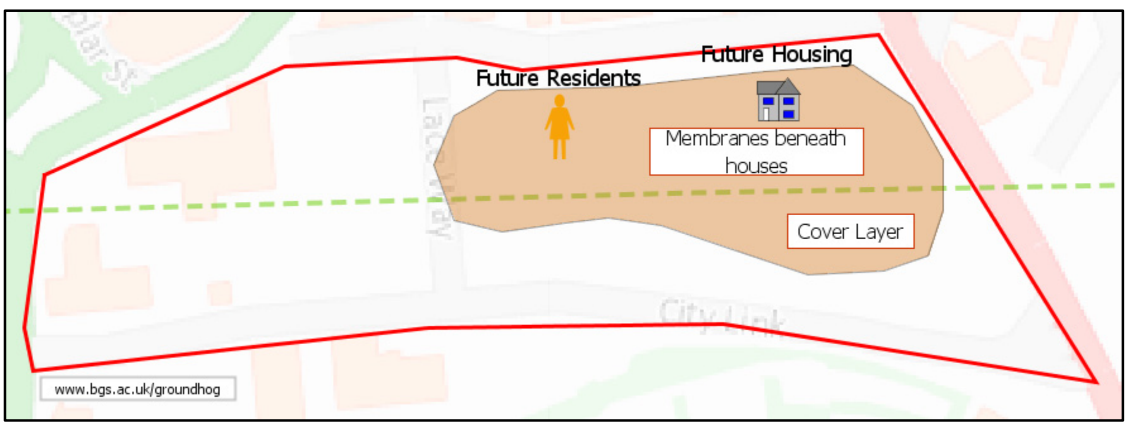

Figure 3.8-6 - Post remediation CSM – Plan View – remaining linkage broken by cover layer and membranes beneath houses. © Land Quality Management Ltd reproduced with permission.

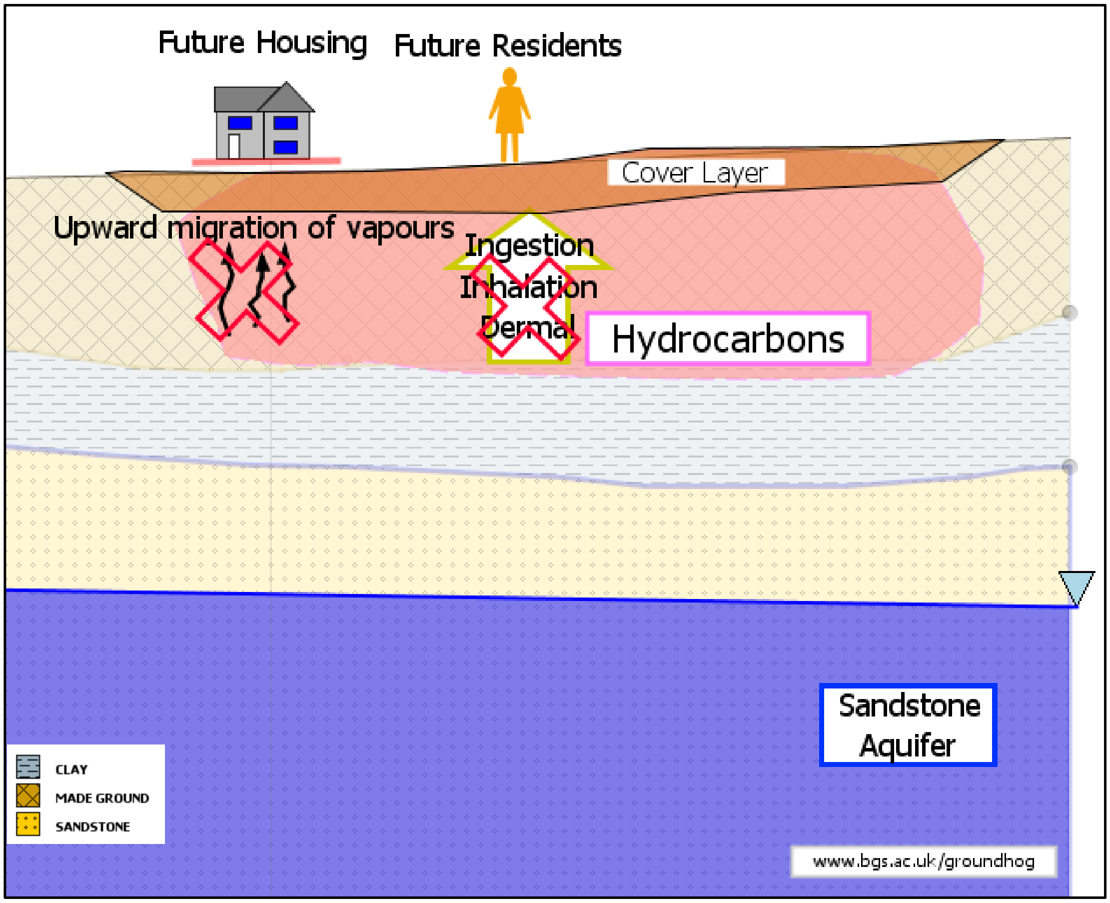

Figure 3.8-7 – Post remediation CSM – Cross Section – in this example remediation with a cover layer and membranes beneath the houses demonstrably breaks the remaining relevant contaminant linkages. © Land Quality Management Ltd reproduced with permission.

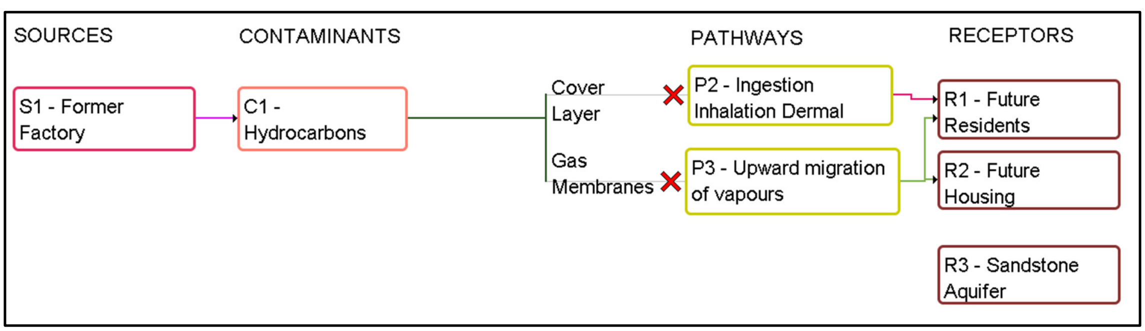

Figure 3.8-8 - Post remediation CSM – Network Diagram – in this example all remaining relevant contaminant linkages shown as broken, with reasons. (The site investigation and QRA demonstrated that P1 was not present at the Site). © Land Quality Management Ltd reproduced with permission.

3.9 EGMS FOR OFFSHORE STUDIES

David Waring

Introduction

EGMs in offshore areas have historically been driven by the exploration and extraction of hydrocarbons. More recently they are being driven by the energy transition and development of offshore renewables and their supporting infrastructure.

The development of engineering geological models offshore is challenging, given the fundamental difference with onshore sites, where you are usually able to 'see' the ground. This puts a greater emphasis on the data that will be collected through indirect techniques and a greater reliance on conceptualisation.

Offshore EGMs generally cover larger areas of interest compared to onshore sites. Given the implications for data gathering (discussed below), the distances between exploratory holes tends to be greater, therefore reliance on geophysical methods is more significant. This could be considered the opposite for an onshore site, however, there are always exceptions to the rule for both onshore and offshore sites. Examples of this are (i) onshore locations where you have clear and unrestricted access (for example, inland desert salt salina/playa), and (ii) offshore location for a single oil and gas facility. The reliance on geophysical techniques to develop the model is a distinguishing factor for Offshore EGMs.

Case Study

An example of how seismic data can be used to interpolate/extrapolate the geotechnical data is illustrated in Figure 3.9.-1. The figure shows a piezocone penetration test (131 & 132CPT1) pairing undertaken in two locations within the general vicinity of Site A and along with seismic data showing clear "layer-cake" stratigraphy to 60m BML.

Interpretation of the findings appears to show a stratigraphical sequence expansion between the two CPTs. However, there does not appear to be any significant difference in the CPT profiles, that have similar shear strength profiles increasing with depth. The stratigraphical sequence between 131 CPT1 and Site A appears consistent, indicating that the CPT data can be extrapolated to Site A without further deep geotechnical data being gathered.

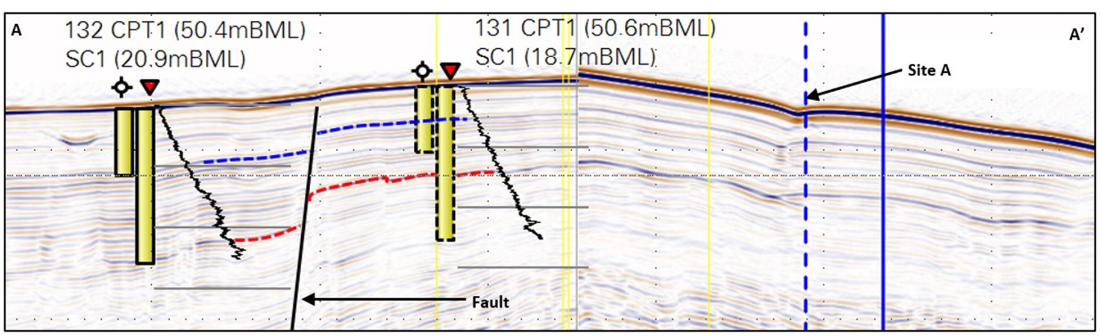

Figure 3.9-1 Simple offshore EGM utilising geotechnical boreholes and seismic data.

Ground Model Data Gathering

Offshore EGMs need to consider several factors that impact the collection of data, including:

- Variable water depths.
- Metocean conditions, such as waves, currents and winds.
- Scale and remoteness of the site.
- Access constraints.

The challenges listed above have a significant impact on cost and schedule and require consideration of the environment and health and safety.

A clear strategy is required before embarking on an expensive and time-consuming campaign. It is necessary to ensure that the approach is aligned to the project's needs and, therefore, fully optimised. An example of an optimised approach is provided in Figure 3.9-2

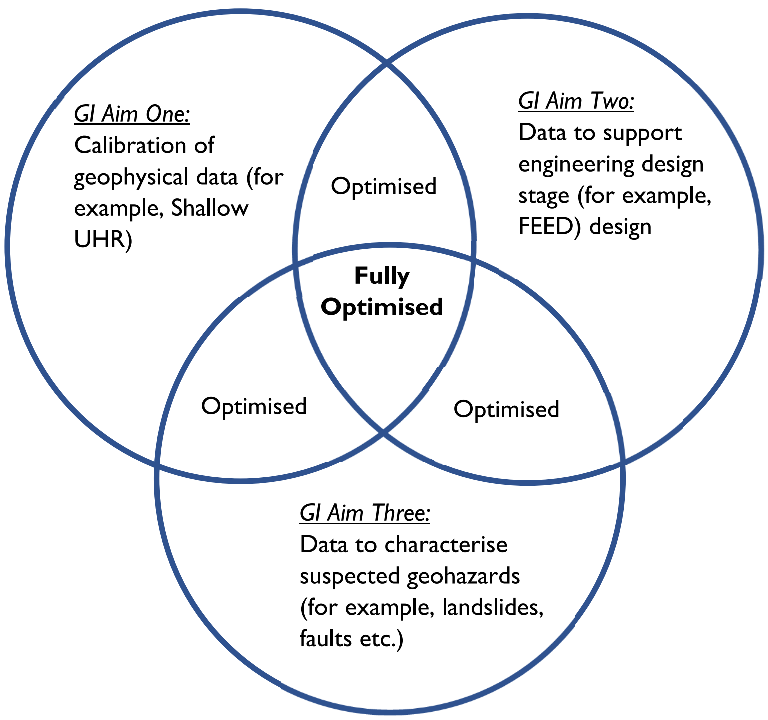

Figure 3.9-2 Aligning approach with Project needs.

Data gathering offshore typically requires a multi-disciplinary approach to understand the engineering complexities associated with morphology, geomorphology and geology. EGMs should consider:

- Seabed terrain (for example, ruggedness, mobility, and hardness).
- Active geomorphological processes.

- Geological history.
- Geohazards.
- Difficult and unusual soils (for example, glauconitic sands, carbonate muds).

Consideration is also required regarding effects that are not commonly associated with onshore EGMs such as (but not limited to) shallow gas, gas hydrates, salt structures, turbidity flows, and hydrocarbon seeps.

Data gathering to support the development of EGMs can be achieved through a variety of methods and can be influenced by the availability of survey vessels and equipment, cost, and technical requirements. The survey can typically be split into two phases: geophysical surveys and geotechnical investigation, with the later typically being used to calibrate geophysical data and to provide site specific understanding.

Deepwater geophysical surveys are typically undertaken utilising autonomous underwater vehicles (AUV) to enable the acquisition of multibeam echosounder (MBES) bathymetric data, sidescan sonar images and high frequency sub-bottom profiles (also known as chirp profiles). In shallow water, hull-mounted or towed geophysical sensors may be preferred because of AUV operational complications. Geophysical surveys may also be undertaken by towing an array behind a marine vessel from which the waves are propagated by use of an appropriate energy source. At a regional scale, 3D exploration seismic data (3DX) and 2D ultra high resolution seismic survey (UHR) data can be utilised; reprocessing of 3D exploration seismic data can enhance their utility for shallow subsurface interpretation and seafloor terrain analysis. Through these techniques, seabed imaging and shallow subsurface (c60m) data are gathered to support the development of the EGM.

Geotechnical investigations are typically designed to support the understanding of the shallow seabed deposits and/or the deeper geological deposits. Shallow investigations using a variety of tools (for example, box cores, gravity piston cores, piezocone penetration tests (PCPTs), vibrocores, grab samples) are undertaken to support geohazard evaluation, as well as input to the design of shallow foundations, pipelines etc. Boreholes are typically used for *in situ* testing, samples for logging and laboratory testing. There are a variety of systems available for this.

Depending on the proposed offshore development there are typically two approaches that can be taken:

a) geophysics is used to broadly characterise the wider site area, with the use of different intrusive techniques to complement that interpretation.

b) site specific intrusive techniques at locations where known individual foundations maybe required (for example, a wind farm project, utilising mono-piles for individual wind turbines).

Varying combinations of the two options are common, depending on the challenges outlined above, as well as the type of development being proposed.

EGM Development and Interpretation

The EGM is typically developed in a similar fashion to that of an EGM onshore. It will have a series of inputs that will include:

- Regional environmental and geological data
- Geophysical data
- Geotechnical data

Through the interpretation, calibration, and detailed mapping of those data the following staged outputs are typically developed/identified:

- Sea floor elevation.
- Geological processes.
- Seismic stratigraphy.
- Geohazard identification and assessment.
- Preliminary soil/rock provinces.

Typical final outputs that are required include:

- Terrain units (specific geological setting, with depositional history, with similar geological forms and processes).
- Geohazards (for example, presence of landslides and their influence on terrain units).
- Soil/rock provinces (linked closely to terrain units; areas of the seabed and subsurface that have broadly similar geotechnical characteristics and properties.
- Soil/rock units (soil/rock layers and strata within each soil/rock province).
- Presence of anthropogenic materials (wrecks, seafloor debris, UXO's etc.)
- Geotechnical parameters.

To enable the communication and sharing of the information the data are typically presented in idealised 3D block models, as well being incorporated into a GIS format. More recently, software packages more traditionally used to model complex geological situations for exploration purposes are now being used to develop 3D interactive geological models for use in engineering. An example of a work process diagram is presented in Figure 3.9-3.

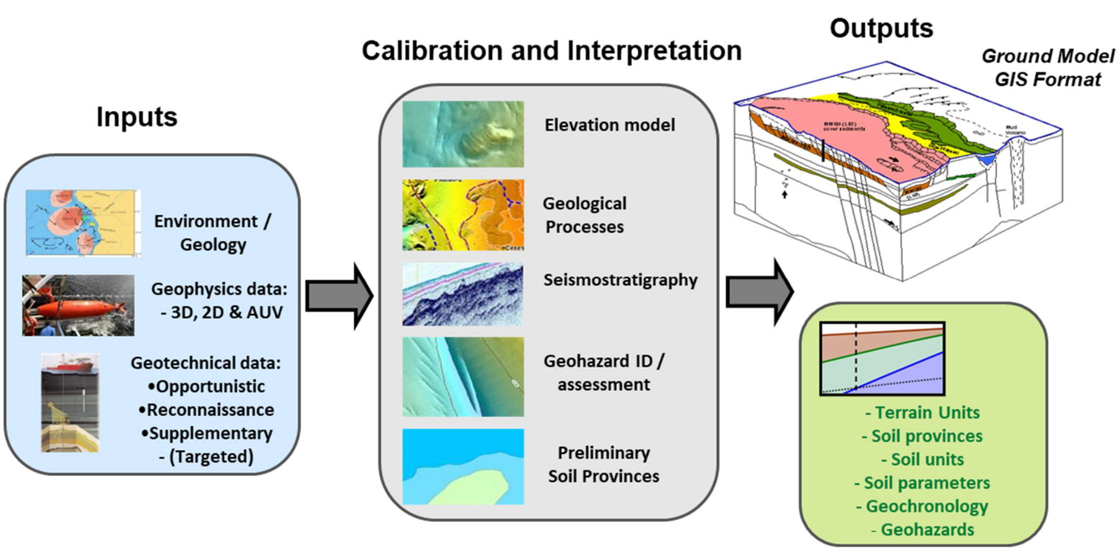

Figure 3.9-3 Work process diagram for EGM development in an offshore setting. © BP 2022

END OF GUIDELINES