Engineering Geological Models - an introduction: IAEG Commission 25

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Abstract

The generation and use of engineering geological models should be a fundamental activity for any geotechnical project. Such models are an essential tool for engineering quality control and provide a transparent way of identifying project-specific, critical engineering geological issues and parameters. Models should also form the basis for designing the scope, the method and assessing the effectiveness of site investigations. However, whilst the idea of models in engineering geology has existed for several decades, there has been little published that systematically distinguishes the different model types and how and when they might be used. This paper presents the views of IAEG Commission C25 on the 'Use of Engineering Geological Models'.

Introduction

The Commission of the International Association for Engineering Geology and the Environment (IAEG) working on the 'Use of Engineering Geological Models' (C25) was established as a result of wide-ranging discussions following the First

Hans Cloos Lecture (Knill 2003) at the 9th IAEG Congress in Durban, South Africa. Baynes & Rosenbaum (2004) noted that the primary focus of these discussions centered upon the "*use of models within engineering geology*", and in particular, posed the question: "*do practitioners need guidelines for the preparation of models and how should uncertainty be addressed within such models?*"

C25 was initiated to address some of the issues raised at the 9th IAEG Congress. However, the aim of C25 is not to provide a 'cook book' for generating engineering geological models. Rather, it is intended to present the philosophy behind the development and use of these models, suggest appropriate terminology to describe them and provide general guidance for their construction, primarily through the use of examples. This paper presents the Commission's conclusions on the different types of engineering geological model that can be used and their applicability at different stages of a project.

Models as hypotheses

The term *model* is used by scientists and engineers to describe things as varied as scaled physical replicas, drawings, governing equations and computer simulations. C25's working definition of the term model as used in engineering geology is simply:

A model is an approximation of reality created
for the purpose of solving a problem.

Thus an engineering geological model is any approximation of the geological conditions, at varying scales, created for the purpose of solving an engineering problem. As such, the model is a hypothesis that is tested, usually by some form of investigation. This problem solving approach commonly follows the classic scientific method, which McLelland (2006) noted *"…is not a recipe: it requires intelligence, imagination, and creativity. In this sense, it is not a mindless set of standards and procedures to follow, but is rather an ongoing cycle, constantly developing more useful, accurate and comprehensive models and methods. The scientific method is a form of critical thinking that will be subjected to review and* *independent duplication in order to reduce the degree of uncertainty. The scientific method may include some or all of the following "steps" in one form or another: observation, defining a question or problem, research (planning, evaluating current evidence), forming a hypothesis, prediction from the hypothesis (deductive reasoning), experimentation (testing the hypothesis), evaluation and analysis, peer review and evaluation, and publication."* This description sets the scene for C25's thinking.

Models in Engineering Geology

Morgenstern and Cruden (1977) provide one of the earliest discussions on the use of models in engineering geology. They considered that geotechnical complexity arises from three processes; genetic processes associated with the original formation of the geological material, epigenetic processes resulting from diagenesis and deformation, and weathering processes. They noted that these processes could be described by models with, for example, the distribution of materials being described by facies models and process models and that "*while a process model may not be correct in every detail it should explain the general assemblage of properties being investigated and assist the engineering geologist or geotechnical engineer to anticipate features that may not yet have been mapped*".

An early description of the development of specific engineering geological models by Stapledon (1982) involved outlining the approach as a flow diagram (Figure 1) and identifying the key point that the engineering geological model should be based on *"an understanding of the regional geology, geological history and detailed site geology described in… terms that are ….quantitative… related to engineering requirements …… (and) …… understood by both geologists and engineers".*

Importantly, in the context of this paper, Stapledon also indicated what he considered to be the type of training (engineering or geological) best suited to the different activities involved in the process, although he stated his preference for *"an engineer - geologist team approach",* a strategy that C25 enthusiastically endorses.

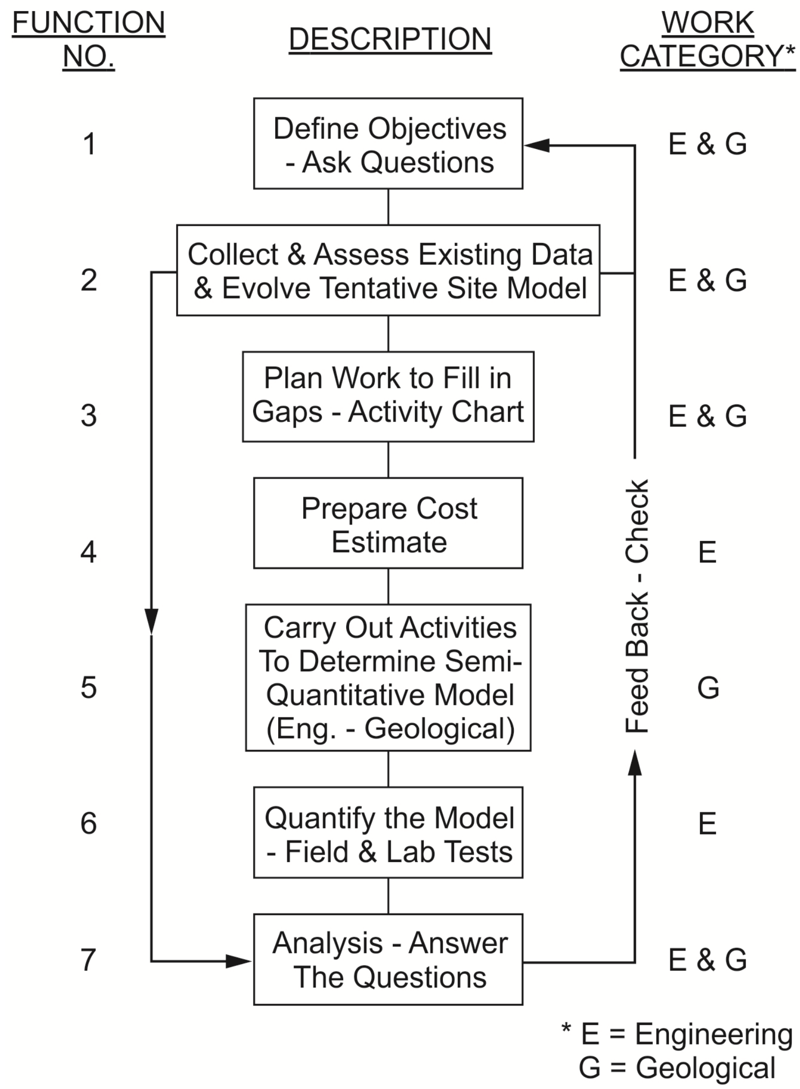


Figure 1: Activity flow and the use of models in site investigation redrawn from Stapledon (1982).

In his seminal paper on the subject, Fookes (1997) used the term "*geological models*". The models that he described were developed for use on engineering projects by practitioners of engineering geology. He defined engineering geology as being "*more than geology that is simply useful for civil engineers. It differs from geology for engineers in that its practitioners have training and experience in ground problems that arise in civil engineering and in the investigation, classification and performance of soils and rocks related to civil engineering situations; and a working knowledge of basic soil mechanics, rock mechanics and* *hydrogeology. Such practitioners provide engineering geology.*" Thus, although he used the term "geological models", the models he described include both a geological and an engineering content and clearly are a type of engineering geological model.

This idea that engineering geological models are more than just geological models was articulated by Knill (2003) when he stated that "*the geological model is inadequate, on its own, for engineering purposes because it does not sufficiently define the engineering conditions within the natural ground or deliver a design. It needs therefore, to be converted into a ground model in which is embedded the engineering parameters required for subsequent engineering analysis.*" The implication being that geological models *sensu stricto* do not have an engineering content.

Knill (2003) differentiated three forms of model within the broader field of knowledge of geotechnical engineering (which C25 takes to cover engineering geology, soil mechanics, rock mechanics, and hydrogeology) namely:

- Geological models which are largely based on geological knowledge;
- Ground models which contain geological knowledge and embedded engineering parameters;
- Geotechnical models which support a mathematical or physical analysis.

Sullivan (2010) used the term *"The Geological Model"*, but made the same point and considered that a "*narrow geologically based approach has a significant chance of generating problems with the models that are developed, because it is difficult to see how all the important information can be captured unless there is a thorough understanding of all the geotechnical implications of the data and the observations from the start of the model process*". With reference to the use of models in engineering geology, Sullivan (2010) noted that the subject is not well covered in the literature, is rarely taught in universities and that a paucity of information exists about models, what they should depict or contain and how they should be prepared. Sullivan went on to say that the generation and use of models should be a fundamental component of any geotechnical project. They form the basis for determining the scope, methodology and effectiveness of the site investigation. They are also an essential tool for quality control, providing a transparent methodology for identifying and documenting project-specific, critical engineering geological parameters.

Model Types and Terminology

Typically, engineering projects develop in stages from pre-feasibility to feasibility, various stages of design, construction and through to operation. With each stage of the project more data become available. Consequently, a range of engineering geological models are required during the life of a project.

A variety of terms have been applied when discussing the use of models in engineering geology and, in the past, there have also been attempts to relate the model type to the project stages. For example, using Knill's (2003) terminology, some practitioners consider that geological models are generated at the initial desk study stage, whereas a ground model is generated following a site investigation and laboratory testing, finally some form of geotechnical (analytical) modelling is undertaken.

However, C25 considers that there are two fundamentally different methodologies for developing engineering geological models that are independent of the project stage. This distinction was drawn by Baynes *et al*. (2005) who differentiated two types of engineering geological model - conceptual, and observational. The different methodologies used for the generation of these model types are:

a) *The conceptual approach*, which is based on understanding the relationships between engineering geological units, their likely geometry, and anticipated distribution. This approach, and the models formed, are based on concepts formulated from knowledge and experience and are not related to real three-dimensional (3D) space or time. For example, a *conceptual* model is presented in Figure 2 for a project that involves loading the ground in an area where recent sediments are known to overlie granite. The conceptual model has been built up by looking at geological maps, reading relevant geological memoirs, incorporating local geological knowledge and adding general geological knowledge and experience of what might be anticipated in these circumstances. Importantly, the model is largely based on consideration of *geological concepts* such as age, stratigraphy, rock type, unconformity and weathering.

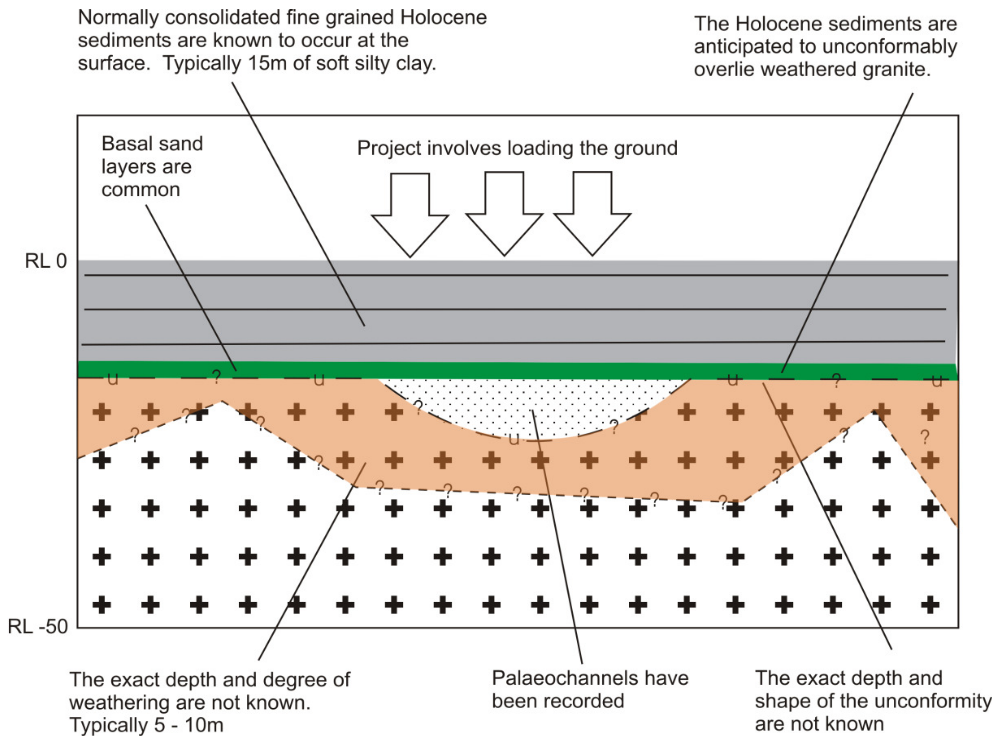


Figure 2: Conceptual engineering geological model for an area where sediments overlie granite

b) *The observational approach,* which is based on the observed and measured distribution of engineering geological units and processes. These data are related to actual space or time and are constrained by surface or sub-surface observations. For example, the site investigation for the project shown in Figure 2 comprised mapping and three boreholes. The results of that investigation are illustrated in an *observational model* presented in Figure 3 which is based on observations which constrain the distribution of the geological units. The geological concepts have not changed markedly however the distribution of the geological units is now known reasonably well and the specific engineering implications of those observations can now be considered. Note that like all models, further refinement may be necessary if the engineering questions have not been satisfactorily answered. For example, further investigations into the depth to fresh rock may be required, as BH3 is not sufficiently deep.

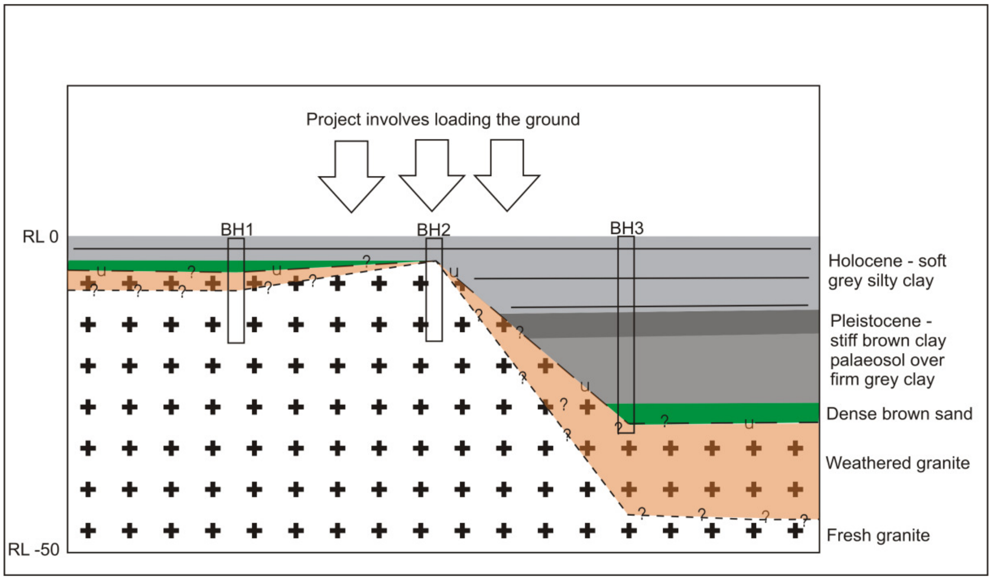


Figure 3: Initial observational model for the project in Figure 2 based on mapping and boreholes.

Whilst the engineering specifications and performance of the project must be known to the engineering geologist for the development of a model, C25 also believes that, regardless of the model type, it is absolutely essential that geological concepts must be the starting point for building models. Given that the conceptual model can be developed without site specific information they should be the first type of model produced. Figure 4 illustrates what C25 considers should be a mandatory process for engineering geological model building; the process must start by understanding the geology, before any attempts are made at geotechnical characterization.

As illustrated in Figure 4, it is clear that the accuracy and completeness of observational models depends on the accuracy and completeness of the associated conceptual models; similarly, analytical models depend on the observational models. If the conceptual model is wrong, then any subsequent observational models and the analytical models are likely to contain errors or even be incorrect. Importantly, especially for those responsible for engineering design, it is most unlikely that any analytical modelling will be correct if the geology is not understood.

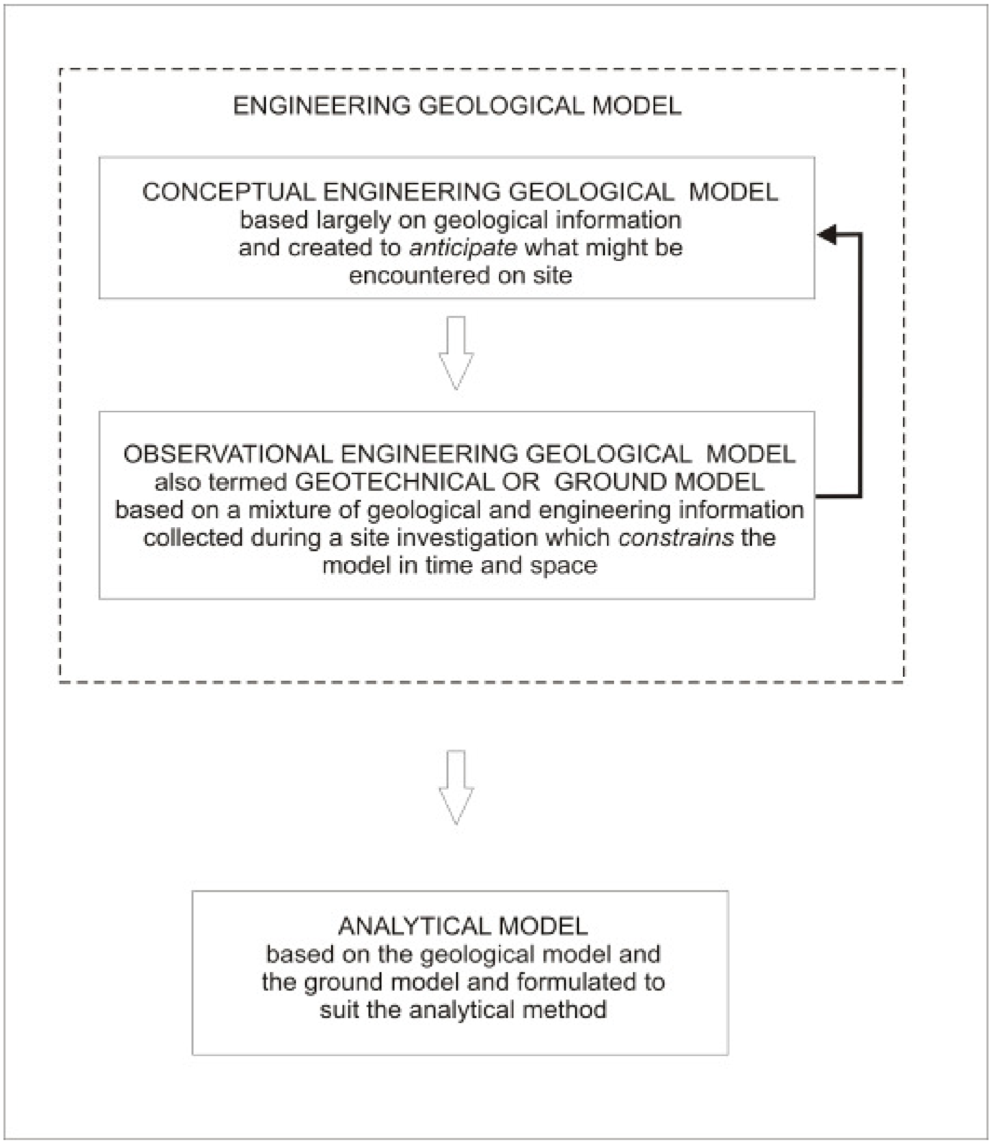


Figure 4: Mandatory process for developing engineering geological models.

C25 therefore considers that engineering geological models encompass both "geological models" and "geotechnical models", they involve understanding geological concepts as well as defined geotechnical data and engineering requirements and there is an overlap between geologist's responsibilities and engineer's responsibilities – hence the term engineering geological models which has been adopted in this paper.

In summary, an engineering geological model is any approximation of the geological conditions created for the purpose of solving an engineering problem and includes models which are based mainly on geological characteristics as well as models which are based mainly on engineering characteristics. In reality, the development of any particular engineering geological model will involve a range of techniques so a specific and restrictive distinction is neither possible nor useful.

Any analytical models must be developed from good engineering geological models and, clearly, are dominated by engineering considerations and analysis but engineering geological input is essential for guiding and supporting the ground-based engineering activities. Similarly, the engineering project parameters must be understood and factored into the engineering geological model so that the relevant geological information is evaluated. For example, very different geological details would be incorporated into the engineering geological models developed to support a rail project in mountainous terrain involving tunnels with underground stations, as opposed to above-ground tracks with bridges and surface excavations.

The Importance of Engineering Knowledge

Provided the engineering objectives of a project are understood, it is possible through the use of models to assess the impact of the project on the ground, as well as the impact of the ground on the project, both during construction and over the life time of the project. However, for exactly the same geological setting, different engineering projects will require different questions to be asked, different models to be developed and different types of investigations to be carried out, because of the varying interaction and demands of specific engineering works and the ground. Furthermore, depending on the project, certain ground characteristics may be more critical than others and some projects, by their very nature or setting, will be exposed to more geotechnical risk. This is illustrated schematically in Figure 5 which shows the same geological setting for three different types of projects, a building, a road bridge and a tunnel.

The geological setting is a broad valley and floodplain which is underlain by a buried palaeo-channel. The floodplain also contains abandoned river channels, infilled with organic-rich soils, both at the surface and at depth. The palaeo-channel is associated with a vertical fault and there is a variable depth to rock.

There is no evidence of movement on the fault having occurred during the last 2 million years.

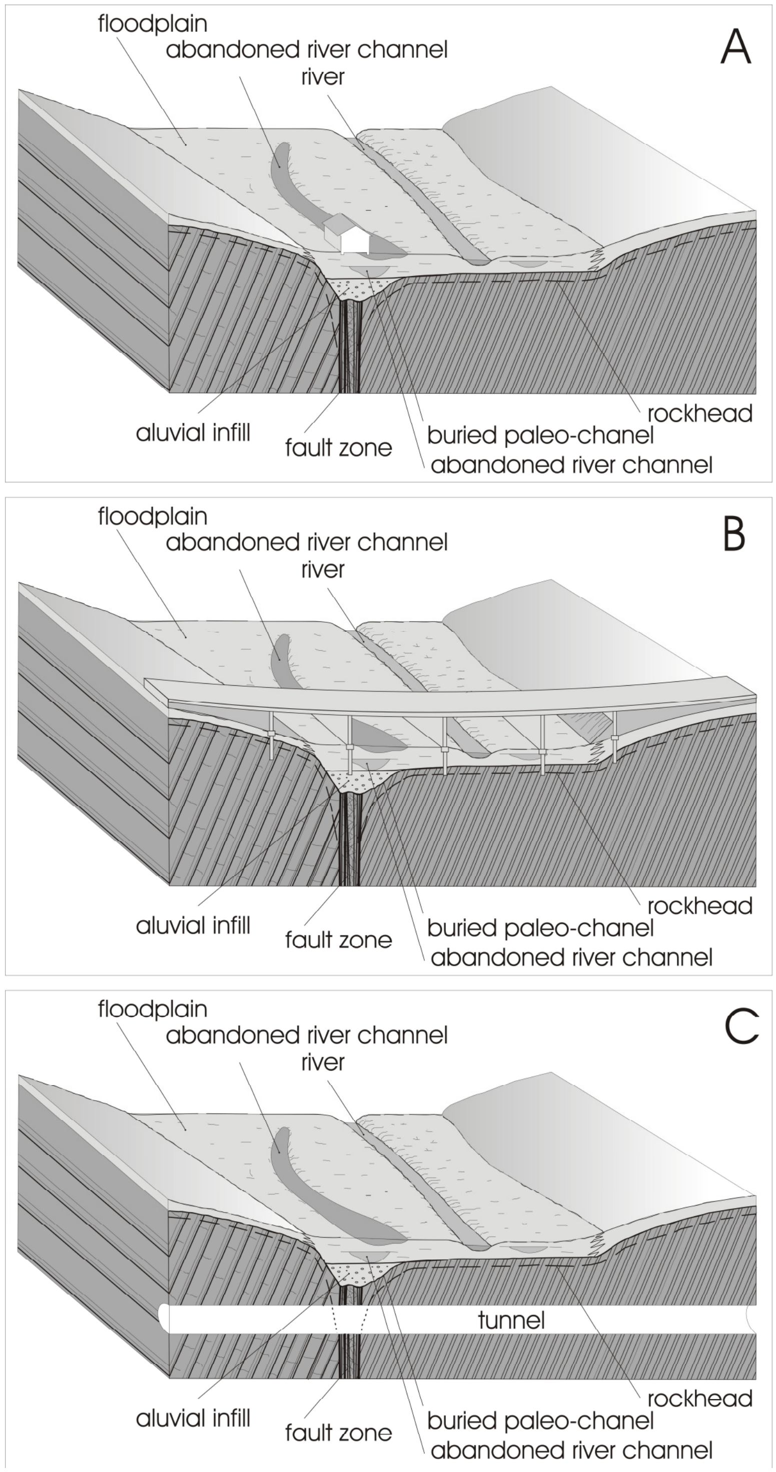


Figure 5: The influence of project type on the engineering geological considerations. Refer to text for discussion.

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.

Based on the conceptual approach, the following general ground characteristics could be anticipated:

- Material Properties: Two types of high strength bedrock, moderate-strength sheared rock in fault zone, moderate-strength weathered bedrock, permeable gravel (palaeo-channel infill), low strength clay (floodplain), compressible, organic-rich soils (infilled channels).

- Mass Properties: Two types of jointed bedrock, major fault through bedrock.

- Environmental Processes: Chemical and mechanical weathering of bedrock (variable depth to rock), flooding, erosion, deposition and channel realignment associated with fluvial processes, groundwater flow generally parallel to ground surface.

- Geological Hazards: Natural consolidation and subsidence of organic-rich soils, acid sulphate soils, methane and carbon dioxide generation.

Based on a conceptual model an assessment may be made of how the ground might respond to the changes imparted by the project or how the ground might influence the project.

The building (Figure 5a) is unlikely to be affected by the palaeo-channel due to the channel's position at a depth greater than the influence of stresses created by the building foundations; although, if the palaeo-channel were to be dewatered by a separate project, associated settlement could affect the building performance. The organic-rich, high-plasticity clay infilling the abandoned floodplain channels could present the hazard of differential settlement to the building because of its low strength and modulus (stiffness). Geo-environmental hazards, such as methane and carbon dioxide production and migration, may also be problematic. The building is also exposed to the hazard of flooding.

The road bridge (Figure 5b) will be supported on end-bearing piles that may be affected by negative skin friction from secondary compression associated with settlement of the organic materials in the abandoned river channels. The presence of the fault and the palaeo-channels could result in variable pile depths. Flooding associated with the discharges up to the design flood will have a lesser effect on the bridge but would be a potential hazard during construction and scour is a potential hazard during operation.

The tunnel (Figure 5c) will encounter two types of bedrock and the fault zone. The fault zone will have different support requirements for the tunnel and could result in high groundwater inflows from the palaeo-channel with associated settlement at surface. Face collapse and groundwater inundation, potentially contaminated with methane and carbon dioxide are potential hazards.

This example illustrates how the engineering geologist is ideally placed to identify and evaluate the ground characteristics that are potentially significant to the engineering project, assess their likely variations and their potential impact on the project. As such, the role of the engineering geologist should include that of being risk identifiers or “risk managers” (Knill, 2003), through the use of models. Consequently, a fundamental objective of the engineering geological model should be to evaluate and, where necessary, investigate the potential 'unknowns', that is, ground conditions that consideration of the model suggests could be present and which could potentially affect the project, but which have not been specifically observed. By identifying potentially critical conditions, these can be factored into the site investigation and design, for example, through additional targeted ground investigation or by contingency planning. Ultimately the understanding of the project embodied in the engineering geological model becomes an understanding of the *site conditions that an experienced contractor could reasonably have foreseen*, with all of the contractual overtones associated with these words.

The Conceptual Engineering Geological Approach

The conceptual engineering geological approach and the resulting models typically provide input to the earliest stages of a project. The conceptual model is critical in assessing the potential engineering geological variability that may be present at a geographical location and, when combined with the specific engineering requirements of the project, has the potential to identify elements that can result in hazard to that project, i.e. it is site and project specific. Fookes & Shilston (2001) observed that "*models are not always easy or straightforward to create. This is particularly so at the desk study and field reconnaissance phase of the site investigation. However it is during these early phases that a model (or models) can be particularly useful by helping to set out what is known, what is conjectured and where significant gaps in knowledge may lie.*" Consequently, a fundamental purpose of the conceptual model is to identify what credible engineering geological unknowns may be present, so that these unknowns may be targeted for investigation and, if found to be present, to assess their potential for hazard to the project.

The conceptual approach is typically based on an evaluation of existing data such as geological maps and memoirs, topographical maps, remotely-sensed images and other published and available information. However, a comprehensive desk study, in itself, does not form a model, it also requires wide ranging geological and engineering knowledge and experience to evaluate and synthesize the data and formulate relevant and appropriate conceptual engineering geological models. A fundamental strategy in the conceptual engineering geology approach is to attempt to understand the 'total geological history' of the site because "*the ground conditions at any site are a product of its total geological and geomorphological history which includes stratigraphy, the structure, the former and current geomorphological processes and the past and present climatic conditions. The total geological history is responsible for the mass and material characteristics of the ground. To help understand the total geological history, the development of a site specific geological model is required based on the consideration of the regional and local geological and geomorphological history and the current ground surface conditions.*" (Fookes *et al*. 2000). This strategy involves the systematic evaluation of the inputs to the conceptual engineering geological model and might typically include:

- Identification of the major geological units present, their interrelationships and where and how the engineering geological properties of each geological unit might vary due to geological features or processes, either observed or inferred.
- Identification of current and past stress regimes, and how these relate these to local geological structures and ground conditions.
- Evaluation of the past, current and future climatic and other environmental conditions and associated processes, and assessment as to how these may affect the ground, i.e., engineering geomorphological considerations.
- Identification of geological hazards that might affect the area, such as landslides or earthquakes, and a forecast of their severity.

The resulting conceptual models can be broadly sub-divided into two types:

1. *Conceptual models that deal with relationships in space*; these are extrapolated from existing knowledge of geological environments and processes. The most comprehensive examples of such models are provided by Fookes (1997) and Fookes *et al* (2000) and Figure 6 is an exquisitely detailed, hand drawn example of such a model that is obviously the work of Geoff Pettifer.

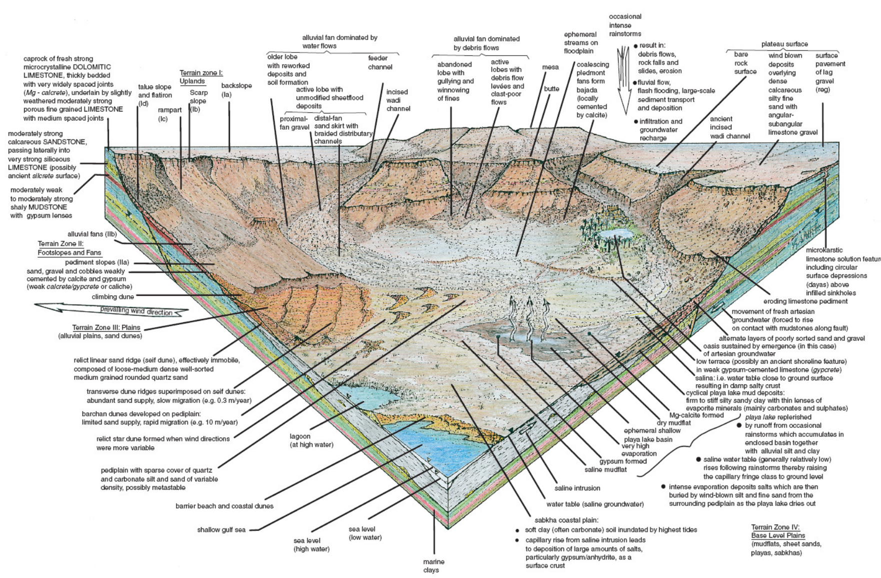


Figure 6: Conceptual Model of hot dry climate, from Fookes et al (2007) reproduced with the permission of the authors.

A simpler example of a conceptual model showing relationships in space is presented in Figure 7. An important advantage of these models is the ease with which they can be used to communicate the geological conditions to engineers who may have little or no knowledge or understanding of geology but have to make critical decisions that are driven by geological factors – the saying “a picture is worth a thousand words” is particularly relevant to judging the usefulness of these kinds of conceptual engineering geological models.

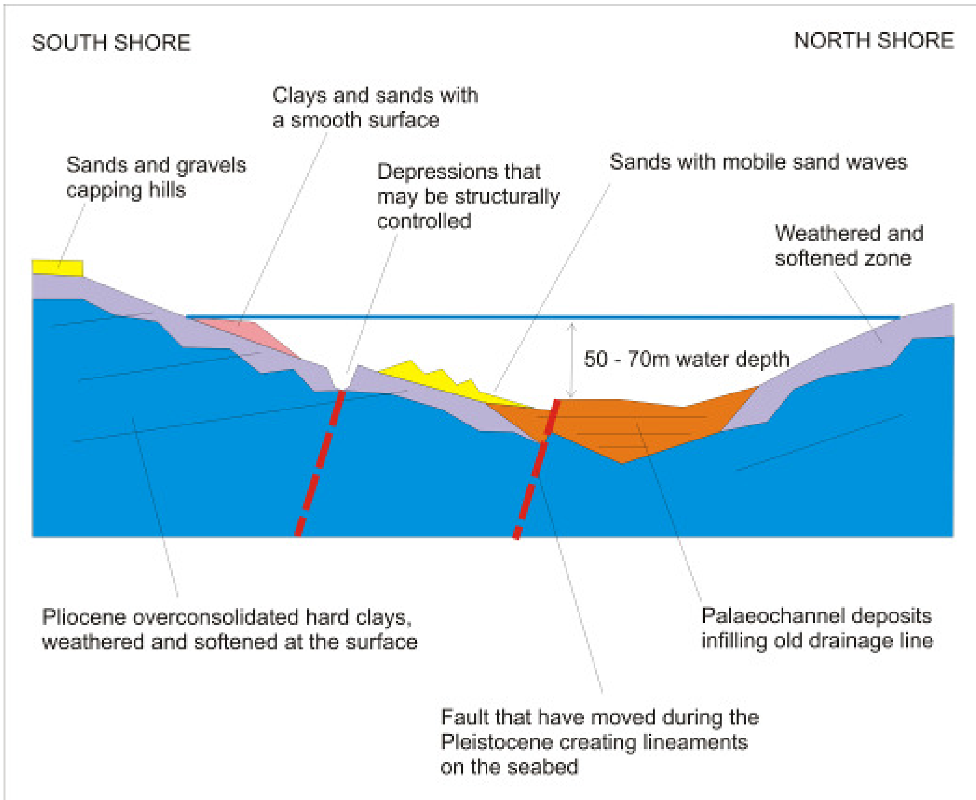


Figure 7: Simple conceptual model used to explore and communicate the range of offshore foundation conditions and geohazards that could be anticipated within a project development area.

A conceptual model portraying schematic fault traces in an idealized stratigraphy is shown in Figure 8. This sketch was used to communicate the geometry of fault traces to engineers and other non-geologists after considerable site characterization studies had been carried out; hence, it is not a pre-investigation conceptual model, but one that was developed after the construction of various observational models.

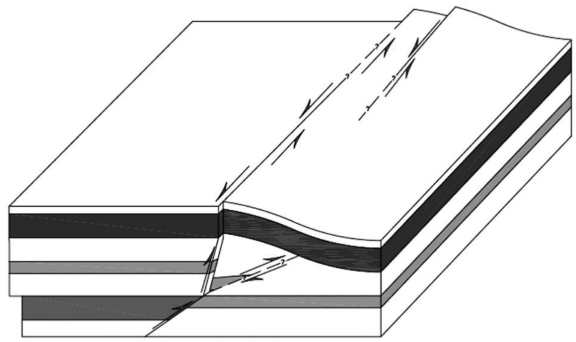


Figure 8: A conceptual model of faulted sedimentary strata used to convey conceptual fault geometry information to non-geologists for an unspecified project in a seismically active area.

2. *Conceptual models that deal with relationships in time*; these illustrate the geological evolution of a site or particular geological conditions or processes which are relevant to the project. Figure 9 is an example of a conceptual engineering geological model used in the investigation, design and construction of a major railway in Western Australia (Baynes *et al.*, 2005).

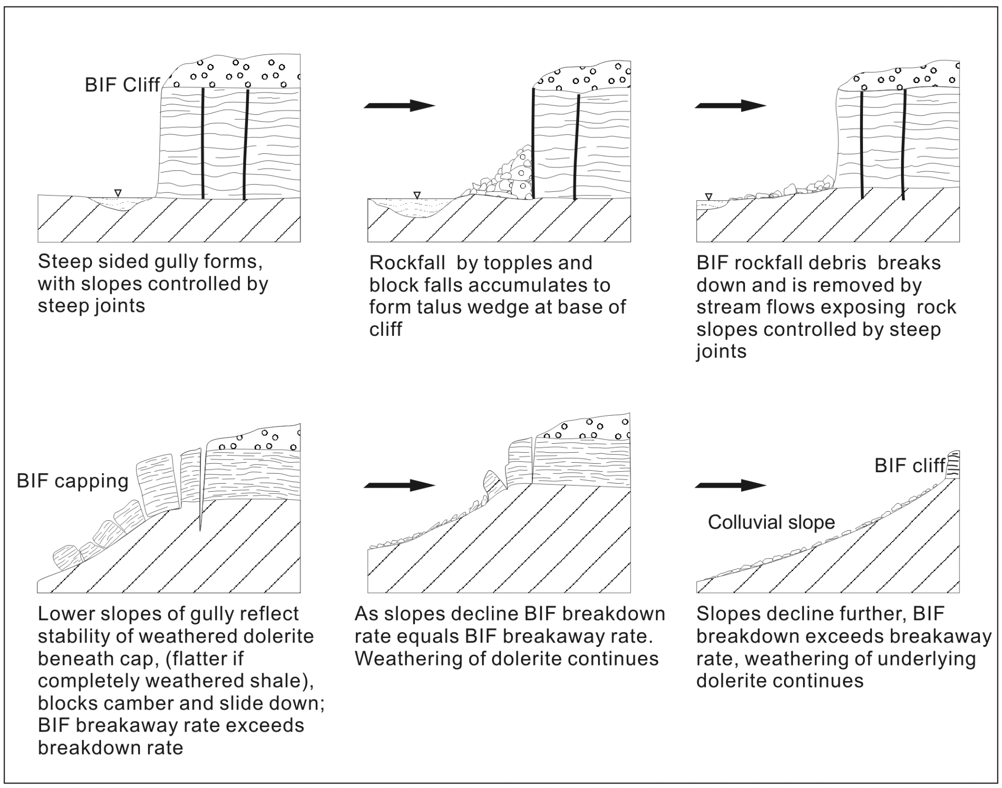


Figure 9: Example of a conceptual model that shows how slopes formed entirely from rocky cliffs and soil slopes capped by small cliffs might develop with time and the conditions that might be anticipated beneath the surface of the different slopes, from Baynes et al. (2005) reproduced with the permission of the authors.

Figure 10 is a conceptual model that presents a relationship that exists mainly within a temporal framework. The model depicts the generic relationship between landslide frequency, magnitude and process rate. When the model is quantified for a specific site, which can only ever be an approximation of reality, it can be used to solve the problem of assessing the magnitude of the landslide risks at the site.

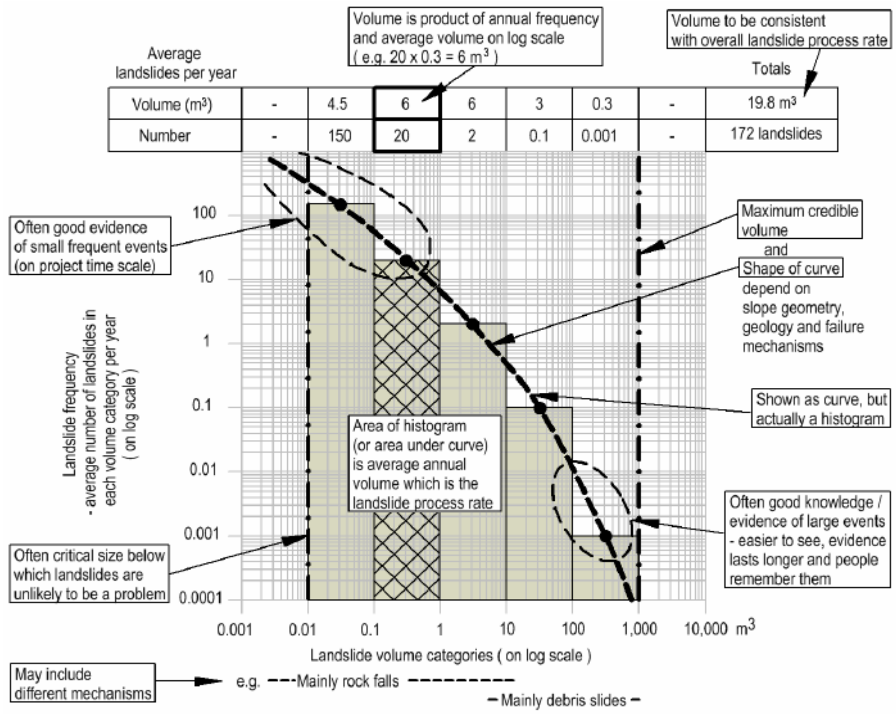


Figure 10: A generic landslide magnitude frequency model, from Moon et al. (2005) reproduced with the permission of the authors.

By its very definition, the conceptual approach and resulting models are associated with considerable uncertainty. The uncertainty is rather abstract in that it relates to whether or not the set of concepts that have been identified as being relevant are the most reasonable set of concepts, which is inherently difficult to judge. However, the power of the approach is that when a good conceptual engineering geological model is developed, it should be capable of anticipating most of the engineering geological issues that could potentially affect the project.

The Observational Engineering Geological Approach

The observational engineering geological approach and the resulting models are usually based on observations and data from project-specific ground investigations. These ground investigations should be designed using conceptual models and, in particular, should seek to verify the basic components of the conceptual models and target the uncertainties identified by them. Observational models may be developed directly from conceptual models or they may be developed following the acquisition of new, site specific, observations. An observational model is usually constrained by observations and/or measurements, even though some observations and measurements themselves are interpretations of incomplete information or remotely sensed data, such as geophysical measurements. These observations usually can be constrained in space by actual position (x,y,z) data; occasionally the model is constrained in time by a record of observations made at certain times or by radiometric dates that demonstrate a history of relevant events, for example, fault displacements or successive tsunami-generated deposits.

The generation of an observational model generally comprises two-stage process (Figure 11)

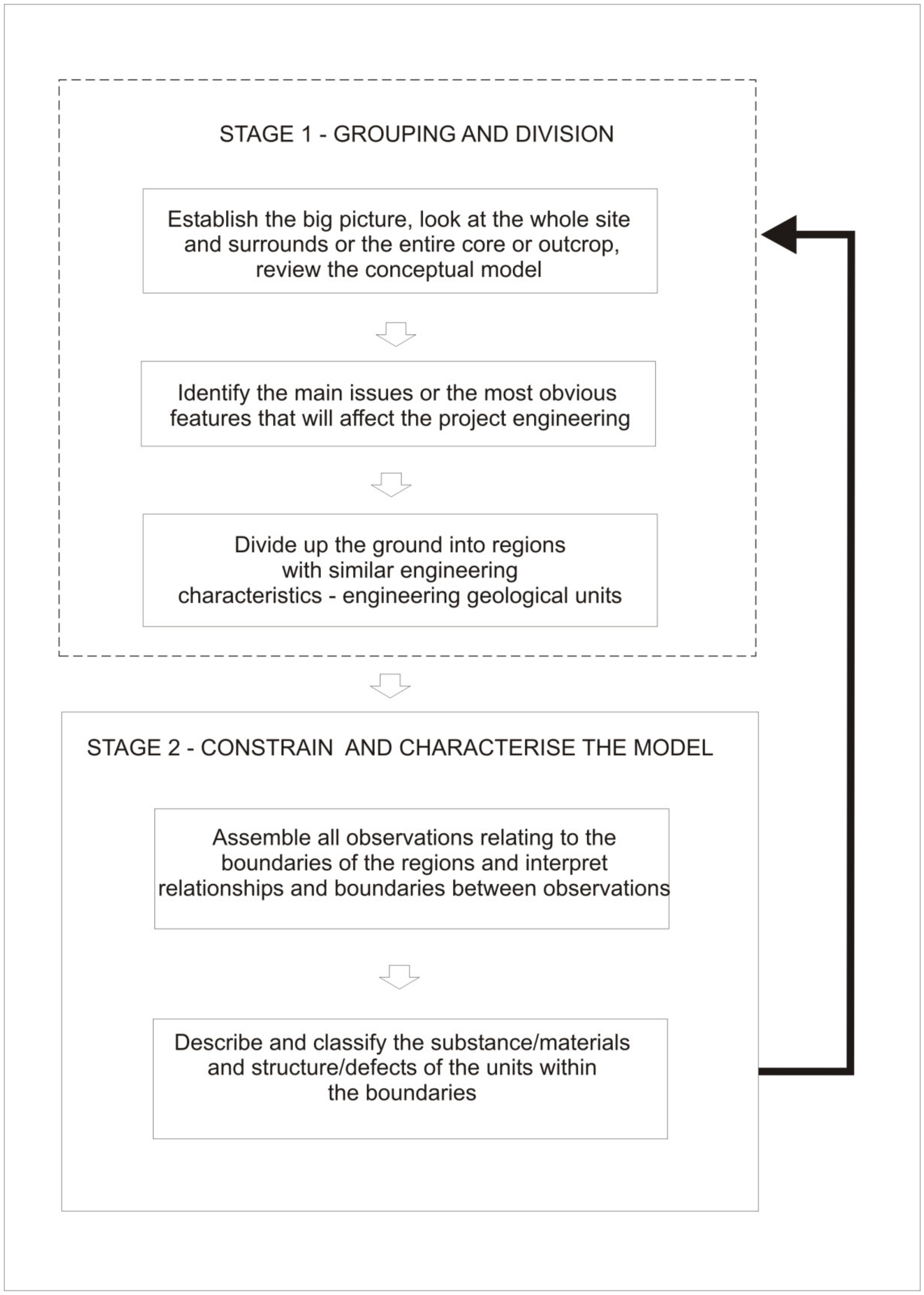


Figure 11: The process involved in the Observational Model Approach

Stage 1 involves defining the most important engineering geological units and identifying the relevant geological processes for the project, as such it uses the conceptual approach. The engineering geological units should be grouped into classes with similar characteristics. Data relating to the site must be processed by "grouping" and/or "division" into meaningful classes (Varnes, 1974). It is these grouping/division functions that must be carried out effectively for the observational model to be useful. If the engineering geological units that are defined (i.e. the conceptual model) are inappropriate or illogical then the resultant model will be incorrect or problematic, resulting in increased, rather than decreased, uncertainty.

Stage 2 involves analyzing observations and measured data, interpreting the distribution of the defined engineering geological units in three dimensions, establishing process rates, and constraining the model in space or time with real data.

This approach is applicable to engineering geological tasks that range from core logging to regional mapping. Consequently, the resulting observational engineering geological models can take a wide variety of forms: graphical borehole logs (one dimensional), engineering geological cross sections and maps (two dimensional) and spatial engineering geological models (three dimensional). These models can be generated as solid models (for example, Turner & Dearman 1980), on paper, or, increasingly, as three dimensional digital models (for example, Culshaw 2005).

Figure 12 illustrates some of the “architecture” that a 3D observational model based on a large data set might contain. Such models are highly visual and allow the illustration of relatively complex engineering geological data to none specialists. However, as noted by Kessler et al. (2009), the processes that form geological units and their resulting distribution cannot currently be simulated accurately by computers. Hence the results of these processes can only be captured and expressed by the construction of geological boundaries by experienced geologists, in particular where data is sparse or of poor quality.

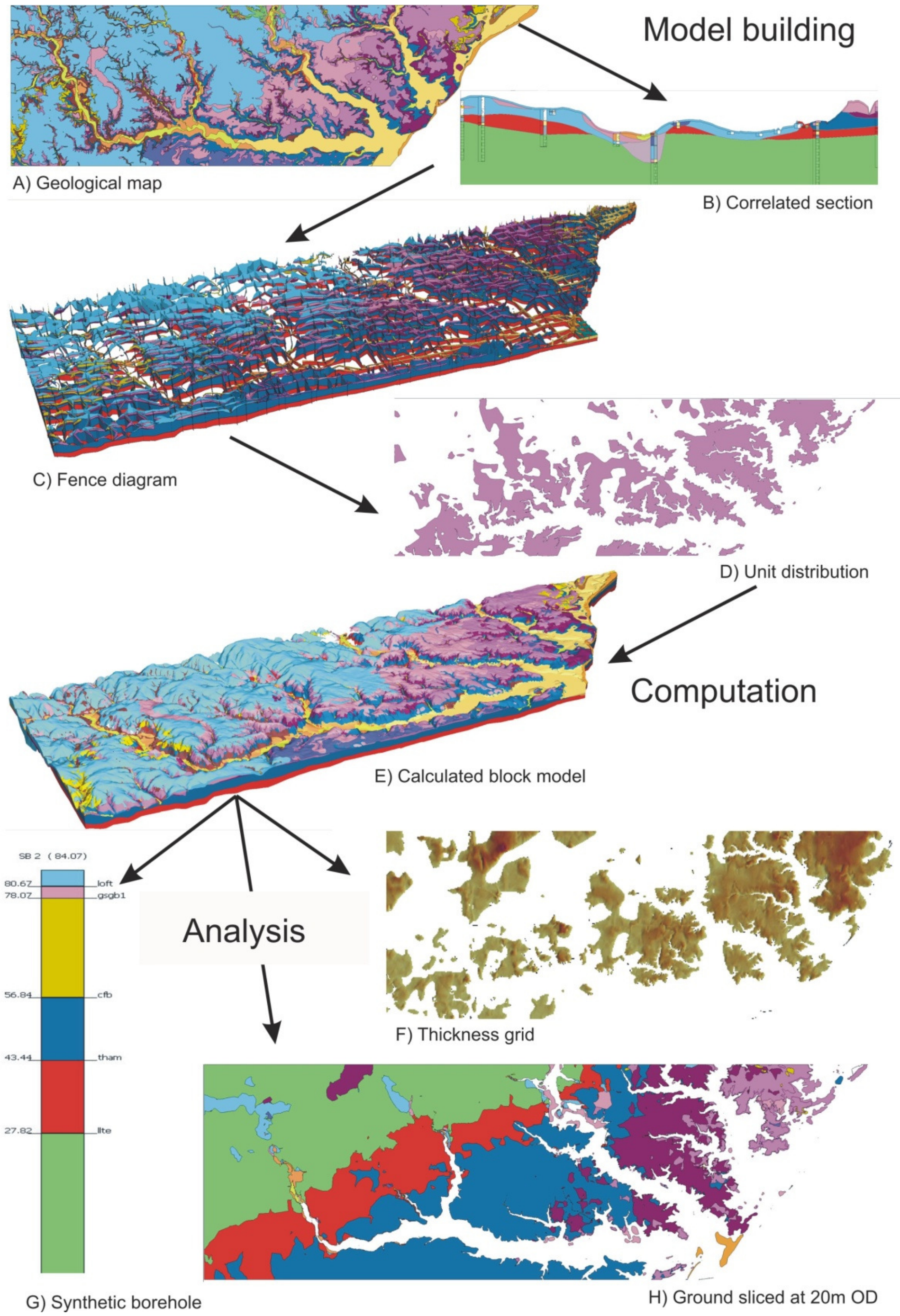


Figure 12: Varying techniques in the display of data extracted from a 3D observational model, from Kessler et al., (2009) reproduced with the permission of the authors

Figure 13 illustrates this approach for a tunnelling project. Unlike some other modelling software, the one that is used in this example is based on the manual construction (so called "wire framing") by a geologist of cross sections that link together borehole records placed in their correct relative locations, i.e. it is a geological interpretation not a mathematical interpolation (Aldiss et al., 2012).

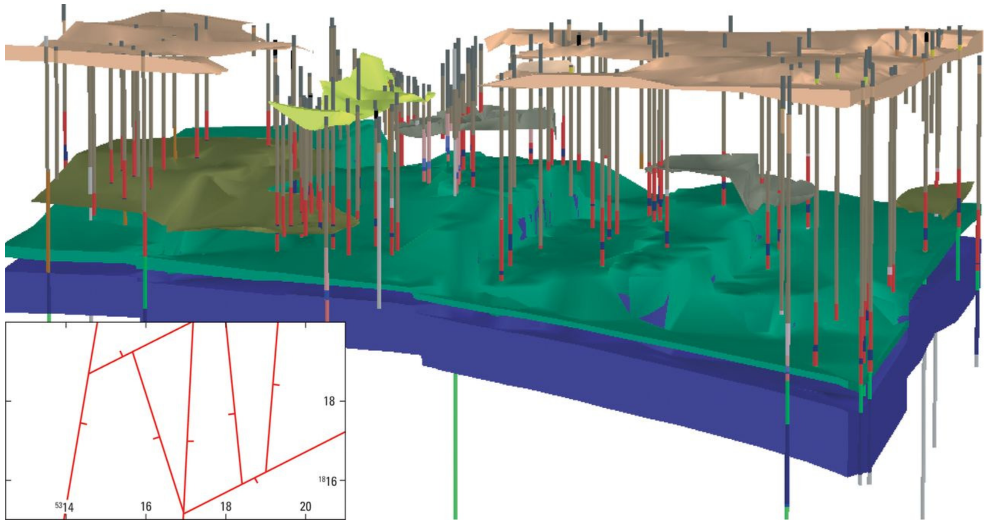
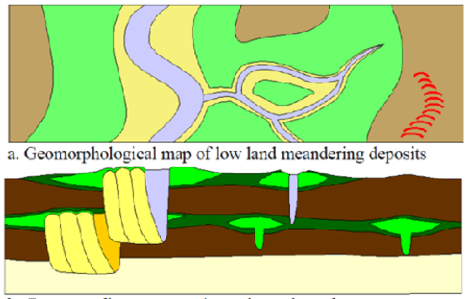


Figure 13: – Visualization of an observational model constructed from a large borehole data set with “exploded” wire framed surfaces. Inset is a plan showing faults within the model, from Aldiss et al., (2012) reproduced with the permission of the authors.

It is important to note that the geological interpretation required to construct an observational model should be based upon the knowledge encapsulated in the conceptual model. Whilst observational data, such as boundaries in boreholes, are constrained in x,y,z space, the conceptual model is used to establish the relationships that support interpretation of geological surfaces between such points. Furthermore, the interpretation of the observation data themselves is based on a conceptual approach to differentiate the significance of each specific piece of observational data.

Figures 14a and 14b illustrate the evolution from a conceptual model to an observational model (cross section) for a motorway investigation in the Netherlands (Munsterman *et al.* 2008). Figure 14a shows a conceptual model comprising geomorphological terrain units and corresponding illustrative geological cross sections for a meandering river system. Based on this conceptual model and a LiDAR dataset, a ground investigation strategy was developed and the ground investigation undertaken using a combination of cone penetrometer testing (CPT), drillholes and geophysics. The ground investigation data together with the conceptual model were then used to develop the observational model focusing on the 3D configuration of geological units expressed with engineering geological parameters relevant to highway design.



a. Geomorphological map of low land meandering deposits

b. Corresponding cross section at lower boundary

Legend of geomorphological map (a)

Terrain units	
	Stream belt, natural levees
	Overbank deposits
	Flood plain
	Inversion ridge, buried channel

Members		Types
Echteld Formation (Ec) – lithofacies units		
	Channel belt (FG/FZ)	Gravel, coarse sand, fining up-ward, cross stratification, lag deposit
	Natural levee, crevasse (FL)	Fine to medium sand, silty sand, sandy silt, laminated
	Flood plain clays (FKMA)	Clay, sandy clay, organic clay, massive
	Residual channel (FKLA)	Clay, sandy clay, organic clay, laminated, thin sand and peat layers
Nieuwkoop Formation (Ni) – lithofacies units		
	Peat (OVEU/OVME)	Peat, clayey peat, eutrophic to mesotrophic
Kreftenheye Formation (Kr) – lithofacies units		
	Fluvial sands	Medium to coarse sand, silty and sandy clay

Figure 14a: Conceptual engineering geological model for meandering river systems in the Netherlands, from Munsterman *et al*. (2008) reproduced with the permission of the authors.

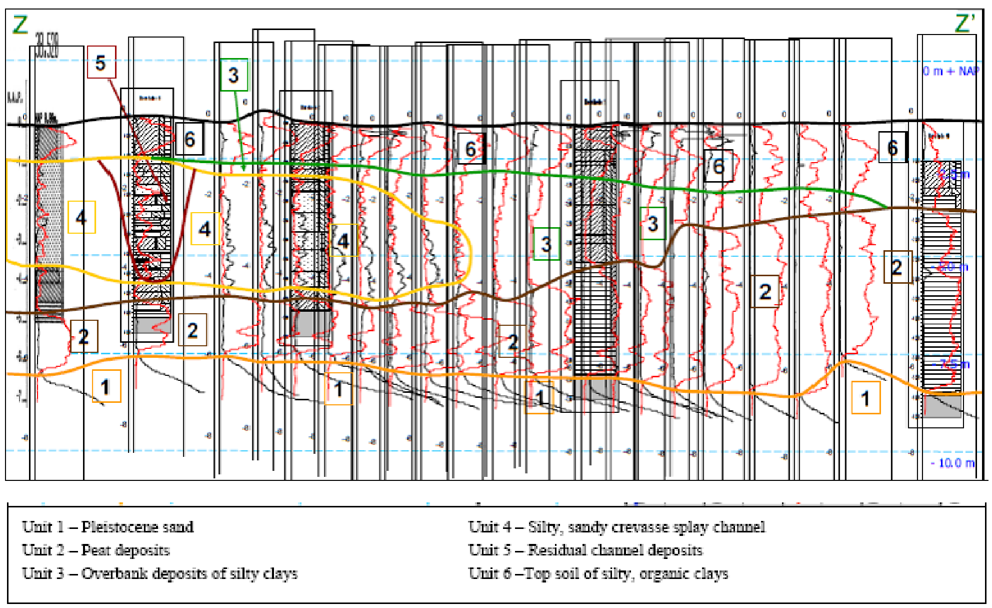


Figure 14b: An example of an observational engineering geological model for a site developed on the basis of both the conceptual model shown in Figure 13a and ground investigation information, from Munsterman *et al*. (2008) reproduced with the permission of the authors.

Observational models are not restricted to soils and rocks. Soil-rock-water systems and groundwater can, and should, be represented in all engineering geological models. Figure 15 is an observational model of the piezometric surfaces within a dam built on karstic limestone, that has been interpreted from measurements of groundwater levels in piezometers installed at different levels in the foundation of the dam. The upper piezometric surface appears to indicate the presence of an active leakage path where the surface is locally lowered.

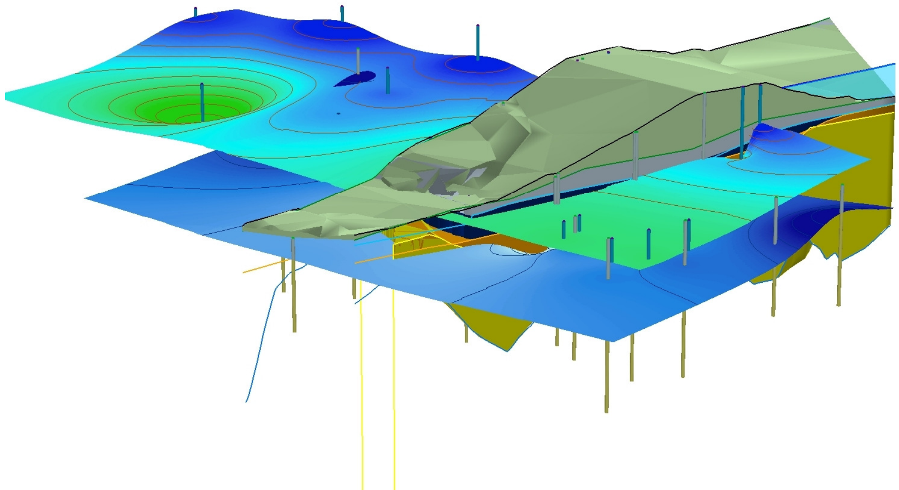


Figure 15: Vizualisation of two separate piezometric surfaces within a karstic dam foundation, from Sheehan et al (2010) reproduced with the permission of the authors.

An example of a different type of observational model that is constrained in time is provided in Figure 16. This observational model provides information on the magnitude-frequency relationship of earthquake data for an area of Peru over a specific time frame.

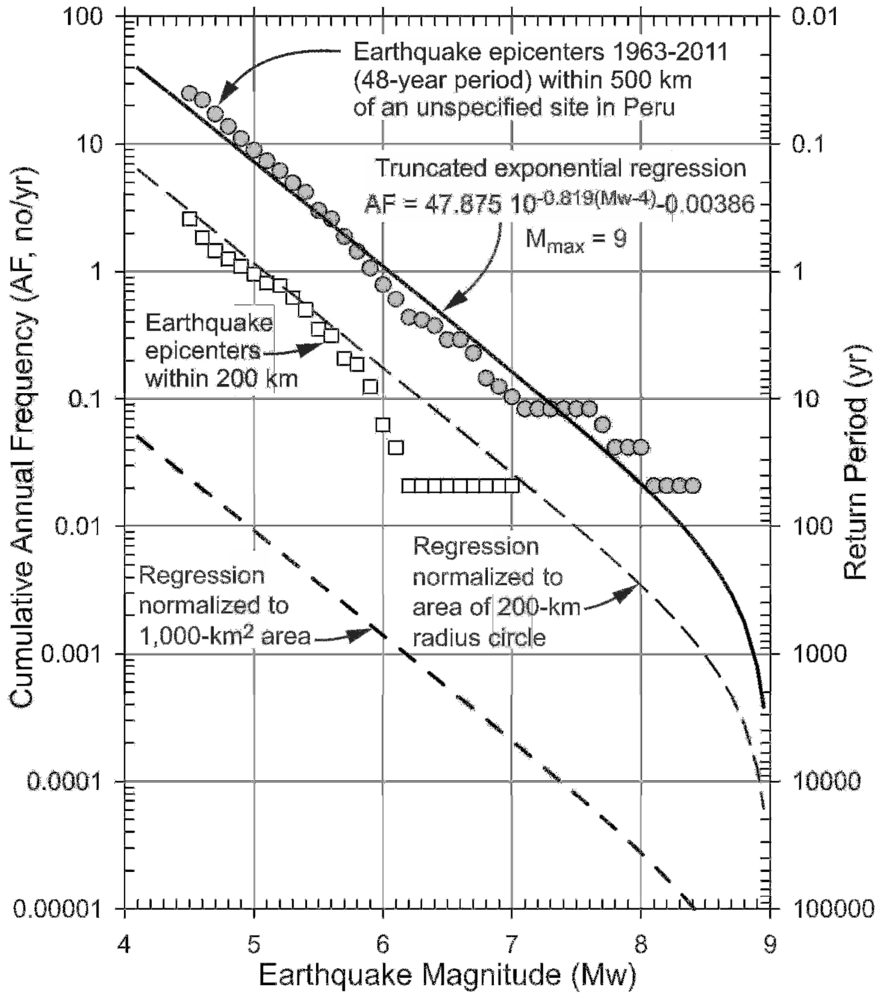


Figure 16: Earthquake magnitude frequency plot for an unspecified site in Peru for the period 1963 to 2011 using the earthquake catalog from Centro Regional de Sismologia Para America del Sur Instituto Geofísico del Perú.

The Analytical Model

Analytical models can comprise both analogue and mathematical models. Analogue models use other media to represent what is being modelled. For example, natural analogue models have been adopted to better represent how materials used to construct radioactive waste repositories will behave in the long-term (Mossman *et al.* 2008). Mathematical models describe or represent a process, system or concept by means of a number of variables and governing equations. These variables represent the inputs, outputs and the internal state of the process and the equations derived describe the interaction of these variables.

The analytical model usually requires considerable simplification of the observational model and, therefore, significant engineering geological judgment is required to ensure that representative ground conditions, including geotechnical parameters and boundaries, are adopted.

Sullivan (2010) noted that developing a simple model can be very difficult, especially when dealing with very large data sets or very complex geological conditions. In such cases he considered that the aim should be to focus on a model that captures the essence of the engineering design issues but is still robust enough to illustrate the inherent engineering geological variability.

Figure 17 (Bandis *et al*. 2011) illustrates the importance of adopting the appropriate method of analysis to accurately model the engineering geological behaviour of weak, bedded, sedimentary rocks with dominant sub-horizontal partings with thin clayey inter-beds. The purpose of the study was to investigate the different predicted responses of explicit dis-continuum solutions (a bedded and structurally anisotropic universal distinct element code [UDEC] model) versus equivalent continuum solutions with implicit rock mass strengths. While both models predict grossly unstable rock conditions for the unsupported state, the mechanisms of failure are very different in terms of implied failure extent, with the explicit dis-continuum model providing a realistic simulation of the failure mechanism observed in such materials.

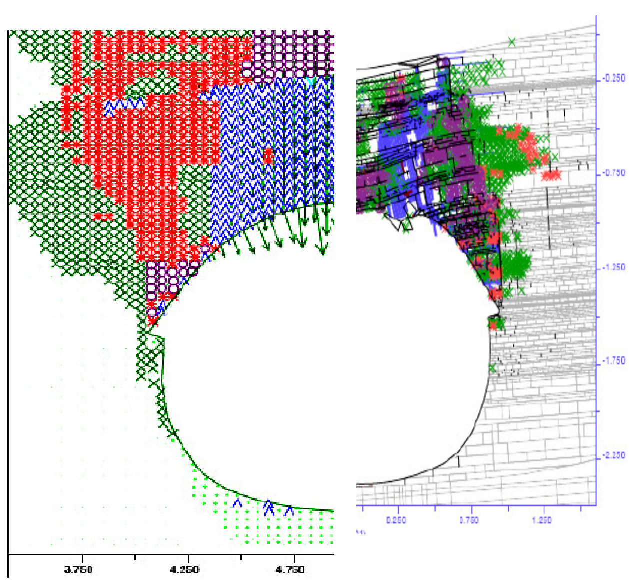


Figure 17: Comparison of bedded rock mass modeled using implicit continuum (left) and explicit dis-continuum (right) models, from Bandis *et al*. (2011) reproduced with the permission of the authors.

Models as they relate to construction

An issue that seems to be poorly covered in the literature is that of engineering geological models and construction. Harding (2004) noted that within the geotechnical industry consideration of engineering geological models with their implicit variability "*is rarely allowed or discussed, particularly at the transfer of knowledge stage between a client or designer and the constructor*" and that "*there is rarely any transfer of knowledge in the form of a …. model to aid the constructor to prepare a tender or allow for potential variations*". Baynes (2010) reviewed the sources of geotechnical risk in projects and whilst discussing contractual risks during construction asserted that "*when the contract and accompanying documentation is inadequate, the source of the risk must be the project staff responsible for managing their procurement and production. The reason this occurs is usually an inadequate understanding of the importance of the geo-engineering aspects of the contract on the part of the contract staff, or a limitation placed on those staff by a higher level project management decision."*

However, this does not always have to be the case and if the right project staff are involved then project risks can be mitigated. Baynes *et al*. (2005) discussed the use of engineering geological models for major railway design in Australia and noted that "*from the Owners perspective, the more that carefully presented information could be provided to prospective tenderers, the less was their uncertainty during the brief period when they prepare their bids. As uncertainty can only be allowed in the cost estimate, these strategies were specifically directed at obtaining the most competitive bids for building the project.*" This approach is not always adopted and in many cases owners choose to issue only "factual" information (i.e. borehole and test pit logs) in the belief that providing any "interpretations" will somehow increase their exposure to geotechnical risk. The members of C25 accept that this is an industry wide practice but are of the opinion that withholding interpretations from contractors can only reduce their ability to reasonably foresee the ground conditions that they might encounter.

General rules for the construction of useful models

To be useful, Moores & Twiss (1995) suggested that any model must satisfy three criteria:

- The model must be *powerful*, that is capable of explaining a large number of disparate observations;
- The model must be *parsimonious* and use a minimum number of assumptions compared with the range of observations that it explains;
- The model must be *testable* which means that it must anticipate conditions that, at least in principle, can be verified by observation.

Regardless of the model type, some of the basic principles that should be followed when developing engineering geological models have been enunciated by various authors (Muller & Fecker 1979, Stapledon 1982, Varnes 1974, Schumm 1991, Baynes 1999, Sullivan, 2010) and are summarized and enhanced below:

1. Formulate an initial model as early as possible, otherwise there is nothing to test against, and refine the model as additional data become available;

2. Start off by developing a good understanding of the geology that is based on the fundamentals – the principle of uniformitarianism and the law of superposition must be complied with;

3. Always work from a broad scale overview to the particular details of the project site (far field to near field);

4. Focus on geology that is relevant to the engineering needed to carry out the project;

5. Continuously test and question the model at all stages of the project and revise as necessary, whilst also using the method of multiple working hypotheses to ensure that no reasonable explanation is discounted;

6. Address and carry forward all of the important geological details and simplify to communicate clearly the critical aspects succinctly, but do not lose any important detail.

In a general sense, the geotechnical risk faced by an engineering project is inversely proportional to the level of detail and accuracy embodied in the engineering geological model. The better the model reflects actual conditions, the lower the remaining risk. However, it is not possible to define every finite detail of the ground. So, ultimately, the objective of an engineering geological model, throughout the project, should be to provide sufficient detail and understanding of the ground, based on the data available at the time, to carry out the engineering to an acceptable degree of reliability.

The most useful engineering geological models define uncertainties and unknowns so that they may be incorporated into the project analyses or so that the project cost estimate can include a contingency to cover the risks associated with them. This allows the potential sources of risks to the project from ground-related hazards to be identified, as far as possible, and investigated and evaluated, thereby reducing ground-related risk to the extent that is practicable.

The authors are of the opinion that distinguishing between the conceptual and observational components of a model will create a better understanding of the type and range of uncertainties that are present within the model.

Conclusions

Engineering geological models should form a fundamental component of any geotechnical project as they provide a systematic methodology to support all of the engineering geological thought processes that must be worked through for successful project completion. The use of models as an approach to solving engineering geological problems, with the inherent requirement for prediction and verification, is also ideally suited to training and education.

Although the concept of geological models has existed for many decades (if not a century or more), in engineering geology the concept has only come to be considered seriously as a means of better understanding project risks since Fookes' Glossop Lecture in 1997. Other authors have discussed different types of engineering geological model and how these can be used as part of the site investigation process. However, little has been published that originates from within the core of engineering geology to systematically distinguish the different model types and how they might be used most effectively. Fookes (1997) claimed that there is "*no model model*"; the authors disagree. In the years since Fookes published his seminal paper a lot of thought has been given to models (in some cases provoked by interacting with Fookes himself) that has resulted in advances in understanding the way models work and which models are most effective. This thinking has taken place particularly amongst practitioners, where the usefulness of models is readily apparent and the pressure to 'get it right' forces them to develop effective tools and work out how these tools can be applied on real life projects (which unfortunately are often less than perfect examples of how geotechnical risks on projects should be managed!).

C25 has concluded that important distinctions need to be drawn between the models that engineering geologists use and has differentiated the following types of model:

- The *Conceptual Engineering Geological Model*. These are typically the first model type generated in a project and are developed from pre-existing information based on geological concepts within a general context of civil engineering. They potentially involve a relatively high degree of uncertainty which is directly related to the type and amount of existing data and the knowledge and experience of those involved. However, when such models are proficiently developed they provide an extremely powerful tool for appreciating and communicating what is known about a site, what is conjectured and where significant uncertainties may remain. Conceptual models should be established as soon as practical at the beginning of a project. Depending on the type and scale of the project multiple conceptual models may be generated to evaluate specific engineering geological issues. They should be refined as site-specific data becomes available and additional models may well be required as new data is acquired. The success of this approach is strongly dependant on the knowledge and experience of those involved in creating the models

- The *Observational Engineering Geological Model.* These are typically created from information generated during the site-specific ground investigation and are constrained by observational and measured data and should present geological information in space or time. They should verify or refine the conceptual engineering geological model. In particular, they should focus on potential engineering issues identified in the conceptual engineering geological model but about which little or nothing is known for the specific site. Observational engineering geological models are particularly relevant at the engineering design stage. Later stage verification and refinement of the observational engineering geological model should take place during construction. If observational models are developed initially using high quality conceptual models, the uncertainties associated with observational models should be reduced. However, the derivation of an appropriate observational model is still dependent upon the knowledge and experience of those involved.

- The *Analytical Model*. This model is used to interpret how the ground is likely to behave when it is impacted by the engineered project during the construction process. Analytical models are likely to vary considerably depending upon the nature of the ground, itself, and the particular engineering process being applied. Engineering geological parameters such as shear strength, hydraulic conductivity, and deformation modulus have to be understood and provided in a suitably simplified but realistic framework for analysis, i.e. in terms of their distribution within the observational models.

Finally, the knowledge encompassed within each type of model must be transferable between project stages, in particular from the site investigation, to engineering design, to project construction, and into facility operation, so all of the different types of models must seamlessly relate to each other. Engineering geological models are an ideal way to *communicate* what is known about the project as it progresses through different project stages.

This discussion of engineering geological models is intended to provide guidance as to the types of model that may be created. The level of detail incorporated into a model should be a function of the geological complexity of a site and project engineering requirements; it should be in line with the general philosophy of promoting project reliability and reducing ground-related risk to an acceptable level. Clearly, the uncertainty associated with the choice of geological details on which to base a conceptual model is very different from the uncertainty associated with the location of a geological boundary within 3D space for an observational model. By acknowledging these different approaches, the different types of uncertainty within the model can be appreciated and hopefully understood.

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