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Engineering Geological Knowledge and Quality

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Summary The nature of engineering geological knowledge is explored in an attempt to understand what constitutes good engineering geology. The knowledge is found to consist of observations made at sites, interpretations of the observations, and five underlying principles that are considered in more detail. The resultant understanding is used as the framework for a quality assurance system for engineering geology.

1. INTRODUCTION

Engineering geology is more than geology that is useful for engineers, it is a type of applied geology in which the practitioners have training and experience in ground problems encountered in engineering and in the investigation and characterization of ground conditions and ground performance for engineering purposes (Fookes, 1997). Engineering geologists have knowledge that is unique to their area of the science of geology. This exploration of the nature of that knowledge is directed to understanding what constitutes good engineering geology.

2. THE NATURE OF ENGINEERING GEOLOGY KNOWLEDGE

Knowledge may be differentiated into empirical knowledge and *a priori* knowledge. Empirical knowledge is knowledge of the things around us, whereas *a priori* knowledge is based on intuitive truths such as logic and mathematics (Russell, 1968). Engineering geology is a part of an empirical science and thus engineering geological knowledge is empirical.

2.1 Observations of Attributes

The most basic knowledge that engineering geologists deal with is typified by observations made at a site. The nature of these observations may be differentiated as indicated in Table 1. Observations made at site are of different types of geological and engineering attributes (Varnes, 1974).

Attributes may be described as being present or absent, but are more commonly measured, to reflect some range or degree. Measurement is simply the assignment of numerals to describe attributes according to rules. The rules are of four kinds as listed in Table 2.

Table 1. Empirical knowledge.

Immediate	Geological examples
Particular things directly perceived:	
- Sense data	The colour and texture of a particular rock
- Ourselves	Personal experience of understanding rocks
Universal qualities or attributes	
- Inherent Qualities	The different colours and textures that rocks have
- Relationships of space	That a rock type occupies a certain 3D space
- Relationships of time	That a rock type intrudes another and is therefore older
- Relationships between objects	That a rock is coarser grained or harder than another
Derivative	
Knowledge of attributes combined with knowledge of truths	That a particular rock belongs to a class of rocks, the class having been established by inductive reasoning, the class being termed "granite rock"

Table 2. Kinds of measurement (after Varnes 1974).

Scale	Operation	Example
Nominal	Assignment of a number or name to each object Assignment of a number or name to each class	Numbered rock specimens Rock specimens named by lithology
Ordinal	Determination of greater or less	Hardness of minerals, strata ranked by age
Interval	Determination of the equality of intervals or differences	Celsius temperature (arbitrary zero), calendar time
Ratio	Determination of the equality of ratios	Length, mass, velocity, size, Kelvin temperature (zero point identified)

Engineering geological observation of attributes should use the full range of measurement methods in characterizing attributes if observational data is to be collected effectively from a site.

2.2 Interpretation

Observations of attributes are then interpreted by engineering geologists. This involves various higher levels of derivative engineering knowledge based on training and experience that are generally derived by progressively developed inductive reasoning driven by a need to understand what is observed (Chalmers 1982). The methods that tend to be followed in developing a geological interpretation may be summarized as follows:

- Acquisition of the observational data sets that are available to develop the most complete knowledge of site attributes. This might include information from desk studies, subsurface investigations, remote sensing etc. Until a wide range of information is accessed the fear that a vital clue may be missing remains.

- Application of pattern recognition skills to the assembled data. Before any grouping of attributes can occur the pattern or trend of attribute distribution should be discerned. This could involve looking at, for instance, spatial data sets or attributes presented in spreadsheets, but in each case any kind of pattern or distinctive trend is being sought. The reason why geologists so often colour in spatial data sets is that underlying patterns may be more easily seen.

- Classification of the distribution of attributes. This basic activity orders the lower level knowledge of site attributes in terms of higher level knowledge that has proved to be useful eg identification of fold types, interpreted rock genesis. Classification provides the building blocks and ultimately merges into a geological interpretation.

- The use of a variety of inference modes to explain the data. Modes of inference may be:

    - Induction or forward inference based on generalization, where knowledge of cause and of effect allows inferences to be drawn about the probable relationship, eg. channel clearing in an area is observed to be associated with increased erosion, so it is inferred that further channel clearing will probably cause more erosion.

    - Abduction or backward inference based on generalization, where knowledge of resultant effects and of controls allows inferences to be drawn about probable causative factors – the unravelling process, eg. channel erosion is observed and channel clearing increases stream velocity and erosion, so it is inferred that some period of previous channel clearing probably caused the erosion.

    - Deduction or logical inference, where knowledge of causative factors and cause effect relationships allows resultant effects to be inferred, eg. channel clearing increases stream velocity, increased stream velocity moves more sediment, therefore channel clearing will cause erosion.

2.3 Principles

If engineering geology is a separate branch of knowledge then it should contain identifiable higher level derivative propositions that have developed within the body of empirical knowledge accumulated during practice. The propositions in question will show a progression towards increasing generality as a branch of science develops and ultimately take the form of regulative principles (Engelhardt & Zimmerman, 1988).

It is suggested that five guiding principles that are central to the way in which engineering geology is practised are as follows:

1. The underlying geological knowledge must be sound and based on an understanding of site specific observations of the spatial and temporal distribution of geological attributes, and their interrelationships, within a general and regional context (Muller & Fecker, 1979).

2. The spatial and temporal distribution of the geological attributes must be presented in an engineering geology model that is logical and reasonable whilst accounting for observed conditions, is project oriented, and is driven in its development by considerations of usefulness (Stapledon, 1982).

3. The geological knowledge must be presented in a form suited to engineering application, thus geological attributes must be encoded in a geotechnical language that has engineering significance (Stapledon 1982).

4. The engineering geological knowledge must be capable of supporting engineering decisions. For this to happen the knowledge must be transformed into an engineering framework ie. presented in a form suited to engineering decisions. (Varnes 1974).

5. All of the knowledge must be effectively communicated. This requires an understanding of the project engineering in order that the engineering geological knowledge is appropriately encoded and transformed; the overt qualification of the nature of the knowledge (be it observation or interpretation); the clear indication of any uncertainty attached to the knowledge; and confirmation that such limitations have been understood (Varnes 1974).

The application of the principles is illustrated as a flow chart of intellectual activities in Figure 1 and is exemplified when engineering geologists are effectively involved in major projects (Rawlings, 1972, Stapledon, 1983).

Engineering geological knowledge may thus be divided into:

- Observations of attributes, which will be made at a site with a project in mind.

- Interpretation of observations, which will be based on training and experience in geology and engineering.

- Five principles, representing higher levels of knowledge accumulated during practice.

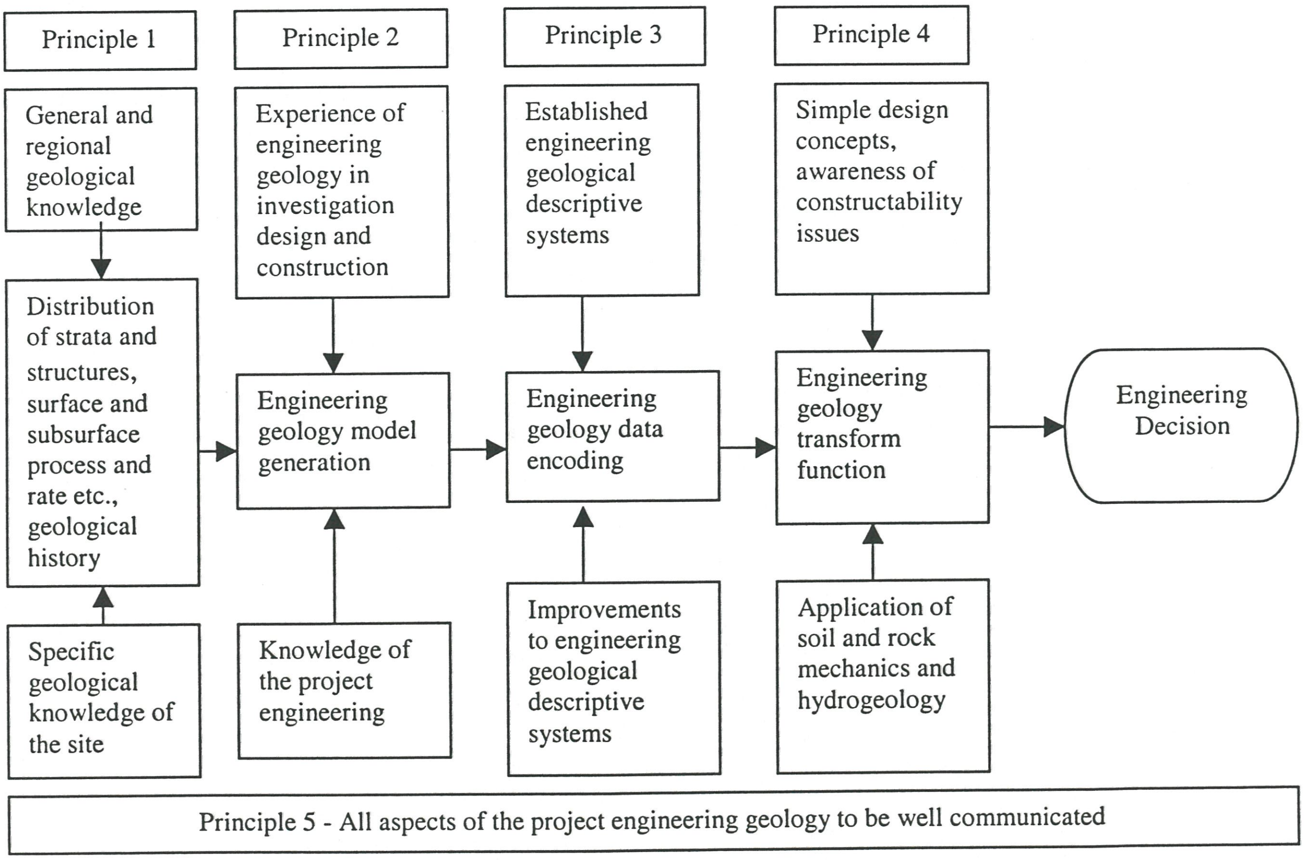

Figure 1. An illustration of the application of the principles of engineering geology.

If it is accepted that these five principles of engineering geology are "general laws" then they should form some framework for judging what is good engineering geology. However to develop that framework it is necessary to consider the application of each of the principles in more detail, to identify those approaches that are adopted to achieve good quality.

3. GEOLOGICAL METHODS

Geologists aim to both observe and understand the earth. There are some distinctive aspects of geological method that characterize sound geology (Seddon, 1996), namely:

- A focus on putting the pieces together. The application of geological science involves finding a comprehensive explanation that deals with the linkages between what might be appear to be superficially unrelated data. When the data consists of observations that may be related sequentially, the explanation can have a strong narrative component. The comprehensive explanation ultimately constitutes a story that is the "geological history". There are similarities to clinical medicine where superficially unrelated conditions become the symptoms once they are linked by a diagnosis.

- An awareness of a range of timescales. The immensity of geological time, called "deep time" by Gould (1988), forms the backdrop to the geological history. Comparison of the age of geological features, often many millions of years, with engineering design lives of tens of years illustrates an important distinction between geological understanding and engineering concepts.

- A tendency for divergent thinking. Geologists tend to avoid pursuing a single explanation and instead favour multiple working hypotheses to explain observations (the infamous one handed geologist is much sought after by engineers, because he or she cannot present advice and then say "but on the other hand"). It is often the case that the final working hypothesis combines elements of originally mutually opposed hypotheses.

- Wide ranging experience on the part of the practitioner. Geology has been described facetiously as the science of "where did I see that before?" and extensive field experience always commands respect amongst geologists because "all other things being equal, the best geologist is the one who has seen the most rocks" (attributed to Professor H H Read). Field experience, in a manner similar to clinical experience in a diagnostician, can only be accumulated through practice, and so geologists peak late in their careers. The age and experience of the geologist is relevant to the quality of the interpretation.

Classical geology relies heavily on abductive inference of unknown causes from known effects to explain what happened. Engineering geological models generally combine abductive inference, to explain the geological history, with inductive and deductive inference to anticipate geological conditions of engineering significance.

4. MODEL DEVELOPMENT

The aim of the model is to represent the geology of a site, indicate where further knowledge would help to reduce uncertainty, and anticipate conditions that may impact upon an project. The development of engineering geological models has been examined in depth by Fookes (1997). The way project engineering decision making and the usefulness of site investigation activities are interrelated with model development has been described by Stapledon (1982). The model should include:

- Both the observations and the interpretation of the site, usually abductively inferred. This involves synthesis of the observational data and interpretation into a three dimensional geometric model of the distribution of rock and soil types and water (usually as maps and sections), plus information on surface and subsurface process rates (time being the fourth dimension).

- Because the model is a tool to aid in engineering decision making it must be driven by the project. Therefore the focus must be on observations and interpretations that are likely to relate to engineering performance. The model should be driven by knowledge of engineering performance based on the nature of the site, the project and experience.

- The model must contain some anticipation of geological conditions that will affect engineering performance, usually inductively inferred. The model should include some wider view of the impact of geological conditions that may occur given the geological setting, that wider view can only be driven by knowledge based on geological experience from elsewhere. Bold models can focus attention on potentially fatal flaws and empower engineering geologists. Bold models also increase the risk of being proven wrong!

5. GEOTECHNICAL LANGUAGE

Engineering geological knowledge should be presented in a standard language so that information may be communicated in concise unambiguous terms.

This approach is epitomized when site observations are encoded in standardized classification systems such as Australian Standard 1726 (Geotechnical Site Investigation) or British Standard 5930 (Code of Practice for Site Investigations). Assuming that such systems are used, the effectiveness of any encoding system for engineering geological knowledge will depend upon how well it has been developed. In this respect there appear to be some inherent limitations on the quality of the encoding method in AS 1726, for example:

- Distinctive material types encountered in Australia, such as areas of duricrust and offshore carbonates, are not well covered in the descriptive sytems.

- The lack of meaningful graphic symbols for soil description is of continuing concern to practitioners concerned with quality (Stapledon 1996).

- The lack of emphasis on geological origins of soils and rocks reduces the amount of information that might be encoded, and thus may tend to reduce the information base available to the decision maker.

Another area of inherent limitations in encoding systems concerns structural geological attributes, which tend to be encoded using rock mass classification systems. These systems tend to record groups of attributes as single ratio measurements in the belief that knowledge has more significance if it is numerical (Bienawski 1989). The resultant filter applied to the range of observable attributes recorded can only result in a loss of information on which to base decisions.

6. TRANSFORMS

Transforms are used to present engineering geological knowledge in ways suited to making engineering decisions. The development of the most basic transforms involves the comparison of engineering geological conditions with engineering performance derived from experience, for example:

- Tunnel support requirements for various rock groups in Terzaghi (1946).

- The allowable bearing pressure values for various rock groups in Tomlinson & Boorman (1986).

More sophisticated transforms involve soil and rock mechanics and hydrogeology in equating engineering performance with geological conditions.

Transforms are synthetic areas of knowledge encapsulated as heuristics or "rules of thumb" (Sullivan 1994) that are derived inductively. Transforms equate to "opinions" in terms of presentation of information for contract purposes (Construction Industry Committee 1987).

The applicability and validity of specific transforms may only be assessed by their general acceptance in practice and, more importantly, by calibration relative to personal experience.

When the individual responsible for site characterization allocates transform values a reasonable input into engineering decision is likely. If the transform values are allocated by someone who has little understanding of site conditions or the complexity of the geology, there is a significant risk of a decision being based on a misconception.

7. EFFECTIVE COMMUNICATION

The knowledge that is channeled towards the decision making process has to be effectively communicated. A communications model for engineering geology on a large complex project consists of the elements represented in Figure 2. The critical aspects of this process are:

- That filters exist which can reduce the transfer of information. Effective communication can only be achieved if the impact of the filters is limited.

- The filters will always be there so their effect needs to be recognized.

- The feedback loop is essential to ensure the adequacy of communication.

On a very small project it is possible that less opportunity will exist for communication problems as one person can be responsible for most of the process, from characterizing the site to making the engineering decisions. However most projects involve the flow of information through various groups in the manner indicated

There are some aspects of communication that are particularly relevant to engineering geology:

- Because a lot of engineering geology knowledge is spatial and three dimensional, maps and sections are essential for effective communication.

- One peculiarity of geoscientific texts is that information is conveyed not only in verbal language but also to a greater extent using photographs, drawings, graphs and maps (Engelhardt & Zimmerman, 1988). As "one picture is worth a thousand words", it is important to ensure the economy and effectiveness of non-verbal communication methods are fully used.

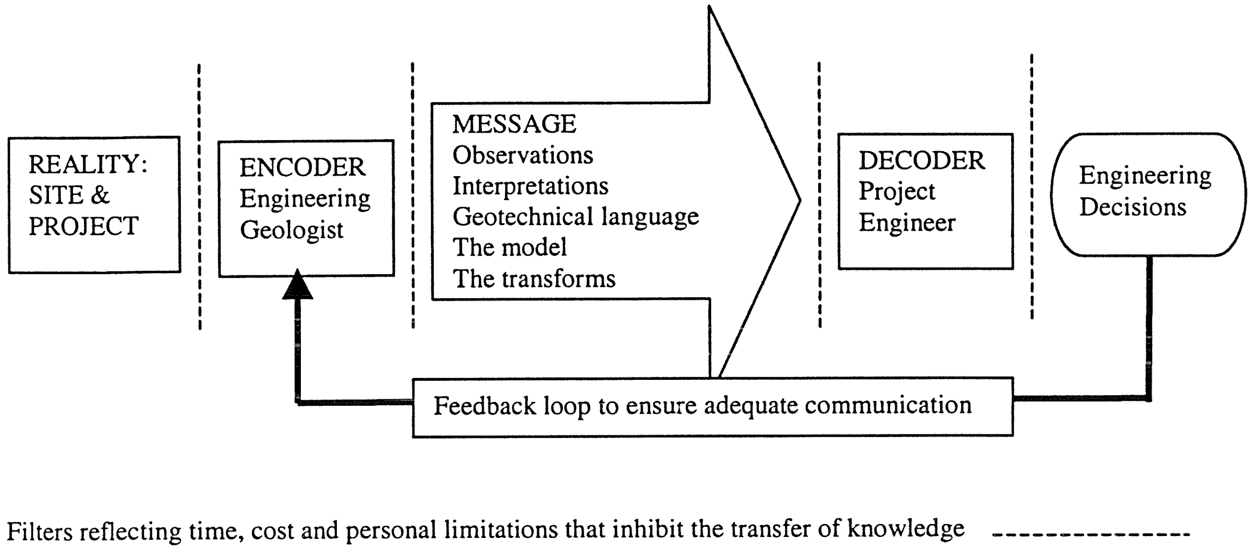

Figure 2. Illustration of Communication Model for Engineering Geology on Large Projects.

- Engineering geology involves uncertainty and it is essential that this attribute is also properly encoded. In most cases uncertainty cannot be expressed quantitatively and therefore agreed qualitative descriptors are useful. For example a legal model for some terms could be:
  - On the balance of probabilities: >50% certain
  - Beyond reasonable doubt: >95% certain.
  - Almost certainly: >99% certain.

8. QUALITY ASSURANCE

This rather esoteric exploration of the nature of engineering geological knowledge is directed towards understanding what constitutes good engineering geology. With that understanding it should be possible to create a Quality Assurance System for engineering geological studies. The following checklist of questions is an initial attempt to develop a system that may be used to assess the quality of the engineering geology content of a project.

Principle 1 – Geological Inputs

Has the available data been accessed?

Are any patterns recognized and explained?

Have the attributes been effectively classified?

Does the geological interpretation start from a regional perspective before focussing on the site?

Is there a sufficient geological understanding, and a sense of geological time?

Is the geology presented in terms of observations, where relevant, of:

- the stratigraphy
- the structure
- the in situ stresses,
- the surface effects
- process rates?

Have various alternative explanations been considered?

Are the observations and the interpretations distinguished?

Are the geological inferences reasonable?

Is the geologist adequately experienced for the project?

Principle 2 – The Model

Is a model presented that is logical and reasonable whilst accounting for observed conditions, project oriented, and driven in its development by considerations of usefulness?

Does the model contain observed 4D information, ie. maps and sections, process rates, a story in time and an interpretation?

Is the model oriented to the project engineering?

Does the model anticipate geological conditions that may affect performance?

Is the model sufficiently bold to allow consideration of fatal project flaws?

Principle 3 – Geotechnical Language

Is a geotechnical language employed to describe the engineering geological conditions, is a copy of that system provided for the user?

Is the information presented subject to any inherent limitations of the geotechnical language and have those limitations been reasonably addressed?

What are the wider implications of any remaining inherent limitations in the language and how have those limitations been addressed?

What relevant geological information has been lost as a consequence of encoding in the geotechnical language?

Principle – 4 Transforms

Is the geological knowledge presented in a form suited to engineering decisions?

Are the transforms that have been used based on sound precedent?

Were the transforms applied by the observer?

Principle 5 – Communication

Is the engineering geological knowledge effectively communicated?

Are maps, sections, photos, colour and imagery used to maximum effect?

Does an understanding of the project engineering ensure that the engineering geological knowledge is appropriately encoded and transformed?

Is uncertainty quantified or described systematically?

Has the communication been understood?

Are observations, interpretations and opinions distinguished?

9. CLOSURE

Even if the assertions made in this paper are demonstrated to be incorrect, it is still likely that, in the process of discussion, our understanding of what constitutes good engineering geology will have progressed. Thus some progress will have been achieved. Thanks to Alan Moon for discussions.

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