Diversity in the science and practice of engineering geology

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The 1992 statutes of the International Association for Engineering Geology and the Environment (IAEG) define engineering geology as follows.

‘Engineering geology is a science devoted to the investigation, study and solution of engineering and environmental problems which may arise as the result of the interaction between geology and the works and activities of man as well as to the prediction of, and the development of, measures for the prevention or remediation of geological hazards.’ (Delgado et al. 2014)

The New Penguin Dictionary of Geology describes engineering geology as the ‘application of geological information, techniques and principles to the design, construction and maintenance of engineering works’ (Kearey 1996). Hencher (2012) defines engineering geology as the ‘scientific study of geology as it relates to civil engineering projects such as the design of a bridge, construction of a dam or preventing a landslide’. These are glimpses of the many definitions that can be found in the literature. A commonality in these descriptions is geology and in particular the application of geological sciences to engineering study.

Broadening this discussion a little further, geology can be described as ‘the study of the Earth as a whole, its origin, structure, composition, and history...and the nature of the processes which have given rise to its present state’. (Whitten & Brooks 1972). An important reflection of this definition is realizing the immensity of the science of geology. The variety of topics is far-reaching, from plate tectonics to mineralogy with everything in between. The essence of this argument is that all branches of geology are relevant occurring in all environments. This universality of awareness and comprehension is unique within geology and its applications’. Finally, de Freitas (2009) said: ‘There is scope for all interests in geology to contribute to the advance of engineering’. Diversity is a fundamental tenet of engineering geology. In science diversity is an essential part of the tremendous appeal presenting a vast array of opportunities to explore, enquire and test ideas to the benefit of solving engineering problems. In practice however, diversity can be a complexity if it is not well understood and adequately managed; as such, it also represents a challenge to the profession. These issues are explored in this introduction to Developments in Engineering Geology.

This book is a showcase of the diversity in the science and practice of engineering geology. It is based on talks presented at the 34th International Geological Congress (34IGC) held in Brisbane, Australia in August 2012. The papers in this book are written accounts of a selection of the presentations from Theme 31 of the Congress on Engineering Geology and Geomechanics.

A very short history of engineering geology

An excellent account of the history of engineering geology is provided in the IAEG 50th anniversary book (Delgado et al. 2014). It is also addressed by Knill in the First Hans Cloos Lecture (Knill 2003) and again by Griffiths in the 14th Glos sop Lecture (Griffiths 2014). These sources form the basis of this summary.

While the science of engineering geology has essentially been in existence as long as the science of geology, it has been traditionally thought that the practice probably only began towards the end of the nineteenth century and beginning of the twentieth century with classically educated geologists providing assistance to civil and mine engineering. However, that thinking is being challenged with the discovery of human-excavated caverns in Longyou, China which are thought to be some 2000–2500 years old (Fig. 1).
These caverns are discussed by Li et al. (2016) and demonstrate that people at that time understood the influence of geology on stability conditions and then used this knowledge in design of the caverns.

Aside from these discoveries in China of the possible ancient practice of engineering geology, the modern development of the discipline started to evolve from the 1920s to the 1960s with the concept of applied geology, helped along by lessons learnt from a number of catastrophic engineering accidents such as the 1928 Saint Francis dam collapse in the USA, the Malpasset Dam failure in France in 1959, the 1963 Vajont dam disaster in Italy and the Aberfan waste dump collapse in Wales back in 1966. Workers around that period such as American geologist Charles Berkey and Karl Terzaghi in Europe and the USA recognized that the safety and economy of engineering projects required geologists with more than a classical education in geology.

Around the 1950s and 1960s, courses on geology were introduced into civil engineering undergraduate programmes and engineering subjects were incorporated into geology degrees. From this engineering geology emerged as a new discipline, culminating in the creation of the IAEG in 1964 arising from the lack of engineering geology subjects in the 22nd International Geological Congress held in New Delhi earlier that year. This led to dedicated educational programmes in engineering geology commencing from the 1970s onwards.

In the period before establishment of the IAEG, and during the association’s early years, there was significant diversity around the world in the way geology was applied to engineering and natural hazard studies. The diversity was very much driven by the varying degree of economic development in each region around the globe, with the large national building projects after the First World War and since the Second World War playing a major role. The size and importance of these projects demanded an increased quality in engineering design to improve reliability; accordingly, the pressure was put on engineering geology to match the challenge. Examples of signature projects which promoted the regional development of engineering geology include the Hoover dam in the USA, constructed during the Great Depression in the 1930s where Berkey made a major contribution, the Snowy Mountains hydropower and irrigation scheme built between 1949 and 1972 in Australia, and the Waitakari, Tongariro, Manapouri and Clyde dam hydropower schemes built between the 1960s and 1980s in New Zealand. To help manage the emerging diversity in approach during this period, standards and codes were developed during the 1960s–1980s, particularly for material descriptions and investigation methods.

Maturing of the IAEG as an international organization, together with the positive influence of the dedicated educational programmes, lessons learnt from the national building projects in the mid-twentieth century and the development of codes and standards, has seen engineering geology grow and progress since the 1980s. The profession is accepted as an integral part of the wider practices of geotechnical engineering, environmental engineering and natural hazard studies.

Diversity in the science of engineering geology is a significant part of the attraction to the profession both for academics and practitioners. The concept of models is now well established and is helping to promote new thinking and research avenues. Innovation and new technologies are being tested by science and introduced into practice. The papers in this publication are testimony to this growth and development in knowledge.

Given the wide scientific frontier and historical diversity across the globe in the application of geology in engineering, how is the profession coping with practising the science? A review of the literature suggests engineering geology has undertaken its fair share of ‘hand wringing’ in recent times. What are the issues, what role is diversity playing in characterizing engineering geology and what is the way forward?

The following discussion is a personal view of several key papers which discuss the state of play and future of engineering geology. The collection and discussion is not exhaustive and is biased towards the experience and views of the author, selected to emphasize how diversity both defines and constrains the development of engineering geology.

**Education, communication and the relationship between geology and engineering**

In the First Glossop Lecture given in 1997, Professor Peter Fookes was very specific in clarifying the difference...
between engineering geology and geology for engineers. He says: ‘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). Whereas traditional definitions of engineering geology tend to emphasize the importance of geology as a keystone of the science, Fookes goes further in his explanation by highlighting the skills required in characterization of soils and rocks, knowledge of the behaviour of natural systems and understanding of ground-related problems. This rather eloquent description by Fookes highlights the double battlefront that engineering geology must manage: the exciting scientific opportunities with its geological association, and the challenges in maintaining and growing its relevance in engineering.

Fookes’ lecture talked about both Glossop’s 1968 Rankine lecture and his retiring address as Chairman of the Engineering Group of the Geological Society (Glossop 1969), stating Glossop’s wish that ‘geology and engineering should move closer together’. However, Fookes noted that ‘Geology for engineers sat uneasily, and often still does, with other more quantitative subjects in engineering education...’ current attitudes and practices still reflect some of the earlier difficulties’. Although it is nearly 20 years later, not much has changed where this attitude still drives the struggle to maintain geology as an essential topic in geotechnical engineering education.

Sir John Knill presented the first Hans Cloos lecture at the 9th IAEG congress in Durban, South Africa in 2002 (Knill 2003). Knill also discussed the relationship between geology and engineering, pointing out ‘Engineering and geology are... inherently and intellectually very different subjects... These intellectual differences must be overcome in the application of engineering geology, lying as it does at the borderline between two disciplines having their own contrasting characteristics’.

There is no doubt that geologists and engineers can be quite different beasts and their brains are often wired differently. In the 1996 John Jaeger lecture to the Australian Geomechanics Society, Professor David Stapledon, in his paper entitled ‘Keeping the “Geo”; Why and How’, used the work by Roberts (1963) to illustrate the communication gap between geologists and engineers (Fig. 2). Stapledon (1996) noted that ‘geotechnical engineers seem to have difficulty moving to the left’ on this matrix diagram. To help explain why engineers have difficulty with geology, Stapledon quoted Terzaghi (1961) including:

‘...in order to be of any practical value, the knowledge of this difference [between actual properties of natural ground and those assigned on the basis of investigation] must be combined with the capacity to adapt procedures and decisions to the possible consequence of the prevailing uncertainties. Unfortunately this capacity, like that for creative writing, cannot be developed by systematic training... and some students may never acquire it. On account of this fact, combined with the educational background of the civil engineer, the teaching of the subject involves considerable pedagogical difficulties. ..., the student in civil engineering is supplied with information ... which can be applied to the solution of practical problems almost without any original thinking on his part. By contrast, in engineering geology, no such direct application of the information supplied to the student is practicable [and] most courses on engineering geology fail to make any lasting impression on the students.’

Fig. 2. Knowledge v. solution skills matrix from Roberts (1963) as reported in Stapledon (1996). (a) Communication gap between geologists (G) and engineers (E). (b) Measure of value for individuals Case I Specialists, Case II Narrowly trained engineer, Case III Broad-based geotechnical engineer or engineering geologist.
To overcome the learning problems, Stapledon (1996) agreed with Terzaghi’s recommendations that the teacher should have adequate geology training, case histories should be presented by visiting industry lecturers and time should be spent in the field ‘where the real soil and rock are’. Some 55 years later, these educational values are still legitimate and pertinent to the successful integration between geology and engineering. Stapledon (1996) concluded ‘The essential requirement is that engineers and geologists become progressively better educated in each other’s field. This will result in better communication, team work, results and utilization of staff’.

Cross education between geology and engineering has arguably improved in the last 20 years; however, at best it can be described as patchy and the momentum is different around the globe. This stilted growth is partly driven by a consolidation of geoscience departments within institutions that offer geological education, which has been ongoing for the last 10 years or so. But even within educational institutions which are fortunate to have both an engineering geology program and an engineering school, there is resistance to fit geology into a crowded undergraduate engineering degree. Disparity in the educational approach to engineering in geology and geology in engineering is a prime cause of diversity in the global development of engineering geology.

While education and communication are fundamental to the relationship between geologists and engineers, spending time in the field together is also a great way to enhance mutual respect. At the 9th Glossop Lecture presented in 2008, Professor Mike de Freitas warns the interface between geology and engineering ‘is delicate and easily broken’ and he points to the need for geologists and engineers to work together in the field to ‘share the satisfaction of understanding the ground’ (de Freitas 2009).

With regard to the education of engineering geologists, Fookes stated he prefers ‘an engineering geologist to be a good geologist with a good geological degree and postgraduate training with experience’ (Fookes 1997). He reinforced this by saying ‘The main role of the engineering geologist is to get the geology right’ and also ‘the skills of the field geologist and field geomorphologist are still a cornerstone, if not the main strength, of engineering geology. There is yet no substitute for an informed brain and trained pair of eyes’.

The last sentence in this quote is rather famous and a correlative of the decree ‘all other things being equal, the best geologist is the one who has seen the most rocks’ (attributed in Baynes 1999 to Professor HH Read).

Fookes’ statements are based on fundamental values in engineering geology. Today the educational objectives remain the same where arguably the best engineering geologists have a Bachelor degree in geology and a Masters degree in engineering geology. It is important the undergraduate degree maintains a pure focus on providing all the fundamental geological skills and knowledge, in particular the mapping and observational skills highlighted by Fookes. The engineering geological education should substantially only start during the post-graduate studies; there is a temptation to squeeze too many applied subjects into the undergraduate level, to the detriment of the fundamentals needed to form the most successful educational platform for an engineering geologist. With that being said, some engineering-related ideas are introduced as part of undergraduate geological studies, such as the concept of stress and strain in structural geology, which help prepare the graduate geologist for post-graduate education in engineering geology.

Core issues, principles of geology in geotechs and an integrated approach to site investigation

Near the start of his Hans Cloos lecture, Knill (2003) poses the question ‘is there reason for concern about engineering geology?’ asking ‘whether the subject of engineering geology could be regarded as a free standing discipline equivalent in status to the position which soil mechanics and rock mechanics have in the formulation of geotechnical engineering’ or instead ‘is engineering geology simply a practical vocation providing the necessary functional underpinning to soil and rock mechanics but without sufficient intellectual merit to be regarded as independent in its own right?’ He quotes from Terzaghi, Mueller-Salzburg and Morgenstern and says ‘each, in his turn, found it impossible to identify an intellectual heart to engineering geology which characterised the subject as a discipline as distinct from a vocation’. He called Fookes’ (1997) view of engineering geologists (described above) ‘ambivalent’ and provides a quote from Baynes (1996) where he describes Australian engineering geology as ‘failing to contribute to geotechnical practice in proportion to its importance’ and ‘the branch of knowledge known as engineering geology seems to have stagnated and is not generating anything new, relevant or exciting’.

Fookes (1997) also quoted the same passage from Baynes (1996) as a ‘salutary warning for British engineering geologists to maintain their integrity as a strong independent discipline’.

Knill frames this rather pessimistic view as a prelude to his lecture on core values in engineering geology saying ‘each constituent subject (in geotechnical engineering) must have its independent characteristics and so aspire to be a discipline; each must display its own set of core values’ (Knill 2003). He started by discussing the issues, that being:

- the role of geology;
- the role of engineering;
- the position of engineering geology;
- geotechnical engineering; and
- external factors.

This list is a strong demonstration of the diversity confronting engineering geology; there are not many disciplines that cross over the boundaries of two major sciences and it is not hard to imagine the difficulties involved in coming to grips with how to cope with the dual demands. Much of the trouble that Knill highlights at the start of his lecture can perhaps be attributed to the ‘growing pains’ in the profession while
learning how to deal with this dual responsibility. In fact, it should be viewed positively that the profession is suitably strong such that eminent people felt sufficiently empowered to express such views.

Under the first issue in the list, Knill (2003) suggests that geology is not a core science like physics, chemistry and biology, is not often taught in schools, has never been seen as an ‘elitist science’ within the wider community and is viewed with some condescension in academia. His conclusion is that this ‘has an unhelpful outcome on the standing of engineering geology’. There is some truth in these statements; however, their relevance is very much contingent on where you live on the globe. Residing adjacent to a plate boundary puts geology squarely in your day-to-day life dealing with natural hazards and active geological processes. Living in a country where the economy is highly dependent on mining of natural resources also elevates the profile of geology to both the community and government. Both these situations also serve to garner interest in geology as a career through natural curiosity, asking questions such as ‘what caused that volcano to erupt’, ‘where did that ore-body come from’, or ‘how do earthquakes happen’.

Geology has a diverse impact on society and it is difficult to generalize about its role around the world. Overall, the expansive scientific frontier that characterizes geology should be viewed as an opportunity to advance the standing of engineering geology rather than be a limitation. There is sufficient public and academic interest in pursuing geology; however, like many scientific disciplines, it suffers from a decreasing pool of government funding in many jurisdictions. This is where private enterprise and industry must step up to the plate as consumers of science to replace the financial shortfall. The profession of engineering geology needs to do more to leverage off societal interest in the popular topics of geology to attract its share of the pie.

The role of geology was also explored by de Freitas (2009) where he discussed the geological principles of uniformitarianism and superposition, and their use in geotechnical engineering. He points out rather effectively that uniformitarianism, ‘the present is the key to the past’, is ‘the basis for reconstructing former geological environments of a site’ and that ‘accurate observation, aided by measurement and recorded by case history are the necessary implements for the proper use of uniformitarianism’. This statement reinforces the role of fieldwork and the study of precedent as recorded in case histories. Many papers in this publication provide examples of studies and work practices from a variety of subjects which can be used as precedents and guides for similar projects. These range from the study of Kozylyakova et al. (2016) of the Carboniferous interlayered carbonate and clay-marl massifs in Moscow, the discussion of Tuğrul et al. (2016) on efficient and sustainable use of aggregates in Istanbul and the illustration of Entwistle et al. (2016) of GIS-based desk studies of Glasgow, to Baxter’s (2016) paper on modelling of Cenozoic detrital sequences in the Pilbara region of Western Australia, Cammack’s (2016) discussion on description in the highly disturbed rocks found in the copper porphyry deposits of SE Asia, the report of Flentje et al. (2016) on landslide inventory and susceptibility maps of southeastern Australia, Goldsmith & McCue’s (2016) case study of a dam in Samoa and the case history of Fabbrocino et al. (2016) on seismic vulnerability assessments for critical infrastructure in Italy.

De Freitas (2009) states that the principle of superposition ‘asserts that if a total can be divided into parts, then that total can be obtained from the sum of its parts’ and explains ‘the overriding advantage offered by superposition is its ability to solve complex problems that can be broken down into smaller and simpler parts, each capable of an independent solution that can be summed to provide the final solution’. He cautions that ‘defining a sequence of events solves only half the problem; the sequence then has to be explained’. Again fieldwork plays an important role in identifying the parts but ‘observation alone is usually insufficient to explain how the parts are able to come into coexistence. As a consequence, it is easy for the parts to be summed incorrectly’. Consequently, ‘this generates great pressure to rely heavily on experience’. To explain this, he quotes Terzaghi about what de Freitas called ‘unthinking reliance on experience’, that is, ‘our practical experience can be very misleading unless it combines with it a fairly accurate conception of the mechanics of the phenomena under consideration (as cited by de Freitas 2009 from Goodman 1999).

To deal with this problem de Freitas (2009) talks about engineering geologists and geotechnical engineers working together rather than in isolation. This policy was encouraged by Stapledon (1982) where he said ‘...it is my belief that for most site investigations of any magnitude, an engineer – geologist team approach is desirable’. Figure 3 shows Stapledon’s suggested rational approach to conducting subsurface investigations, indicating how geology and engineering integrates at each functional level of the investigation. This provides an effective strategy for how the relationship between geology and engineering can work, including the need for separate and distinct responsibilities to be established for engineering geologists and geotechnical engineers to operate successfully together as an integrated team (Baynes 2003).

To assist the interaction between geology and engineering, Baynes (1999) presented a communication model for engineering geology on large, complex projects (Fig. 4). He highlights three aspects as being critical in this process.

1. The filters between each phase of the communication path can potentially reduce the transfer of information; for the communication to be effective, the impact of the filters must be limited.
2. The effect of the filters must be considered as they always exist.
3. The feedback loop is an important part of the communication path.

Geological language can be a barrier to communication and is a large reason for misunderstanding of the model by the
engineer. As such, maps, sections, 3D models, photographs and drawings are essential elements for how the geologist communicates their model and ideas, reducing the need for words as the main form of explanation and description.

Research

At the end of his paper Knill (2003) outlined his list of strengths, weaknesses, opportunities and threats to engineering geology. Griffiths & Culshaw (2004) reviewed Knill’s list of weaknesses and came to the conclusion ‘The concern is that unless engineering geology is willing to push forward its own research frontiers, the very real possibility exists that the discipline will be subsumed as a minor branch of geotechnical engineering’. They identified areas of potential research activity in the UK that may help establish engineering geology as an independent discipline. As background, they show that in the 1970s ‘a greater proportion of published papers (were) concerned with new developments’ in a ‘period that (was) influential in defining engineering geology as an independent discipline’. Contrastingly, in the 1990s and 2000s, their information indicated that a majority of papers were either case studies or data on materials or aquifers. They asked the question has engineering geology ‘now dealt with the main problems that geology posed for engineering?’ Given the wide scientific frontier that characterizes engineering geology this question was very much rhetorical, provided to provoke industry and researchers into action. To back this up they provided an excellent discussion on research topics which should be explored, most of which is still relevant today. While it is comforting to say that some 12 years later engineering geology still exists as its own entity, the paucity of research in general remains both a weakness and a threat to the profession.

De Freitas (2009) also contributed to the conversation about research, saying ‘for engineering geology to grow these days the driving force needs to be the potential geology has for developing engineering’ and that this potential ‘is the study of geological controls of geotechnical parameters . . . It is research into the origins and controls of these properties that is largely missing at present’. This led de Freitas to a similar conclusion as Fookes (1997) about the difference between engineering geology and geology for engineers: ‘It is the study of what controls the behaviour of ground and its response to change that separates the “engineering geology” in need of development from the “engineering geology ≈ geology for engineers” now practised in industry’. De Freitas (2009) illustrated this relationship between geology for engineers and engineering geology as reproduced in Figure 5. This chart captures the process of how to assess the need for research, which can be summarized as follows (de Freitas 2009).

• Arrow 1 (Fig. 5): routine practice (geology at a simple level) no longer provides an answer to a problem; in many of these cases, answers can be provided by experienced engineering geologists involving a greater geological understanding
• Arrow 2: problems for which current solutions are expensive or there is a lack of knowledge which requires research; powerful companies may develop in-house research potential to help answer these questions or this is achieved via good links between industry and academia
• Arrow 3: curiosity-driven research as undertaken by research institutions.

Due to their battlefront position in engineering, industry has a tendency to focus on short-term engineering-led solutions to design. However, industry should also be sending these problems back to academia to find the geological cause and research smarter solutions as per Arrow 2. Curiosity-driven research is also an essential element of academia which helps generate enthusiasm from researchers, and

* E = Engineering   G = Geological

Fig. 3. Rational approach to conducting subsurface investigations from Stapledon (1982), showing how geology and engineering integrates at each functional level of the investigation.

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>DESCRIPTION</th>
<th>WORK CATEGORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DEFINE OBJECTIVES - ASK QUESTIONS</td>
<td>E &amp; G</td>
</tr>
<tr>
<td>2</td>
<td>COLLECT &amp; ASSESS EXISTING DATA &amp; EVOLVE TENTATIVE SITE MODEL</td>
<td>E &amp; G</td>
</tr>
<tr>
<td>3</td>
<td>PLAN WORK TO FILL IN GAPS - ACTIVITY CHART</td>
<td>E &amp; G</td>
</tr>
<tr>
<td>4</td>
<td>PREPARE COST ESTIMATE</td>
<td>E</td>
</tr>
<tr>
<td>5</td>
<td>CARRY OUT ACTIVITIES TO DETERMINE SEMI-QUANTITATIVE MODEL (ENG. - GEOLOGICAL)</td>
<td>G</td>
</tr>
<tr>
<td>6</td>
<td>QUANTIFY THE MODEL - FIELD &amp; LAB. TESTS</td>
<td>E</td>
</tr>
<tr>
<td>7</td>
<td>ANALYSIS - ANSWER THE QUESTIONS</td>
<td>E &amp; G</td>
</tr>
</tbody>
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† Arrow 1 (Fig. 5): routine practice (geology at a simple level) no longer provides an answer to a problem; in many of these cases, answers can be provided by experienced engineering geologists involving a greater geological understanding

† Arrow 2: problems for which current solutions are expensive or there is a lack of knowledge which requires research; powerful companies may develop in-house research potential to help answer these questions or this is achieved via good links between industry and academia

† Arrow 3: curiosity-driven research as undertaken by research institutions.
this is often the source of ‘blue-sky’ solutions which result in
major leaps in science and technology (de Freitas 2009). A
collection of papers in this volume provide examples of
recent research targeting the interaction between engineer-
ingeering geology and geomechanics. For example, Takahashi
et al. (2016) report on research of how void space and perme-
ability factors control movement and storage of fluids in rock
and sediments. Consolidation behaviour of brown coal from
Latrobe valley in Victoria, Australia is discussed by Moein
et al. (2016), the properties of clay used to line ponds to store
saline water from coal seam gas (CSG) production in
Queensland, Australia are investigated by Indrawan et al.
(2016) while He & Wen (2016) studied the effect of pore-
water salinity on the residual shear strength of clays.

Mapping and technology

There is one part of the narrative by Griffiths & Culshaw
(2004) that deserves to be highlighted and that is in regard
to engineering geological mapping. They describe mapping
as ‘… an under-used and possibly under-developed tech-
nique …’ and suggest ‘… it appears that the geotechnical
fraternity, not really understanding the scientific rigour
involved in mapping, remains sceptical about its application

Fig. 4. Communication model for engineering geology on large, complex projects. After Baynes (1999).

Fig. 5. Relationship between geology for engineers and engineering geology and the origin of research questions. After de Freitas (2009).
and prefers to rely on physical holes in the ground’. De Freitas (2009) also emphasized the importance of mapping, explaining that to ensure geotechnical professionals are familiar with the tenets and operation of the principle of uniformitarianism, the answer ‘is simple: fieldwork that studies geology, as much and as often as possible’. These statements strengthened the thoughts of Fookes (1997) that field skills are a cornerstone, if not the main strength, of engineering geology.

These opinions on mapping were expressed some 7–19 years ago, but what about today? Modern engineering geology practice has certainly embraced new and innovative mapping tools such as photogrammetry, laser scanning, GIS-based techniques including hillshade modelling of Lidar data and 3D computer modelling of subsurface data. The advent of new technology such as these mapping tools presents tremendous opportunities to obtain datasets previously not thought possible. For example, we can now survey slopes remotely where previously it was unsafe to directly field map and large areas can now be covered in a fraction of the time required to physically walk the ground.

However, these techniques are essentially tools and presentation systems and, in many instances, should not completely replace the need to undertake traditional field mapping. In this sense traditional mapping refers to observing, describing, recording and drawing boundaries on a map or plan while in the field; the stratigraphy, structure and hydrogeology of the rock; and the morphology, materials, hydrology, landslides and other processes of the near-ground surface. Models produced remotely in the office using such modern tools should still be checked and enhanced by field mapping.

There can often be a reluctance to undertake traditional field mapping due to a range of circumstances. These include restrictions in approaching outcrops due to project-specific health and safety procedures through to a lack of training and confidence in undertaking field mapping. This latter situation has arisen due to a decreasing pool of educational resources to fund university field trips to teach students mapping. As a core value, field mapping skills are time independent and should therefore be regarded as ‘untouchable’ by university regulators when updating course programmes. Perhaps this is one of the biggest challenges facing our profession, and it is our responsibility as engineering geologists to promote the use of field mapping in all applications. The profession must come up with a plan to ensure there is no further degradation in mapping skills in the face of these threats.

The challenge of managing new technology in engineering geology practice is not new. For example, in 1986 Stapledon brought our attention to the deficiencies of standards and computer engineering logs. Figure 6 taken from Stapledon (1986) illustrates the difference in the geological message between (a) use of basic symbols used with ‘artistic flexibility’ and (b) computer-generated log. After Stapledon (1986). While computer logging has come a long way since 1986, a degree of inflexibility remains in graphically illustrating important geological features.

![Fig. 6. Comparison of graphic log systems illustrating the difference in geological message between (a) use of basic symbols used with ‘artistic flexibility’ and (b) computer-generated log. After Stapledon (1986).](http://egsp.lyellcollection.org/)

There are modern tools, while the user of the log would also have to spend time and effort understanding the log from the words. He concludes ‘that “dominantly words” approaches prevent or discourage engineers (and geologists) from drawing geological features that they see, and from the next step, trying to understand and interpret them’. Computer logging has come a long way since 1986; however, a degree of inflexibility remains in graphically illustrating important geological features on logs that may impact on engineering design.

This is an issue not just for logging but also mapping, where an apparent reluctance or diminishing opportunity for drawing and sketching geology in the field is impacting on the quality of interpretation in the geological model. Today this extends to the use of photographs and digital terrain models, where geological features are too often drawn on the computer screen without the benefit of understanding the scale and geological context of the feature that can only be obtained in the field when making direct observations. These modern tools provide superb frameworks for presenting, illustrating and communicating the model, but they do not necessarily replace the need to undertake and record observations in the field via mapping and description.
Rigidity of codes, misuse of classification systems and stewardship

As part of his Glossop Lecture, de Freitas (2009) addressed the rules of suitable descriptions and the use of appropriate scales in the application of uniformitarianism and superposition in engineering studies. He stated that appropriate descriptions and scales require ‘judgement that calls on the personal relationship developed between a geologist and the ground in question’. He then protests, ‘Every automated intervention especially tick boxes and software, designed to offer a geologist predetermined choices so as to assure uniformity, consistency and quality of work, interferes with the development of that relationship’.

The circumstance that de Freitas is addressing includes the use of logging and description systems which do not allow sufficient flexibility to record observations that may not fit the standard. Such systems blunt the promotion of free thinking and risk understating important elements of the model. This can be a significant issue for large client companies which use multiple consultants. Logging standards are introduced to provide uniformity of product across the different consultants and to ease processing of large quantities of data during development of the geotechnical model. An unfortunate outcome of these systems can be that the benefits of the consultants’ experience, expertise and innovation are lost to the client. Stapledon (1996) rather crudely summarized ‘this approach to logging . . . effectively treats the field logging staff as “well trained monkeys”’. As de Freitas (2009) succinctly says ‘Geologists [and engineers] who experience difficulty relating to ground they have to study do not need software and tick boxes but further field experience’.

Flexibility is required in the adoption of description and logging systems so that the skills, knowledge and experience of the geologist can be brought to bear on the design problem and to allow freedom of judgement to focus on the real needs of the project. This is comparable to a medical practitioner as illustrated by Fookes when he described himself as ‘largely similar to a medical GP (i.e. not a specialist) in trying to understand the patient’ (Fookes 1997). Similar to engineering geology, a medical diagnosis is based on observations of a condition that is not always directly visible and there is reliance on limited sampling of the site together with remote sensing. When managing uncertainty due to the inherent undersampling, both the engineering geologist and medical practitioner ‘must rely on judgement . . . based on an interpretative process . . . and properly tempered experience, with insight and intuition’. Codes, standards and logging systems must maintain the ability of the practitioner to apply their hard-earned judgement, experience, insight and intuition when making their ‘diagnosis’.

Professor Jim Griffiths addressed the impact of rigid codes in the 14th Glossop Lecture (Griffiths 2014). As part of his discussion on risk and uncertainty, he states ‘If codes and standards are adopted without question, then ground engineering overall is stagnating and the lack of appreciation of the ground conditions is leading to designs that are safe but over-expensive, over-elaborate and not an effective use of diminishing resources’. Figure 7 from Griffiths (2014) illustrates the relationship between risk and the role of codes and standards, good practice, risk-based analyses, judgement and innovation in the design process. Innovation has an important place in design but ‘will require a more flexible attitude, and research and testing of new approaches will be necessary’ (Griffiths 2014).

Scrutiny is also required in the application of engineering systems such as rock mass classifications. These systems take observations of several engineering geological characteristics and assign numbers to them, which are then summed in some way to give a single value. This single number is often used to represent total knowledge of the rock mass in the belief it has significance because it is numerical (Bieniawski 1989). While these systems can play a role in engineering parameter selection and design, there is significant danger in using this approach to describe and represent a rock mass. A classification rating provides no information on the collection of physical attributes that make up a rock mass and therefore a rating is unable to promote an understanding of the geological controls on behaviour and process. Even in design it should be remembered that these classification systems are no more than correlation tools taken from a finite database of case studies; use of these systems for design of tunnel support, for example, relies on a degree of faith that the correlations apply to your tunnel (Pells & Bertuzzi 2008).

Care and geological knowledge should be exercised before adopting a particular logging scheme or rock mass classification system. Enabling a consciousness in geological engineers for ‘geological due diligence’ is best initiated during undergraduate studies. Once in professional practice, regular, effective communication is required between geologists and engineers during the course of each project as noted by Stapledon (1982) and Baynes (1999). The engineer is not always to blame for their lack of understanding to what engineering geology can bring to investigation, modelling and design; it is the geologist’s job to educate and demonstrate their ability and value. Tepel (2004) called this ‘stewardship’, which Griffiths (2014) summarized as ‘responsibility for ensuring the long-term health of our profession through improving practice, ensuring a continual supply of new graduates, and developing the state of the art’.

While there may be commonalities between the science and study of medicine and geology, there is much that engineering geology and engineering in general could learn from the practice of medicine in the way they promote their discipline to society. Engineering sciences still has work to do in making the general public aware of its true value to civilization. As Knill (2003) said: ‘Successful engineering geology gains little publicity and as a consequence acquires too little credit’. Some of this is because in recent times scientists and engineers are largely reluctant to promote their work and are reticent to advance themselves to positions in society where they can fairly represent their profession. Professional engineering organizations need to become more
outward-looking with more focus on their role as advocates of engineering science in society.

Models, Total Geology and globalization

The First Glossop Lecture laid the foundation for the concept of Total Geology which is detailed by Fookes et al. (2000), including the founding ideas that ‘The geological history of the area determines the geological condition of the site’ and ‘The power of the model is more in its ability to anticipate conditions than to predict them precisely’ (Fookes 1997). These are the principles that underpin more recent discussions on models in engineering geology such as Sullivan (2010) and Parry et al. (2014). As identified by Sullivan, models have been a major gap in the engineering geology discipline; up until relatively recently the topic was not often taught at university and therefore adoption of the concept has been historically slow in industry. That appears to be changing where the use of models is gaining ground in professional practice.

Models are a powerful tool which can meet the challenge of managing heterogeneity of ground conditions, as described by Fookes (1997): ‘I think the multiplicity of the variables even in a seemingly simple geological situation gives potentially a wide range of problems for rock and soil description, sampling and testing, and of identifying reasonable alternative geological possibilities for the whole or parts of the model’. Understanding the variety and complexity in ground conditions should be viewed as an opportunity to explore and discover and the theory of models is helping to identify and organize these scientific challenges in engineering geology. However, Fookes (1997) also acknowledged that engineering geology needs to be ‘an identity that can offer not only the geological model, but qualification and quantification of subsurface and surface geological and geomorphological processes of all or any facet of geology in engineering circumstances’. To illustrate this point, the link between different types of models and project stages is presented in Figure 8. This diagram shows the role of the engineering geologist in the investigation–modelling–design–construction process, their relationship with the geotechnical engineer and where they can make a contribution to qualification and quantification of geoprocesses for engineering circumstances.

The Total Geology paper was co-written by Peter Fookes and John Hutchinson from the UK and Fred Baynes from Australia, and is a clear example of the increase in globalization of the profession which has occurred since the 1980s. The impact of the Total Geology paper has been profound, and has served to narrow the diversity of method and sharpen the modelling process within engineering geology around the world. It provided a framework for thinking about the
The paper was first presented at the GeoEng2000 conference held in Melbourne, Australia in 2000, which was a collaboration between the ISSMFE (International Society for Soil Mechanics and Geotechnical Engineering), ISRM (International Society for Rock Mechanics) and IAEG. This conference was unique as it allowed international integration across the three sister societies with an interchange of ideas that helped broaden views between disciplines. Professor Norbert Morgenstern presented a keynote address at the conference entitled 'Common Ground' where he states ‘major value added contributions arise from an integrated or holistic approach to geotechnical engineering’ (Morgenstern 2000) in a clear message that all three disciplines of engineering geology, soil mechanics and rock mechanics are important in the practice of geotechnical engineering.

While interconnection still occurs between national groups within each society through their individual international congresses held every four years, surprisingly the successful GeoEng2000 collaboration has not been repeated to date. Morgenstern also said in his 2000 keynote ‘The current organization of the geological community is not adequate to foster this approach’, and this still seems to be the case 16 years later. However, there is some light on the horizon with a reinvigorated Federation of International Geo-engineering Societies (FedIGS) recently approving a modified cooperation agreement between the sister societies, which it is hoped will increase interaction and cooperation between the international groups.

**Engineering geology in mining**

In his discussion on the position of engineering geology, Knill (2003) makes an interesting point that mining geology, resource geology and such fields of extractive geology do not necessarily make good examples for engineering geology to follow. Knill suggests ‘The design of mines is an engineering issue which relates to the application of technologies with which resource-based geology has no direct relationship’.

The connection between resource geology and the rest of the mine design process has evolved in recent times. Previously it was certainly the case that exploration geology was only interested in finding a resource with the focus on how much and what the grade is. Today, resource geology recognizes it is providing a geological model with several customers to satisfy: the mine engineer who has to devise a method and schedule for extracting the resource; the engineering geologist who has to formulate a ground model in the areas within and adjacent to the resource where the underground openings and/or open-pit slopes will be excavated; and also the hydrogeologist and environmental scientist who devise systems for managing the natural resources associated with the mineral deposit. This cooperation...
extends to sharing resources during drilling programs where boreholes are often designed for multiple purposes; less frequent are the days when resource geology, geotechnical, hydrogeology and metallurgical drill programmes are carried out separately, and sometimes concurrently and completely independently.

The role of engineering geology in mining appears to be significantly understated within professional institutions which focus more on civil applications in engineering geology. This is perhaps due to most mine engineering geologists preferring to join mining-related professional bodies such as the Australian Institute of Mining and Metallurgy (AusIMM), The Southern African Institute of Mining and Metallurgy (SAIMM) and the Canadian Institute of Mining, Metallurgy and Petroleum (CIM). A straw poll of employment of engineering geologists in Australia suggests that close to half work in the mining industry, either being directly employed or contracted to a mining company or working for consultants that undertake mine design and/or mine infrastructure development work.

Mining projects invariably involve extensive investigations, relatively large budgets and ready access to new technologies often shared or borrowed from resource geology. They are therefore excellent ‘breeding grounds’ for new ideas and techniques and can speed up the time for adoption of emerging technology into mainstay geotechnical practice. Traditional institutions such as the IAEG are missing out on all these benefits by not actively pursuing mine engineering geologists as members and contributors. Mining represents a diversity in practice area that offers a major opportunity for the development of engineering geology. This is demonstrated by a collection of papers on mine engineering geology in this book.

**Nature of engineering geology knowledge and responsibilities**

The discussion to this point outlines many of the factors contributing to the diverse character of engineering geology. But what constitutes good engineering geology? This question was addressed by Dr Fred Baynes in a paper to the 8th Australia–New Zealand Conference on Geomechanics (Baynes 1999). He summarizes engineering geological knowledge as the following:

- the observations of attributes;
- the interpretation of observations based on education, experience and judgement; and
- five guiding principles that are central to how engineering geology is practised (Fig. 9):
  1. geological knowledge (regional- and site-specific);
  2. spatial and temporal distribution of the geological attributes (the model);
  3. encoding of data in geotechnical language (engineering geological description systems);
  4. transformation into an engineering framework (application of soil and rock mechanics); and
  5. communication of knowledge in cognisance of the project objectives and limitations due to any uncertainties attached to the knowledge.

![Fig. 9. Flowchart illustrating application of the principles of engineering geology. After Baynes (1999).](image-url)
Observation, interpretation and the guiding principles provide the basis for judging what is good engineering geology. Baynes reframed this discussion in 2003 in the form of a list of generic responsibilities when understanding and communicating the geology (Baynes 2003):

- observation and investigation of the geology in engineering projects;
- engineering geological model development;
- establishing standards and scope for the engineering geology activities;
- engineering geological information management; and
- communicating the geology to engineers.

Each responsibility encompasses a number of key competencies which can be used to advocate the profession of engineering geology, including providing a framework for professional registration of engineering geologists to establish a formal profile. With regards to the ongoing promotion of the profession of engineering geology, however, there can be no argument when Baynes (2003) stated ‘my personal preference is to achieve this through the excellence of our work’.

**Some closing remarks on diversity**

Diversity occurs in all elements of engineering geology and is a defining characteristic of both the science and practice of the discipline. In science, engineering geology is in a unique position where the study of all branches of geology is applicable to solving engineering problems. This manifests in the variety of ground conditions and geological environments which confronts the engineering geologist who is prepared to travel and ‘see the rocks’. While this may not be ‘the final frontier’, it certainly represents a wide frontier of scientific opportunities and offers the variety of challenges required to keep the most agitated professional engaged for a lifetime, even ‘to boldly go where no one has gone before’ if they so choose.

In practice, diversity represents a different set of challenges, some of which are weaknesses and threats to the profession. There is variability in the application of engineering geology around the globe, which is partly historically driven due to regional differences in economic conditions driving or limiting opportunities to practice, learning from mistakes and providing resources to educate and undertake research. Globalization initiatives such as the GeoEng2000 conference and papers on far-reaching topics such as the concept of Total Geology are serving to sharpen the practice, together with appropriate application of standards and codes which must maintain flexibility to deal with the diversity in geology to be studied.

The distinctive character of the profession is also somewhat derived from the cross-over between the disciplines of geology and engineering which presents two battlefronts which must be resourced and fostered. This places multiple demands on the profession and, in some respects, diversity in the effort required to manage the discipline means that insufficient attention is paid to other areas. Consequently, resources are spread too thinly, communication suffers and questions about the relevance of engineering geology in geotechnical engineering start to reappear. For example, there is a tendency for too many engineering geologists to become specialists, and this can cause some to get caught up in the engineering design process of their speciality; this results in a loss of focus on the geological contribution they should be bringing to the project. This is not helped by a trend in some jurisdictions to ‘convert’ engineering geologists into engineers, often without the requisite supporting education.

One cannot wholly blame the engineers for this situation; it is the responsibility of the engineering geologist to practise stewardship by continuously reinforcing and promoting the importance of the geological model to the success of the project. Professional registration can also assist engineering geologists in maintaining and enhancing their profile within industry. However, formalization of knowledge and experience with a ticket to practise is only part of the solution, and there will be reliance on all engineering geologists to continue exercising stewardship.

Diversity of effort is also providing challenges with how the profession is coping with the adoption of new technology, how this is best integrated with traditional field mapping techniques to manage the ensuing threat to the degradation of mapping skills, and how to focus more attention on research to help improve the science. It is time for the traditional civil foundation of the discipline to be broadened to embrace the resources, technology and knowledge from the mining industry to enhance the science and practice of engineering geology.

Diversity is a reason to celebrate all the aspects that are exciting in the science of engineering geology. It is also the reason to be watchful about how the practice of engineering geology is developed in the future. There is substantial value in studying the history of engineering geology, not just to record the heritage of our discipline but also to understand where we have come from and to provide a guiding light for future development. The beacon is shining and now is the time for the profession to knock down and get on with advancing the science and improving the practice. As Fookes (1997) summed up: ‘Engineering geology has well served its baptism of pidgeon-holing and “stam-collecting” and now is the time to push back new frontiers’.

**Developments in engineering geology**

The objective of this book is to present developments in the science and practice of engineering geology; it is a salute to diversity in engineering geology. Theme 31 at the 34IGC provided an excellent opportunity for academics and practitioners from around the world to present and debate their recent work. This book brings attention to a number of
major issues and new directions which originated from the conference presentations and resulting discussions, including:

- a broadening of the fields of practice in which engineering geologists’ work is opening new frontiers to the profession;
- the widening frontier is bringing new technology into the profession across a range of applications; and
- this is initiating an evolution in the way geology is modelled in engineering, geohazard and environmental studies, both in new and traditional areas of engineering geology.

These developments are having an impact on the methods used in the communication and teaching of engineering geology. In particular, they are generating new challenges on how to maintain an emphasis on the fundamentals of geology and its application to geomechanics in engineering geology education. An important message arising from the conference is the need for improved communication between engineering geologists and both regulators and the public. This book provides examples of how increasing interaction and consultation with these key groups is helping to improve the range of solutions to engineering, environmental and geohazard problems.

This book presents 20 papers comprising a series of research articles and case histories from 9 different countries. The papers are a mix of contributions from university researchers, consulting practitioners and government-employed researchers and practitioners. The papers are presented according to the symposia in which they appeared at the 34IGC:

- engineering geological challenges for our ever-growing cities;
- engineering geology in mining;
- engineering geology in managing risk from geohazards;
- improving the development of geological models for engineering studies; and
- interaction of engineering geology and geomechanics.

The urban geology papers start with Price et al. (2016), who discuss the management of ground beneath cities and introduce the concept of ecosystem services. They use future scenario analysis in a process termed Urban Sustainable Subsurface Use Methodology (USSUM) to consider the social, technological, economic, environmental and political changes to help find strategies for the future management of the ground and wider environment beneath cities. Issues around urban planning are further explored by Marker (2016), who addresses the lack of geoscience information used by planners when considering sustainable development and why this information is important in planning systems. The paper discusses the presentation of geoscience information, including written results and maps for dissemination of this information to participants in the planning process.

Application of urban geology is considered in the next three papers. Kozlyakova et al. (2016) present a study of the geology of the Moscow area, in particular the occurrence of Carboniferous interlayered carbonate and clay-marl massifs which occur at a depth of 5–150 m below the ground surface. As such, karst-suffusion sinkholes and surface sub-sidence related to buried karst landforms are an issue for urban development and these hazards are mapped together with defined engineering geological zones across the city area. The issue of efficient and sustainable use of aggregate resources is considered by Tuğrul et al. (2016) using Istanbul as an example. Issues discussed include the rapidity of reduction in useable resources, impacts of future closure of quarries near city centres and the inefficient use of current resources. Sustainability of resources is affected by factors such as a lack of detailed knowledge of the geology and availability of suitable transportation infrastructure. Entwisle et al. (2016) advocate the use of desk study techniques, an essential part of civil engineering investigations, for assessment of development and redevelopment of urban areas by government. They describe a spatially defined geotechnical information system to provide geological, geotechnical and geoenvironmental data and information for Glasgow City Council in Scotland. An engineering geological classification has been produced for the city area which can be used to provide rapid assessment of ground conditions.

It is interesting to note all the urban geology papers are from Europe, whereas the next suite of papers on mining is from Australia. This is reflective of the diverse role engineering geology plays in different parts of the world and a great example of the theme of this book. Baxter’s (2016) paper on iron ore mining in the Pilbara region of Western Australia is a demonstration of the utilization of classical geological techniques such as geophysics and geochemistry to help assemble engineering geological models of the Cenozoic detrital sequences in the Pilbara region for pit slope design and groundwater studies. Formulation of an engineering geological model is also explored by Cammack (2016), this time for a copper-gold porphyry deposit in SE Asia. Porphyry deposits are characterized by highly fractured and brecciated rock due to a complicated history of volcanism, chemical alteration and tectonic disturbance. This paper describes efforts to devise a logging and description system to capture the essential elements of the complex rock mass that can be used for assessment of pit slope stability, rock excavatability and haul road trafficability.

Design of open pits for extraction of coal in the Bowen Basin of Queensland is discussed by Pope et al. (2016). Their investigations demonstrate that structural geological controls strongly influence footwall slope design, dividing the deposit into areas of relatively simple structure with uniformly dipping bedding and other areas of complex structure where layer-parallel shortening near fold hinges has resulted in a system of low-angle thrusts and asymmetric minor folds. Strang (2016) reports on a study of a long-time-active slope failure complex in a New Zealand
quarry. This is a case history of how engineering geology can contribute to the understanding of geological controls on slope movement and provide information to assist with resource and safety management of a quarry with pit walls that are actively moving. These four papers are from four different geological environments, and together they provide an excellent example of the evolving role that engineering geology is playing in the mining industry and the contribution mining can make to mainstream engineering geology.

Engineering geology has traditionally been a major contributor to geohazard studies and this is illustrated in the next three papers. Flentje et al. (2016) report on a proposed landmark Australian study to produce a series of medium-scale (1:250 000 to 1:25 000) landslide inventory and susceptibility maps covering southeastern Australia. This will form a series of planning tools to facilitate implementation of the AGS 2007 Landslide Risk Management Guidelines. The paper summarizes the variable approach to landslide regulation at state and local government levels, and addresses the difficulty in preparing a landslide inventory. At a larger scale, Parry (2016) investigates the problems and limitations with landslide hazard assessments. Specifically, the Design Event Approach (DEA) used in Hong Kong government landslide assessments is discussed, including the issues around evaluation of Hazard, as defined in AGS 2007, being the probability of occurrence of an event causing harm. This is examined using a case study from Hong Kong to demonstrate the concerns. The geohazard papers are concluded by Di Capua et al. (2016) with the description of a seismic site classification map of Italy. The study considers the contribution of surface geology to expected ground motion, which is used to incorporate amplification factors provided by the Italian seismic code for use in seismic hazards studies. All three papers come from different geographic areas and illustrate the diverse use of engineering geology to help solve geohazard problems around the world.

The concept and use of models has transformed how engineering geologists think about and approach their work, and provides a structural framework for organizing the investigation and interpreting the ground conditions. Griffiths (2016) starts the discussion with a paper on the importance of incorporating geomorphology in engineering geological models. Understanding geomorphological processes and landforms are fundamental elements to an effective model. However, their incorporation into a fully integrated site investigation is not widely practised as geomorphological research is often undertaken by physical geographers and not always adopted in engineering geological desk and field studies. Geomorphological research should be better utilized by engineering geology to improve the quality of ground models for engineering design.

Application of the model approach is demonstrated in a case study of a dam in Samoa in the paper by Goldsmith & McCue (2016). Regional geological assessments, review of seismic data and drilling provided data to update an existing model to assess the existence of active faulting at the dam site. This case history includes the use of geomorphological studies and geological mapping, which demonstrate there is no evidence for faulting at the dam location. This case study is a great example of how geomorphology can be used in models as promoted by Griffiths. A second example on the use of models is provided by Fabbrocino et al. (2016) in a case history on seismic vulnerability assessments for critical infrastructure. The site studied is from Italy and is used to demonstrate how the regional and local geological, geomorphological and hydrogeological conditions are modelled to assess spatial variability for assessment of site seismic vulnerability.

The final set of papers explores the interaction between engineering geology and geomechanics. This interaction is abundantly demonstrated in the paper Li et al. (2016) which provides a fascinating insight into five large ancient rock caverns discovered in June 1992 in China. It is estimated these caverns were excavated about 2000–2500 years ago, and the paper demonstrates how people at the time understood the influence of geology on stability conditions and how this subsequently led to a change in location and layout of the caverns. This is probably the earliest known use of geological exploration by adits and perhaps the first time the geological observational approach to design was adopted in a remarkable piece of ancient engineering. Researchers in rock mechanics and engineering have conducted various investigations into aspects of these caverns, but most publications are in Chinese and therefore difficult to access for non-Asian geologists and engineers. It is amazing that the general spatial arrangement of the caverns is consistent with modern rock engineering and the underground positioning of individual caverns is of high surveying accuracy. The precision of excavation, the accuracy of underground surveying, the unsupported large-spans under low cover and the integration of the underground shapes with the geology signify these rock caverns are a wonder of underground space development.

Earlier discussions in this chapter on the 9th Glossop Lecture by de Freitas (2009) highlighted the need for more research on geological controls of geotechnical parameters, and the next four papers provide examples on the type of research now underway. Takahashi et al. (2016) report on research of how void space and permeability factors control movement and storage of fluids in rock and sediments. They discuss the use of microfocus X-ray computed tomography (CT) as a non-destructive tool to investigate the number of connecting pathways and to collect data on tortuosity. Consolidation behaviour of brown coal from Latrobe valley in Victoria, Australia is discussed by Moein et al. (2016). They discovered the behaviour of brown coal differs from that of typical engineering soils such that the stress v. strain gradient is higher at lower loads and at higher loads the stress v. strain gradient is almost constant. This suggests that unloading parameters for slope design of open-pit mining in the Latrobe valley requires reassessment.
The properties of clay used to line ponds to store saline water from coal seam gas (CSG) production in Queensland, Australia are investigated by Indrawan et al. (2016). The results show CSG water tended to increase the liquid and plastic limits and decrease the compaction densities of the clay samples. Hydraulic conductivities of the clay samples tended to decrease with decreasing concentration of salt and increasing pH value of the permeating waters. Changes in the index and hydraulic parameters of the clay samples were attributed to changes in the net interparticle forces and in the associated clay structure. He & Wen (2016) also studied the effect of porewater salinity on clays, this time the residual shear strength of clays. While past researchers have shown there is a correlation between residual shear strength of clayey soils and salinity of pore water, He & Wen report on experiments to quantitatively assess the change in residual strength with saline solutions of various concentrations using pure clay and mixtures of clays made from smectite, interlayered illite/smectite and kaolinite. In particular, they investigate whether the residual shear strength of clayey soils continually increases with increasing porewater salinity, and if there is a limit above which the residual shear strength of clays shows little change.

In summary, the collection of work presented in this book clearly demonstrates the wide relevance of engineering geology across a range of research opportunities and design applications. It shows that engineering geologists are getting on with studying the science and bringing new solutions to practice. In the words of de Freitas (2009), case histories are valuable as they are ‘the geological calculators for the engineering geologist’ and ‘allow the principles of geology to be used with confidence’.

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