# Core values: the first Hans-Cloos lecture

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**Abstract** The traditional scope of engineering geology was the application of geology in construction practice, but this has become widened in time to embrace other fields of engineering, environmental concerns and geological hazards. The subject lies at the interface between the observation and description of natural processes associated with the science of geology and the knowledge of numeracy and material properties required for design and manufacturing central to the engineering process. A consequence is that engineering geology has come to be seen as secondary to soil and rock mechanics within geotechnical engineering, even though the subject is required to be applied throughout the construction sequence and cost over-run, delay and failure during construction are commonly ascribed to geological errors. The role of engineering geology as a discipline needs to be defined and the central role of geology has to be re-emphasised by improving the understanding of geological uncertainty in contributing to geotechnical risk, developing improved protocols in the formulation of meaningful geological and ground models, and more systematic methods of presentation of ground-related reporting. National and international organisations in engineering geology have an important challenge in providing the leadership through which an enhanced function and status for the subject can be attained.

**Résumé** Le champ traditionnel de la géologie de l'ingénieur a été l'application de la géologie à l'art de construire, mais ce champ s'est élargi avec le temps, couvrant d'autres domaines relatifs aux travaux de l'ingénieur, à l'environnement et aux risques naturels. La discipline se situe à l'interface entre l'observation et la description de processus naturels relevant des sciences de la Terre et l'étude des propriétés des matériaux et la maîtrise de la modélisation nécessaires au dimensionnement et la mise en œuvre d'ouvrages relevant de l'art de l'ingénieur. Une conséquence de cette situation est que la géologie de l'ingénieur a été perçue comme secondaire par rapport à la mécanique des sols et la mécanique des roches au sein de la géotechnique, bien que la contribution de cette discipline soit nécessaire tout au long du processus de construction, les dépassements de coûts, les retards et accidents pendant la construction étant communément attribués à des difficultés géologiques. Le rôle de la géologie de l'ingénieur comme discipline doit être défini et le rôle central de la géologie doit être à nouveau souligné en améliorant notre compréhension des incertitudes d'origine géologique dans la constitution du risque géotechnique, en développant des procédures performantes pour la définition de modèles géologiques réalistes et en établissant des méthodes systématiques pour la présentation des rapports géologiques. Les associations nationales et internationales de géologie de l'ingénieur ont un important défi à relever en indiquant la direction à suivre pour que le rôle et le statut de la discipline soient mieux reconnus.

**Keywords** Hans Cloos · Core values · Engineering geology

**Mots clés** Hans Cloos · Valeurs fondamentales · Géologie de l'ingénieur

It is with great regret that we record John Knill's death on 31 December 2002.

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## Tribute to Hans Cloos

Hans Cloos was one of the main contributors to the development of modern structural geology during the first

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half of the twentieth century. Despite his writings being almost exclusively in the German language his thinking had an enormous influence at the time; it forms the basis of much modern structural geology and his work is still quoted.

Cloos was born on 8 November 1886 in Magdeburg in Germany and he gained his geological training at the University of Freiburg im Breisgau which is located near the juncture of the Alps and the Black Forest [much of this section draws upon Balk (1953)]. His PhD thesis was concerned with the mechanism of disturbance of the Jurassic cover rocks which form the Jura mountain chain. He then travelled to south-west Africa at the invitation of his uncle where he mapped in the Erongo Mountains. This visit is described in graphic, almost poetic, language in his book "Conversation with the Earth" (Cloos 1954), originally published in German in 1947. The book vividly describes episodes in his professional career which is seen as a voyage of both personal and scientific discovery. The opening chapters, on his African experience, illustrate features of his working style which characterised the remainder of his career. In particular he is seen to be a careful field observer who was able to prepare detailed, precise field sketches of structures and lithological relationships on all scales. However, most impressive are his superb three-dimensional interpretations of regional geological structures and topographical landforms which he continued to draw throughout his life. Some of his drawings were reproduced by Richard Wolters, a former student of Cloos and a Hans-Cloos Medallist (Wolters 1976), to mark the 25th anniversary of Cloos' death.

Almost immediately on his return from Africa he signed a contract to travel to Indonesia to work as an exploration oil geologist for 2 years. This decision caused him some torment because he felt that "*I had sold something much more valuable and irretrievable—two long years of my young life and of my capacity for work*" (Cloos 1954) However, he recognised that he needed financial capital to fulfil his ambition to establish himself in an academic career. Fifty years later, my own Professor told me, in all seriousness, that I was "*selling my soul to the devil*" when I advised him that I was to pursue a career in engineering geology. Nearly 50 years farther on it is regrettable that such arcane views are still firmly fixed in academic minds. Nevertheless, the relevant chapters in "Conversations with the Earth" indicate that his period in Indonesia was by no means intellectually sterile, notably in relation to the appreciation he gained of modern volcanoes. Like most field geologists he became frustrated by days of exploration in the jungle searching for rare exposures, and never appeared to return to such terrain.

On his return to Germany he began lecturing at the University of Marburg, but this was overtaken by service in the First World War from which he was released on grounds of ill-health after acting as a military geologist in France. He then worked for Krupp in Silesia and soon became associated with the Department of Geology in the University of Breslau. The head of this department was killed in Turkey and in view of the quality of some guest lectures Cloos had been invited to give it was not surprising that in 1919 he was appointed to the chair of geology when only thirty four.

The economic difficulties in post-war Germany restricted opportunities for fieldwork so Cloos concentrated his activities in the granite quarries of Stehlen, 30 km south of Breslau. He was able to map in detail the relationships between joint orientation, mineral alignment and dykes associated with the intrusion and post-intrusion history. This experience married well with his earlier observations in the Erongo Mountains where he had observed the role of wall-rock fracturing in controlling stoping at the granite contact and thus the intrusion of the igneous mass. In 1927 he carried out preliminary studies of the Sierra Nevada batholith in the USA which formed a perceptive and accurate framework to subsequent more detailed studies by others, including his brother Ernst Cloos. His major contribution to the understanding of granite tectonics is reflected by his name being incorporated in the sub-title to Robert Balk's monograph on the "Structural Behaviour of Igneous Rocks" (Balk 1948).

During a student field trip to the Harz Mountains he had been able to observe the north-eastern margin where Palaeozoic rocks have been thrust over a younger succession. He recognised the manner in which large-scale structural deformation leaves a fingerprint in the form of small-scale structures, thereby indicating the direction and style of tectonic translation.

In 1925 Cloos became head of the Department at the University of Bonn where he spent the remainder of his career. He was able to follow up his interests in small-scale tectonic structures in the west German Devonian and Carboniferous slates, amongst other areas, where he and colleagues addressed issues such as the relationship between folding and slaty cleavage, relative ages of quartz veins, variations in fold trend and the role of underlying basement rocks on the deformation of the cover. He published many papers on these subjects which underpinned a major concentration of his research effort in Germany and other countries for the rest of his life.

Many individuals, almost unknowingly, will be familiar with one aspect of his research and this relates to the laboratory experiments in which large blocks of clay were progressively extended under tension. Textbooks on structural geology commonly contain reproductions of photographs of the model graben formed in this way. He had recognised, from field observations, that the direction of the imposed stress influenced the resulting fracture system and that clay provided a suitable, scaled medium by which to model rock mass behaviour. Using these dramatic experiments he was able to confirm field interpretations of the relationship between stress, deformation and fracture formation. Direct field observations made within the Rhine graben confirmed that the styles of faulting seen in the model were actually present. Although such observations may, at the present day, be regarded as self-evident, they were unique at the time, demonstrating that Cloos was at the leading edge of research in tectonics. Throughout this period he travelled extensively, particularly to the USA and Scandinavia but also widely in Germany. Such visits are documented in "Conversations with the Earth" as he applied his experiences in granite tectonics, volcanic processes and rift valley faulting to explain and then illustrate the features that he saw. He was an inveterate field sketcher.

The Second World War brought great stress to Cloos, but he was able to gently resist the pressures brought to bear on him by the regime in power. Throughout, he was loyal to his Department and to the interests of students, colleagues and friends who chose different sides of the political divide. It was only towards the end of the war, in 1945, that he eventually found it necessary to take active steps to evade arrest. After the war he was invited to be Mayor of Bonn but refused, devoting himself to the Department and to the needs of students and friends. Through careful management and protection, the geological collections and library had been saved so that his school was one of the very few intact departments remaining in central Europe at the time. On his last visit to the USA in 1948, Cloos received the Penrose Medal of the Geological Society of America, an act that reflected the debt which the geological community owed for his massive contributions to our science. He died on 26 September 1951.

Those who knew Cloos speak of him as being an inspirational teacher, kindly, humorous, skilled in languages and tolerant. As a geologist he was outstanding, being able to translate field observations into dynamic processes. Once he had solved an intellectual problem he moved on, so many of his publications provide a condensed analysis of a challenging problem. He had a major grasp of the literature, placing his own contributions fairly within the context of the work of others. His approach was regarded as unorthodox, whether in writing or orally. He paid particular attention to clarity both in text and graphics.

He was, however, not an engineering geologist and it is interesting to reflect on the choice of naming of the Hans Cloos Medal in his tribute. He demonstrated all the characteristics of a good engineering geologist—he was an excellent field observer and recorder, he pioneered the collection of data on discontinuity systems, he related his observations to natural stress systems and he was able to present his observations and deductions within a three-dimensional environment. Nevertheless, he "*left to others*" (Balk 1953) numerical studies of his work and was keen to create at Bonn a centre for "*all members of the profession who desired to maintain honest scientific work without selling their soul*" (Balk 1953), reflecting his reaction to being employed for 2 years in the petroleum industry. Sometimes he added a section at the end of a paper entitled "limitations", thereby exposing his own reservations on the extent to which his work had been, or could be, taken. This was a recognition of the need for some form of uncertainty or risk assessment well ahead of its time.

We have every reason to take pride in the premier award of the Association being named in honour of Hans Cloos.

## Is there reason for concern about engineering geology?

For many years I have puzzled as to whether the subject of engineering geology could be regarded as a free-standing discipline equivalent in status to the position that soil mechanics and rock mechanics have in the formulation of geotechnical engineering. On the other hand, is engineering geology simply a practical vocation providing the necessary functional underpinning to soil and rock mechanics but without sufficient intellectual merit to be regard as independent in its own right? Leopold Müller-Salzburg (also Müller), the doyen of modern engineering rock mechanics who was a former student of Cloos as well as a Hans-Cloos Medallist, appeared in no doubt when he stated that "*The establishment of engineering geology as an independent scientific discipline and basis of all geotechnical practice, which was only a concept and a distant goal at the time of Josef STINI, the grand old man of Engineering Geology, has become a reality. So great has been the success of this new branch of science that sound practice of construction in rock and soil has become unthinkable without it*" (Müller-Salzburg 1976). In contrast, Martin (2000), a senior member of a very large geotechnical office in Hong Kong, states that "*The engineering geologist's role (in slope engineering) has broadened over the years but the key inputs are still those of rigorous site observation, recording and analysis of geological (including groundwater) and geomorphological detail*" and "*the geologist's role in local slope engineering is essentially that of a service agent, with relatively specialist geological skills and inputs being integrated by a project engineer*". Fookes (1997a) offers a somewhat ambivalent view, arguing that engineering geologists need to "*maintain their integrity as a strong independent discipline which is one of service to the engineer...*", and that their main role is "*to get the geology right*".

Morgenstern (2000), in his millennial lecture at GeoEng2000 in Melbourne, recognised that there was common ground between the three discrete subjects which comprise geotechnical engineering. However, if there is common ground, then each constituent subject must have its independent characteristics and so aspire to be a discipline; each must display its own set of core values. This lecture addresses this issue in so far as it applies to engineering geology.

Karl Terzaghi made a unique contribution to the development of soil mechanics, rock mechanics and engineering geology. Throughout his life there was a fascinating interplay between his contributions to soil mechanics, for which he provided the unifying foundation, and his closely parallel interests in geology and engineering geology (Bjerrum et al. 1960; Goodman 1999). During the early part of his professional career he had observed striking discrepancies between the forecast and actual behaviour of earthworks and foundations. In 1912 he travelled to the USA with the hope of rationalising this apparent conflict and achieving some correlation between geological reports on projects and the construction experience. However, "*In* *spite of utmost concentration on his self-appointed task, this first attempt turned out to be a discouraging failure*" (Bjerrum et al. 1960). This experience led Terzaghi to turn his attention to developing a systematic, rational approach to soil mechanics based upon the study of the physical properties and behaviour of soils, although his interest in engineering geology and geology never left him. Goodman (1999) records how in 1916 Terzaghi was applying himself to "*a soils engineering book on a geomorphologic foundation*" and that in the 1930s "*Writing a practical volume on engineering geology...had been Karl's ambition from the earliest days...*". In 1943 Terzaghi commented (Goodman 1999), at the time that he and Peck were working on "Soil Mechanics in Engineering Practice", that "*I do hope that the practical consequences of my excursions into Engineering Geology will be less catastrophic than those of my doings in Soil Mechanics*" and that engineering geology was "*a strangely elusive subject, slippery like a reptile*". An opportunity arrived in 1945 when he co-operated with R.V. Proctor and T.L. White in contributing a section on tunnel geology and its relationship to the design of steel supports to their joint text. This was a start, but, as commented by Goodman (1999), Terzaghi "*never got around to writing the rest of the book on engineering geology*". Some years later Müller commented that "*There are engineers who are in the habit of asking: What is engineering geology good for when soil mechanics is available to us! (Some lecturers of soil mechanics are said to tell the students that after reading soil mechanics they may forget all what they had to learn in geology.) This false idea probably stems from those books of 'Engineering Geology' which are in fact but a compendia of soil mechanics with a 'relay' of a few concepts from general geology. Such geological introduction was indeed in the intention of TERZAGHI, who wanted to base his 'Erdbaumechanik auf bodenphysikalischer Grundlage' (1925) on sound geological knowledge and who was thoroughly instructed in geology. As early as 1929 he declared in his first lecture that every soil mechanist should also be at least half-geologist. In a discussion I had with him shortly before his death, he expressed disappointment in having failed to convince his successors of this necessity. There are even today few soil mechanists who are able to transfer geological data into mechanical parameters and, for example, to decide which soil samples can be regarded as representative of the respective geological environment. There are even fewer who can interpret the depositional conditions genetically, which must result in wrong inter- and extrapolation of boring profiles*" (Müller 1974). Although work continued on the book, towards the end of his life, Terzaghi recognised in 1963 that he no longer could hope to finish this book "*because the subject is, for the time being, too much in a state of flux and my time is running out*" (Goodman 1999). Goodman drew the analogy between Terzaghi's ambition to complete his book on engineering geology and Ahab's search for the white whale, with the flux referred to before his death as being possibly "*the stern wake of Moby Dick*". Terzaghi's unrewarded travails in trying to rationalise engineering geology are not unique.

Müller-Salzburg, in an extension of the quotations given earlier, commented that "*However, it appears to me the development of the science in the recent years does not seem to head in a direction that one could feel satisfied with. Again and again we seem to divert from the right path and one could say that many of us do not even seem to know the ultimate goal. This explains why one gets such different answers to the basic question what Engineering Geology really is. Many engineering geologists actually engage in activities which would rather fall within the scope of soil mechanics or rock mechanics. Instead they should rather deal with the influence of geological factors on the planning, design and execution of construction works by making use of their geological knowledge and construction experience. At the same time many engineers feel obliged to deal with engineering geological problems because of the gaps in knowledge left open by the geologist*" (Müller-Salzburg 1976). He recognised that there was authoritative recognition that soil mechanics and rock mechanics must be practised in association with engineering geology. Further, he stated that "*The numerous examples of unsuccessful cooperation between engineers and geologists would fill many books. This shows that it is not sufficient to bring two experts from different fields to work together. Since they even seem to speak two different languages, so they can hardly understand each other, progress must be limited. A jurist and a medical doctor working together on a corpse: this is not necessarily forensic medicine! Similarly engineering geology is not identical with applied geology*". Müller-Salzburg saw "*engineering geology as an independent science...from the beginning associated with impulses towards quantitative interpretation of geological facts, required for engineering calculations or at least for a rational assessment of engineering problems*". This article is quite brief and it is regrettable that he did not rise to his own challenge of defining more closely his concept of the nature of engineering geology. Rather, he closes the article with the telling phrase that engineering geologists are scientists "*who have accepted the difficult task of tilling the barren interdisciplinary land*".

In a recent Keynote Address entitled "Common Ground", Morgenstern (2000) addresses "*the unifying elements in geotechnical theory and practice*" in which he recognises that "*major value added contributions arise from an integrated or holistic approach to geotechnical engineering*" but that "*The current organization of the geotechnical community is not adequate to foster this approach*". In an analysis of the origin of the components of geotechnical engineering, he recognised that, first, it was Karl Terzaghi who built upon the contributions to earth pressure theory and slope stability in the nineteenth century to create coherence in the subject of soil mechanics, leading to its emergence as a discipline, in its own right, in the 1920s. Terzaghi recognised that it was essential to assign engineering properties to geological materials before it was possible to anticipate, through numerical analysis, the behaviour of the material in practice. Morgenstern recognised the various historical and interdisciplinary strands within the development of rock mechanics which were drawn together so effectively by the first Congress of the

International Society of Rock Mechanics in 1967. Apart from the difference in material state, Morgenstern drew attention to the major distinction between soil and rock mechanics which arises from the role of discontinuities, and the bulk properties of jointed media. The development of modern rock mechanics resulted in the powerful numerical methods used to analyse such discontinuous behaviour relevant to the behaviour of both soil and rock masses.

The text of Morgenstern's analysis of engineering geology is as long as that for soil and rock mechanics taken together. Engineering geology was established in an institutional international context following discussions at the 22nd and 23rd International Geological Congresses held in 1964 and 1968 which led up to the establishment of the International Association of Engineering Geology (IAEG) (Arnould 1970), with its first Congress being held in Paris in 1970. However, the development of engineering geology as a subject has had a much longer history (Legget 1962; Kiersch 1991) through the application of geology in major construction projects largely in the USA and Europe, from the latter part of the nineteenth century. By 1910 geology was being widely taught to student civil engineers, by 1950 the practical use of engineering geology was well disseminated, and formal postgraduate training was established by 1960. Morgenstern recognised that the definition of the subject could be most simply provided by identifying the tasks expected of engineering geologists, and their role within the engineering organisation. He comments that "*While the special scientific principles underpinning soil and rock mechanics are readily discerned, those of engineering geology are more elusive*", echoing Terzaghi's "*slippery like a reptile*", and questions with regard to engineering geology practice "*whether this classical inductive approach limits the role of the engineering geologist*". The use of geological process modelling (Morgenstern and Cruden 1977; Fookes 1997a) is seen as a way in which complexity, and the distribution of geotechnical properties, can be resolved. In recognising that "*risk must be managed to overcome limitations of site characterization, knowledge of material properties, other unknowns and the vagaries of construction practice*", the role of the engineering geologist is seen as being elevated to the role of risk manager through geological model-making.

Terzaghi, Müller-Salzburg and Morgenstern each achieved international pre-eminence within geotechnical engineering spanning a period of effectively a century, and each has showed in their personal practice a depth of understanding for, and appreciation of, the role of geology and engineering geology in geotechnical practice which is quite exceptional. Yet 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.

These three sets of observations are, of course, based on personal experience, but are they also characteristic of the wider geotechnical community? Baynes (1996) commented in the context of Australian practice that "*I suspect that engineering geology is failing to contribute to geotechnical practice in proportion to its importance, particularly in Australia. This is not to say that engineering geologists or engineers who think like geologists are not applying their skills, but that the branch of knowledge known as engineering geology seems to have stagnated and is not generating anything new, relevant or exciting....This situation is possibly reinforced by the Geomechanics Society being a branch of the Institution of Engineers with connections between the Australian Geological Society and the Geomechanics Society being poorly developed, and the engineering group of the Australian Geological Society irrelevant to most practitioners (it has become an environmental group)*". It is clear from my many discussions over the years that the views held by Baynes regarding experience in Australia are by no means unique.

In the United Kingdom, the British Geotechnical Society (now Association) was established in the early 1960s with the purpose of jointly representing the learned society interests of soil mechanics, rock mechanics and engineering geology. At an early stage the Rankine Lecture was established as a prestigious, international event which would be delivered by an individual on a subject within the scope of the Society. Not one of the 42 lectures delivered to date has been given by a mainstream engineering geologist, although the title and subject matter of a number of lectures has addressed both geology and engineering geology. The Engineering Group of the Geological Society of London was established at a slightly later date and recently created the Glossop Lecture, with only one of the first five lectures being given by an engineering geologist. These two situations are a remarkable indictment of not only the geotechnical community's view of engineering geology, but also engineering geology's own view of itself.

Why has the situation developed in which engineering geology, which can work so effectively at the level of actual geotechnical practice, does not appear to have fuller recognition or clearly defined disciplinary roots? Furthermore, why is it that engineering geology is seen to have a subordinate institutional role within geotechnical engineering?

## Development and definitions

### Summary history of engineering geology

Engineering geology grew as a separately identifiable subject starting in the late eighteenth century, being derived from the practical contribution made by geologists and civil engineers to construction projects and to the study of geological hazards. It is apparent that a fundamental appreciation of the importance of the engineering properties of rocks and soils, the influence of water and the role of geology in the siting of engineering structures originated much earlier, having already been in place for at least five millennia (Kiersch 1991). Throughout much of this period the skills of miners, who also needed a parallel understanding of geology, were separately directed to the search for, and safe exploitation of, useful minerals. Public works such as roads, aqueducts, canals, harbours and tunnels had all been constructed in the region surrounding the Mediterranean Sea in the three millennia B.C. These works were essential to the infrastructure supporting the growth of major cities, the centres of which contained many large buildings and monuments. The Pyramids of Egypt, built in the third millennium B.C., one of the very few man-made structures visible from space, required considerable engineering knowledge in the selection, working, transportation and placement of stone blocks in order to avoid adverse structural deformation and decay. Strategic sites, for the location of defensive positions and castles, benefited from the geological controls offered by isolated rock outcrops and hills. The abstraction of groundwater in areas of arid pediment had been carried out using sophisticated adit systems (e.g. the qanats of Iran) and for the purposes of improving conditions in waterlogged ground by pre-drainage.

However, it was not until Europe moved from Medieval times into the Renaissance that scientific observations of geology and geological processes began to be recorded and to be used for practical purposes in construction. Indeed, it has been argued by Kiersch (1991) that Leonardo da Vinci was the "*earliest recorded 'applied geologist' for engineered works*".

William Smith, a canal engineer working in England at the close of the eighteenth and start of the nineteenth centuries, has two claims to geological fame. He first recognised that the sequence of layers exposed in canal cuttings could be identified in other areas, and that these layers were characterised by the included fossils. His understanding of stratigraphy led to systematic mapping, and to the publication of the first coloured geological map of England in 1815. His second contribution was the ability to apply this knowledge in the construction of canals and excavations, and in groundwater control. Nevertheless, deemed a "practical man" by his peers at the time (Winchester 2001), he was never fully accepted as intellectually respectable by the more academic, contemporary geological establishment. Many engineering geologists might feel, at the present day, that little has changed. Despite this early advance by Smith, the development of engineering geology in the United Kingdom was, for well over a century, to remain in the hands of civil engineers directly concerned with construction.

Much of the progress in the understanding of the importance of geology in construction during the nineteenth century was associated with the driving of tunnels (Rziha 1874) and dam building (Lapworth 1911). The excavation of the first tunnel under the River Thames in England was started in 1823 and, after many difficulties, took 18 years to complete, still remaining one of the largest soft-ground tunnels in current use (Skempton and Chrimes 1994). The succession of trans-Alpine tunnels, preceded by geological investigations, encountered demanding ground conditions including severe groundwater inflows, elevated rock temperatures, high rock stresses and permeable river channels. This same mountainous environment also provided opportunities for studies by Albert Heim, following the Elm rockslide in 1881, of the rapid lateral displacement of rock debris, or stürzstroms. Although there was extensive construction activity in the USA during this period, there are few recorded examples of projects in which geological studies were carried out as a preliminary (Kiersch 1955). Academic courses in engineering geology, delivered to engineers rather than geologists, were restricted to few universities.

By the start of the twentieth century there was abundant documentary evidence that a prior understanding of geology should be an essential component of any major construction project. It was, however, to be some decades before this came to be universally recognised and still longer for the consequences to begin to be implemented. Civil engineers, for some time to come, either ignored geology or sought out geological knowledge for themselves.

Two events in the first decade of the new century focused particular attention on the importance of geology in relation to civil engineering. Early studies of the materials to be excavated along the route of the Panama Canal by French geologists indicated that they were weak, readily softening and liable to disintegration in water. These warnings went unregarded and the large-scale landsliding, which subsequently started in 1906 and culminated in the Culebra slide of 1910, resulted in the recognition that a knowledge of geology was fundamental. C.W. McDonald was then appointed as the first resident geologist recorded to be present on any engineering project. Sliding continued both during and following construction; the side-slopes to the Canal remain under active monitoring and maintenance. The massive damage associated with the second event, the San Francisco earthquake of 1906, drew attention to the effect of displacement on a large-scale active fault system on engineering structures. Of particular importance was the recognition that local ground conditions, as well as building design, significantly influenced the resulting earthquake intensity and structural damage.

At this same time, the City of New York Metropolitan Board of Water Supply appointed James F. Kemp and William O. Crosby as consulting geologists for the Catskill Aqueduct in 1905. Both had previous experience in engineering geology and were soon to be joined by Charles P. Berkey (Paige 1950). This highly successful collaboration demonstrated the value of the timely application of geology in civil engineering, further adding to the slowly growing acceptance by civil engineers of the contribution that could be made by geologists. This resulted, in the USA, in the progressive involvement of consulting geologists and then full-time staff on major water-supply projects, involving aqueducts, tunnels and dams, associated with the Bureau of Reclamation, the Tennessee Valley Authority and the Corps of Engineers. The failure of the St. Francis Dam in California in 1928 as a result of inadequate foundation conditions, and the difficult ground conditions encountered in the excavation of the Moffat Tunnel in Colorado (1923–1927) served to justify and reinforce this trend.

Although the growth of engineering geology in the first four decades of the twentieth century can be best illustrated from the USA, there were significant developments elsewhere. The occurrence of major landslides in quick clays on the railway system in Sweden resulted in the establishment of, first, a research institute and then a geotechnical commission in 1914. Maurice Lugeon, in France, became closely associated with the geological aspects of the siting, investigation and construction of dams. His contribution is still preserved as the name of the unit applied to the results of in-situ permeability tests in boreholes in rock which he devised (Lugeon 1933). The status that engineering geology had achieved by the late 1930s is effectively illustrated by Robert Legget's book (Legget 1962), which was derived from a comprehensive study of case history experience. Legget recognised that his approach was descriptive, containing neither mathematics nor formulae, cogently arguing that there was no substitute for sound observation and good judgement. By this time, therefore, there was increasing acceptance, and application, of the role of geology in the civil engineering of many countries. Engineering students were being taught some geology and engineering geology on a systematic basis, but training of geologists in engineering geology was effectively non-existent. The consequence was that geological advice on engineering projects was still normally provided by geological consultants who were commonly based in universities. The larger-scale deployment of geologists on engineering projects, as in the USA, was exceptional.

During the opening decades of the twentieth century, Terzaghi recognised that close links existed between geology and the engineering behaviour of soils and rocks and, throughout his life and writings, there was a continual search to understand, through engineering geology, the geological influence on engineering projects (Goodman 1999).

The accelerating growth of soil mechanics from the 1940s onwards, driven by the post-Second World War increase in economic development and construction, brought with it a worldwide need for geologists to be employed in site investigation, by consulting engineers and by civil engineering contractors. Universities created postgraduate and undergraduate courses in engineering geology in order for geologists and engineers to meet the consequential demand for trained personnel. By the 1960s the numbers of practising engineering geologists had become such that national and international representative organisations began to be established, together with journals and serial publications. The role of geology in civil engineering, and the employment of geologists in the construction industry, had become established.

The failure of the Malpasset Dam in France in 1959 and the fatal rockslide into the Vaoint reservoir in Italy in 1963 could be interpreted to be the result of a continuing lack of understanding of geological conditions by engineers. However, in each case, substantial, prior geological advice had been taken. These incidents became contributory to the recognition of the need for greater numerical understanding of the behaviour of rock masses, thereby contributing to the establishment and growth of rock mechanics within civil engineering. Traditionally, rock mechanics had been regarded as a part of mining engineering, being applied in mine planning, support design and subsidence control. The growth in construction from the 1940s onwards resulted in both larger and more sophisticated structures being built, as well as the need to develop sites that were less favourable geologically. The consequence was the recognition that some aspects of geological uncertainty could be answered by the application of fast, sophisticated computational methods in rock mechanics associated, for example, with concrete dam foundations, large underground structures, tunnel support and rock slope design which were capable of handling large amounts of data.

An understanding of groundwater is essential to engineering geology. In regions of the world where aquifers are developed for water supply, hydrogeology has developed as a discipline separate from engineering geology. Thinking has been largely resource-driven, being based on the search for, and exploitation of, geological conditions which can provide major supplies. However, because water contained within soil and rock masses has an influence on most engineering works, mainly as a nuisance rather than a resource, hydrogeology is also a basic part of engineering geology.

As the construction industry is responsible for the building of visible structures that can directly influence and contribute to day-to-day life, the role of engineering geologists has progressively widened into the environmental impact of surface development and mineral extraction, the remediation of brown-field sites, waste disposal and geological conservation. In addition, engineering geologists have the appropriate skills and awareness needed for the identification of risks as well as the consequences of geological hazards and processes. This aspect of engineering geology, which self-evidently embraces social issues, is generally termed environmental geology (Knill 1970).

By the close of the twentieth century, therefore, engineering geology had established itself, with soil mechanics and rock mechanics, as one of the component members of the field of geotechnical engineering. The strength of the subject undoubtedly lies within the practical application of the subject which has, almost universally, been highly successful. However, unlike soil and rock mechanics, the practical application of the subject has not been matched by the development of a scientific rationale for the subject, which provides the foundation for a scientific rationale for engineering geology as a subject. It could be that the parts of the jigsaw exist, but they have never been brought together to create a logical whole, though it may be that those parts of the jigsaw that appear to exist could never be fitted together.

## Definitions of engineering geology

Engineering geology is most simply described as the application of geology in construction practice. This straightforward but traditional definition (Paige 1950) makes it apparent that the subject draws together four separate strands. First, engineering geology is based upon a fundamental, comprehensive knowledge of geology and this, for engineering purposes, needs an understanding of the range of geological materials and processes. Second, the subject requires a grasp of the engineering properties and behaviour of the solids and fluids that occur at, or close to, the Earth's surface. Third, the subject requires some knowledge of mathematics and a comprehension of the relevant mechanical principles. Finally, actual experience of the subject will largely be derived from construction projects applied within the framework of civil engineering procedure extending from inception to completion. The first Statutes of the IAEG (Arnould 1970) record the scope of engineering geology as covering "*the application of the Earth Sciences to Engineering planning, construction, prospecting, testing and processing of related materials*".

Although this definition has stood the test of time well and remains central to the subject, the scope of engineering geology is now much wider, being applied more broadly than the civil engineering industry alone. This development has occurred because engineering geology is that branch of applied geology that deals with the mass behaviour of natural materials and such issues arise within other aspects of the industrial aspects of geology, such as open pit mine and quarry stability, groundwater inflow into mineral excavations and borehole stability.

There has been an enormous growth in the importance of environmental issues for which engineering geologists are appropriately trained, including solid and liquid waste disposal, pollution migration and retention, and contaminated land. The identification of satisfactory sites for different types of waste storage and disposal and the remedial treatment of contaminated sites form an important part of engineering geology. With pressure for the re-use of land for construction purposes, investigations are commonly focused on changes that have resulted from human interference, including waste disposal, quarrying, shallow mining and fluid abstraction. Greater concern for the proper management of the landscape as a natural resource and the importance of archaeological features is enhancing the role of geological conservation within which engineering geology has an important role.

Engineering geology originated from both the application of geology to construction and the study of catastrophic natural processes, such as landsliding, subsidence collapse, earthquakes and volcanic activity. Whereas such natural processes may have been studied from a scientific viewpoint for two centuries or more, they are now of far greater practical importance, particularly where they act as hazards causing injury, loss of life, damage to property, erosion and deposition and loss of land. Four of the disaster-forming processes, volcanic activity, landsliding, droughts and earthquakes, recognised by the International Decade of Natural Disaster Reduction which commenced in 1990, create issues relevant to engineering geology. Longer-term global environmental change (Knill 2001a, 2001c) is resulting in an increased probability that geotechnical methods will be needed to an enhanced degree in future decades as a result of rising sea level, climatic variation causing both increased precipitation and drought, rising temperatures as well as social change.

The consequence is that engineering geologists are now being increasingly employed in non-traditional areas to deal with environmental issues for industry, site owners and government agencies including regulators. The IAEG responded to this development by adding "*and the Environment*" to its title in 1997, and the Bulletin of the Association now states that "*Engineering geology is defined in the statutes of the IAEG as the 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 or activities of man, as well as the prediction and development of measures for the prevention or remediation of geological hazards*".

The USA-based Association of Engineering Geologists (AEG), which is somewhat older than the IAEG, states that "*Engineering Geology is geologic work that is relevant to engineering, environmental concerns, and the public health, safety and welfare*" and "*as the discipline of applying geologic data, techniques and principles to the study both of a) naturally occurring rock and soil materials, and surface and subsurface fluids, and b) the interaction of introduced materials and processes with the geologic environment, so that geological factors affecting the planning, design, construction, operation and maintenance of engineering structures (fixed works) and the development, protection, and remediation of groundwater resources, are adequately recognized, interpreted and presented for use in engineering and related practice*" (Association of Engineering Geologists 2002). The AEG also recognises that "*In recent decades the scope of Engineering Geology practice has grown beyond its original close connection to civil engineering practice*". It could be argued that such modern definitions of engineering geology as now drafted by both the IAEG and the AEG reflect an expansion of employment opportunity and are therefore opportunistic, demonstrating an imprecise basis to the subject. Alternatively, it can be countered that this broadening in the practical application of engineering geology is a reflection of the ability of the subject to take advantage of new opportunities which, until now, have awaited exploitation. Thus, the training of engineering geologists in natural geological processes, their awareness of the natural environment through fieldwork, and their subsequent experience make them particularly well prepared to be able to understand and respond to the burgeoning challenges of global environmental change.

## What are the issues?

There are a number of issues that, either explicitly or implicitly, influence the status and function of engineering geology and are based upon the relative role of, or interactions between, geology, engineering geology, engineering and geotechnical engineering. In addition, there are a number of external factors that are undergoing change and are thereby modifying the conditions within which engineering geology is applied. In this analysis I have incorporated the views of a few engineering geologists who were invited to comment on the position of engineering geology, and what change was needed.

## Role of geology

A comprehensive understanding of geology is central to engineering geology and it is widely accepted that the preferred training for an engineering geologist is based on geology supported by extensive fieldwork experience. Geology is a broadly based observational science relying on the description and classification of phenomena in the natural environment and then applying analysis and synthesis to the data that have been collected. Geological observation is only partial because most rocks and soils can never be fully exposed and are either buried or otherwise obscured. Conclusions must be based upon extrapolation, deduction, inference and intuition and experience. Of these, experience is of particular importance, drawing upon prior field awareness, practical knowledge or the literature, thereby providing the confidence upon which conclusions can be based. Inevitably geology is imprecise based as it is on the resolution of uncertainties; it can also be disputatious as different opinions are aired. In such circumstances success in winning minds requires effective communication of observations and ideas.

The traditional concept of the geologist has been that of the field scientist, collecting information and specimens which are then inspected and analysed, eventually being drawn together and published as a learned contribution. Mathematics has not played an important role in geology, other than where the analysis of numerical data has been a necessity. However, modern developments in geology at research level demand both the introduction of numeracy and the greater application of physics and chemistry. Nevertheless, this change has only been acknowledged to a relatively limited degree in the basic training of geologists. Geological fieldwork, upon which much engineering geology is based, is by its very nature a solitary task, resulting in observations maturing into ideas and concepts with limited prior debate. In consequence, culturally geologists tend to be trained to think and work as individuals, rather than as team members. Training offers little opportunity for team activities and research can be carried out in an atmosphere of competition.

Possibly, because it has a reputation based on observation and deduction, rather than that of a science based on certainty, geology has never been regarded as one of the core science subjects together with physics, chemistry and biology. As a result geology is little taught in schools. The consequence is that geology has never been viewed, within the wider community, as an elitist science whereas, within geology, the application of the science to industry or public service, even though this is where most geologists find employment, is viewed with some condescension by academia. This has an unhelpful outcome on the standing of engineering geology.

## Role of engineering

Engineering is concerned with the design and manufacture of artefacts which requires numeracy and a knowledge of the properties and behaviour of, in the case of geotechnical engineering, both natural and man-made materials. This process begins with a concept which then proceeds through an iterative sequence to achieve an object that has a pre-determined function. An engineering education is based on mathematics, physics and some chemistry, requiring logical thought and precision. Students in civil engineering, normally but not always, have some introduction to geology during their training and this may include an introduction to the science as well as illustrations of the applications of geology in construction. However, such courses are generally brief, and are commonly poorly integrated into engineering.

Engineering and geology are, therefore, inherently and intellectually very different subjects with potentially very different deliverables. Whereas geology is concerned with the interpretation of the state of natural materials which are pre-existing, engineering is concerned with the creation of a new object using materials of known properties. A well-trained geologist can formulate conclusions, from inherently incomplete and imprecise geological data, within a three-dimensional framework of scale and time which ranges in space from the near-field to the far-field. In contrast, a engineer works within more constrained, precise limits where the behaviour of materials with measurable properties over a known time span is governed by established mechanical principles. 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.

## Position of engineering geology

To be successful engineering geology must demonstrate a balance between high-quality understanding of geology and a sufficient appreciation of engineering to ensure that the relevant information will be processed and communicated effectively. Geology has its own terminology which is too complex for virtually all engineering uses. Descriptive geological terms must be used in a manner that provides a consistent guide to the properties and behaviour of materials and masses. One of the most common criticisms of engineering geology has been that reports can be written in terms that were difficult or impossible to interpret, irrespective of the quality of the geology itself. This situation became more serious in the international construction scene where the inconsistencies and inadequacies of geological language became a major source of misunderstanding. Although the words might be geologically precise, they were meaningless in engineering terms. From about the 1960s, considerable effort was put into the development of geological terminology that was simplified, adequate and reliable (Geological Society of London Engineering Group 1970), systematic methodologies and consistent classification systems. One consequence has been that such engineering geological reports written in clear language for an engineering audience have been regarded, by geological academia, as intellectually na, which has not assisted the standing of engineering geology within its own scientific discipline.

At the same time that it was being recognised that the needs of the engineering community required that descriptive geology had to be directly translated into a form that was internationally recognisable, several rock mass classification systems were developed which related geological description to engineering performance through points scoring systems. In parallel, it was recognised that reports should carefully distinguish between the factual record, the geological inferences drawn from that record and the consequential implications of the geology on the proposed engineering development. Whereas much has been achieved in providing vehicles to ensure the proper transfer of geological information into an engineering form, effective communication remains a continuing challenge.

Engineering geologists are best trained through a first degree in geology followed by a graduate course in engineering geology which also provides the foundations to soil and rock mechanics, and hydrogeology. The syllabus of first degree courses in engineering geology inevitably places time pressures on the geological content of the degree by the introduction of engineering material.

Some engineers who have gained a knowledge of geology and engineering geology through experience do not rely on the specialist knowledge that can be provided by engineering geologists. Such an approach has its dangers. An engineering geologist provides an unusually broad knowledge and experience of the subject ranging from the softest to the hardest rocks, and from the oldest to the youngest. Many have worked in a considerable range of climatic and topographic environments in many parts of the world. If unexpected issues were to exist or arise during a project, an engineering geologist is best placed to respond to such a situation. In some situations a geotechnical engineer may use a geologist, without engineering geological skills, who is familiar with a particular area to provide the geological background but without any awareness of engineering context. It is also not unusual for young civil engineers, who have completed their training recently, to be given responsibility for site investigations and their subsequent reporting, thereby avoiding direct engineering geological input throughout. Those engineers who, within their professional activities, supplant the engineering geological function by their own input need to be able to understand the limitations of their own knowledge and so appreciate the adverse consequences that can arise. Engineering geology has a proper role within geotechnical engineering which contributes to minimising risk, cost over-run and delays within the engineering process. This needs to be acknowledged on the one hand by geotechnical engineers and drawn attention to by engineering geologists and their representative professional bodies.

At an institutional level the role of engineering geology is recognised in a number of ways. Professional bodies provide qualifications that have minimum requirements for academic training and professional experience which define a particular level of professional competence. To be successful such bodies need to convince the outside world that such qualifications have real value. This requires the provision of continuing professional training as well as a willingness to identify and disenfranchise incompetent practitioners. This necessitates acceptance, in particular, by employers and owners that such qualifications are meaningful. Licensing or registration which ensures that particular responsibilities can only be carried out by properly qualified specialists (e.g. location of new real estate in unstable ground) provides a restrictive system which protects the rights of the profession. Legal precedent can demonstrate the importance of particular qualifications. Thus, in England and Wales, there is a precedent to the effect that primary evidence by an individual who was Chartered would carry weight over evidence, in commentary, from another individual who was Chartered but not from the same discipline. Thus an expert report by a Chartered Geologist acting for a claimant could be given greater weight than a contrary report by a Chartered Engineer acting for a defendant. However, acceptance of a professional qualification, or other forms of recognition, can only be achieved through demonstrating the value of engineering geology and by active persuasion.

The construction industry applies engineering geology within a team environment, which needs effective cooperation between individuals, as well as effective deployment of geological and engineering skills to achieve an out-turn within set timetables. However, engineering geology, like soil and rock mechanics, can be carried out and will provide deliverables in a wholly independent mode contrary to the view of Brunsden (2002) who advocates a team approach as the standard model.

The other branches of applied geology, concerned with mining, industrial and bulk minerals extraction, hydrocarbons and groundwater, do not provide good models, for engineering geology, of the position of geology within industry. This arises because the primary purpose of such fields of extractive geology is to find a resource, rather than to determine how the resource can be exploited. The design of mines, open pits and quarries and well-fields is an engineering issue which relates to the application of technologies with which resource-based geology has no direct relationship. However, where there is such a relationship, as in the case of open pit design, rock support installation and borehole design, then the techniques of engineering geology do become applicable.

The successful application of engineering geology relies, in part, on an adequate synthesis of pre-existing experience. About 50 years ago four up-to-date books on the subject were generally available. The Berkey Volume (Paige 1950) contains a series of papers most of which are related to specific engineering geological subjects, such as dams, materials, groundwater and coastal engineering, each of which is illustrated very largely by case histories. Effectively the same approach is taken by Krynine and Judd (1957) and Legget (1962) although topics related to geology, soil and rock mechanics as well as site investigation are included. Engineering geology is seen very much as a functional profession. Kiersch (1955) writing at that time recognised that there were also a wider selection of texts which were designed to provide some scientific foundation to geology and its applications for engineering students. He also developed a structured approach to engineering geology which was again largely based upon case histories of engineering projects, and investigation. However, none of these writers attempted to place engineering geology within a broader, disciplinary context. Engineering geology was seen to be very much a functional subject, directly applicable to the solution of engineering questions. This position has remained almost unchanged since that time, with most engineering geology texts being derived from case histories of engineering project experience and investigation methods. However, there has been some broadening in that the separate discussion of the properties of soil and rock now provides a further form in which engineering geology is presented (Bell 2000). Over 90% of the papers published in the IAEG Congresses have consistently been related to case histories, material properties and site investigation. There is no all-encompassing, but not necessarily lengthy, book that places engineering geology in the context of a discipline. Two voluminous books (Attewell and Farmer 1976; Legget and Karrow 1982), which were clearly aimed at providing a comprehensive text at the time of publication, fell somewhat short of that target. The definitive text on engineering geology, placing the subject in its disciplinary context, remains to be written.

Because so much of the key material in engineering geology relates to actual project experience, the publication of well-documented case histories is critical. However, the analysis and synthesis of much material, on which the effectiveness of engineering geology as a discipline is dependent, remains to be carried out. One of the growth areas for publications in engineering has been in the field of information technology. Initial interest was created when suitable computer and software resources became available, so that very large amounts of geological and test data associated with major engineering projects and regional studies could be handled. The next steps must involve a more fundamental and wider analysis of the engineering geological information contained within the published literature and accessible project records.

## Geotechnical engineering

Engineering geology should be viewed, at least theoretically, as an equal partner with soil mechanics and rock mechanics in geotechnical engineering. In institutional terms, each subject is independent in that it has its own independent international society. In more practical terms the position is different. Many engineering geologists see their day-to-day contributions, important though they may be, as being that of a junior partner in the geotechnical engineering team. Relatively few engineering geologists achieve positions of leadership in such teams. Where it may be seem appropriate, an engineering geologist may not work on a project, the necessary tasks being given to an engineer who may have neither the necessary training nor experience. One consequence is that engineering geologists see a more favoured career path which leads through to engineering. Some employers use a common terminology of "geotechnical engineer" for all relevant staff, which can have the advantage of providing for equality in human resource terms but may blur the different skills and experience bases that are available. A major contributory factor to this situation arises because an engineering geologist in a design office cannot, and would not be expected to, deliver the design for a complete geotechnical structure, supported by the necessary calculations and drawings. Yet this is the expected output. Further, many engineering geologists are, to a large degree, site-based during investigation or construction. Some engineers, including geotechnical engineers, do not know what an engineering geologist can be relied upon to deliver; hence it may be easier to relate to an engineering-trained team member. For these reasons many engineering geologists act effectively as technicians, recording and interpreting geological information; most would aspire to something more. The effectiveness of the integration of engineering geology within geotechnical engineering remains to be improved.

Burland's "soil mechanics triangle" (Anonymous 1999) provides a clear relationship between the three basic areas of activity that encapsulate the practice of soil mechanics (Fig. 1). Although developed for soil mechanics, the scope of the diagram can be simply adapted to the requirements of geotechnical engineering as a whole. Engineering geology transparently contributes to the triangle through the "ground profile" by an understanding of geological genesis, and the means whereby it can be established. However, the role of the engineering geologist will extend into the area of "ground behaviour", particularly where precedent field observations or test locations are involved. The idealisation process whereby an "appropriate model" is designed in a form suitable for numerical analysis would require review by an engineering geologist to ensure that the idealisation does not misinterpret actuality.

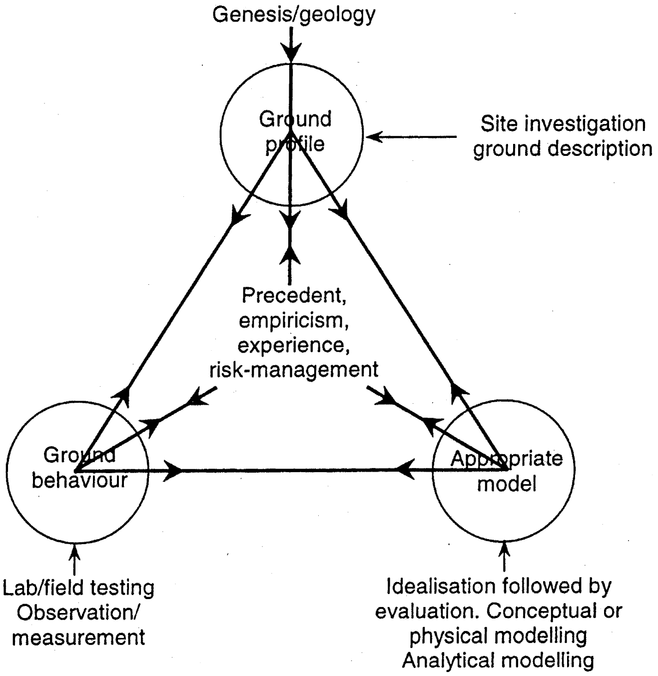


**Fig. 1**
Burland's soil mechanics triangle (Anonymous 1999)

### External factors

The institutional and natural systems within the world are undergoing modifications which, in turn, have an influence on engineering geology. The nature of construction projects is changing so that in general there are now fewer large power and water supply projects, although there may still be some very large such projects. There is now, however, more construction of transportation systems and there will be a massive demand for urban construction and related infrastructure in the twenty-first century, particularly associated with the megacities of the developing world. Construction is being carried out within an environment of greater social awareness so that far more attention is now given to issues such as sustainability and "green" construction methods.

The traditional tri-partite system of an owner or employer who requires the project, a consulting engineer who is responsible for design and supervision of construction and a contractor who carries out the physical work is being replaced by a range of alternative project management structures. These may involve design-and-build contracts where the contractor appoints a sub-consultant to design parts of the scheme, or project-managed schemes with an underlying hierarchy of consultants and contractors. The role of the engineering geologist is changing somewhat in that the use of in-house geotechnical teams is being replaced by specialist geotechnical firms and sole practice consultants. That situation, while offering more employment opportunities, can generate greater insecurity, requiring enhanced professional indemnity cover.

Project budgets and cash flow are now scrutinised more rigorously so that cost recovery is sought in circumstances where there has been financial loss or programme delay. Whereas the contractor has regarded the owner as the legitimate target for contractual claims in the circumstances that the ground conditions encountered have resulted in physical conditions that could not have been foreseen, it is now not unusual for claims to be made in different ways, such as by the owner or contractors against the consultant. Such dispute situations involving owners, contractors and consultants are an increasingly common experience, with a range of means whereby such situations can be anticipated and resolved, including dispute resolution panels, mediation, arbitration and litigation. The costs of arbitration and litigation and the consequential financial risks are considerable. This situation places increased pressure on engineering geologists to record information and interpret geological data with care to ensure the protection of both their employer and themselves. This increasingly litigious atmosphere provides a further opportunity whereby the benefits gained by the proper application of engineering geology can be demonstrated in terms of the value added through minimising the risk of loss.

Global environmental change, resulting from man-made modifications to the Earth's atmosphere, is causing variations in temperature, precipitation, storm frequency, sea level rise and consequential droughts and floods which will provide a major role for engineering geology (Knill 2001a, 2001c). The world-wide consequences of the resulting social change together with the expansion of the world's population will be enormous. Coupled with this situation has been the recognition that disasters, including earthquakes and volcanic activity (not driven by global change), resulting from extreme events, are becoming more common, and as a result global insurance costs are increasing. One consequence to engineering geology has been the greater use of regional engineering geological studies so that the location and scale of potential impacts can be anticipated and mitigated.

## Fundamentals of engineering geology

### Principles

Burland's soil mechanics triangle (Fig. 1) elegantly demonstrates the three main aspects that define that discipline and how they are interlinked, each aspect having its own distinct methodology and rigour. All aspects must be kept in balance and no aspect should be omitted. Although most geotechnical engineers would consider that the triangle represented their own broad field of interest, they would also be able to identify their own personal focus of activity within the diagram. With minor changes of terminology the triangle can also be adapted to represent the scopes of both rock mechanics and geotechnical engineering. Engineering geology is not, however, positioned in a balanced manner within the triangle in that possibly three quarters of the effort is related to the "ground profile" and the remainder to "soil behaviour", with a limited input to validation of the "appropriate model" selected. This situation effectively demonstrates the dilemma within which engineering geology is placed. An engineering geologist can work comfortably within the scope of a soil mechanics, rock mechanics or geotechnical engineering triangle, but that triangle does not provide an all-embracing intellectual framework for engineering geology—it is ill-balanced. Because the disciplinary basis of engineering geology lies within geology, we must look in that direction to achieve a convincing solution.

The assembly, interpretation and synthesis of data to create a geological model is central to the engineering geological function, and the preparation of such a model is symptomatic with Burland's "soil profile" (technically a profile is based on a single line, and is not a two- or three-dimensional model). The literature is filled with examples of different types of geological model, illustrative of particular situations presented either graphically or verbally and supported by data on natural material and mass properties (solid, liquid and gaseous) and geological processes (surface and sub-surface processes associated with soils and rocks respectively). Together these three aspects—material and mass properties, process and model—define the engineering geology triangle, which is illustrated in Fig. 2. The central area of the triangle defines the basic skills for observation, interpretation, experience, intuition and synthesis needed to ensure successful application. The relationship between the geotechnical triangle which has a more generalised terminology than shown in Fig. 1 and the engineering geology triangle is shown in Fig. 3.

These relationship arguments simply endorse the oft-quoted view that engineering geology is based within geology and not in engineering. Dilution of that view, by, for example, the excessive involvement of engineers within the engineering geological function, carries the possible unnecessary risk that the out-turn could be less effective and more costly than it might have been.

The geological model is inadequate, on its own, for engineering purposes because it does not sufficiently define the engineering conditions within the natural ground or deliver a design. It needs, therefore, to be converted to a ground model in which is embedded the engineering parameters required for subsequent engineering analysis. The ground model then needs to be adjusted to provide the geotechnical model, which can then be directly applied within a mathematical or physical model to achieve an engineering conclusion. The steps that need to be taken to convert a geological model, through the ground model, to the geotechnical model will inevitably require simplification to meet the requirements of the selected method of mathematical or physical analysis. The terminology for such models in geotechnical engineering has become loosely defined, and the three terms should be used strictly in the sense in which they are applied. During the conversion from one model to the next an engineering geological involvement is essential to ensure that the actual conditions are represented as accurately as possible in the eventual analysis.

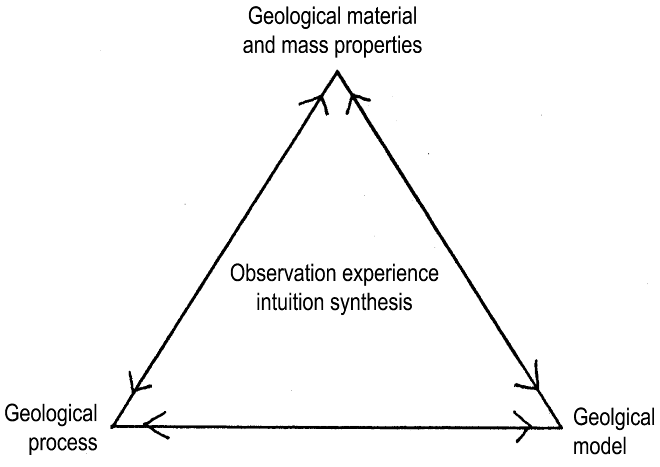
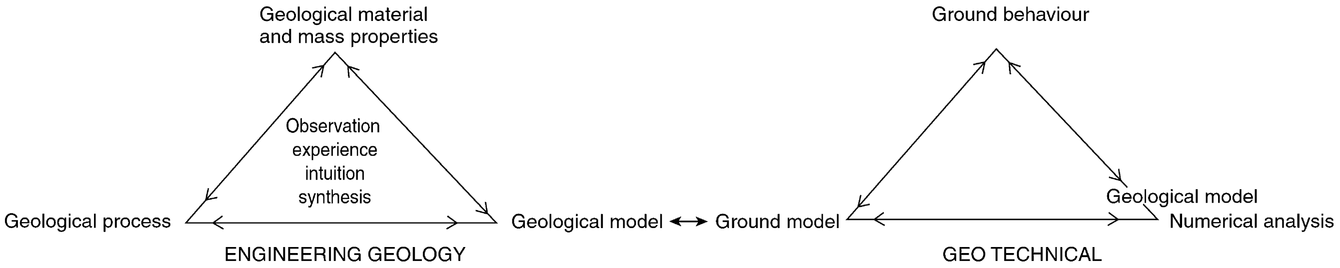


**Fig. 2**
Engineering geology triangle

**Fig. 3**
Relationship between engineering geology and geotechnical engineering triangles



An important relationship that establishes the manner in which engineering geology is integrated into the methodology to create a ground model from the geological model, by means of the introduction of the necessary engineering parameters, is illustrated by the stepwise formulae (Knill 1976) developed jointly by the late Professor David Price and myself and set out below:

The essential components of this relationship will be reviewed below.

## Material properties

The material properties of rocks and soils are derived from the effect of geological processes on the original mineral matter, together with any associated liquids and gases. As a consequence, the different processes whereby rocks and soils have been formed result in contrasting relationships between geological origin and material properties and behaviour. All rocks have undergone lithifaction caused by gravitational compaction and/or crystallisation so that the material properties are largely determined by mineral type and texture. On the other hand, because of consistency in mineral types, the properties of most soils have been very largely determined by the processes whereby the soil particles have accumulated. Special circumstances can occur in the case of soils whose formation has involved chemical processes.

The primary rock types have their own diagnostic behavioural characteristics which are largely derived from their mineral content and texture as follows:

Despite these very obvious differences in engineering behaviour between the range of material rock types (which also have an influence on mass behaviour), the Q (Barton et al. 1974) and Geomechanics (Bieniawski 1989) rock mass classification systems do not contain any parameters that transparently acknowledge such differences between primary rock types. As a result, the role of anisotropy, solution and time-determined durability in rock mass behaviour may, for example, be overlooked in such systems.

Most soils are composed of a mixture of granular material formed by quartz and rock debris (in the case of the larger particles) together with cohesive finer silt and clay. The engineering differences between most soils arise, therefore, from the process by which they accumulated differences in mineral type, and the engineering behaviour of soils is best considered in terms of their environment of deposition.

The dominant geomorphological process on the land surface is associated with the development of fluvial systems which commence with rock disintegration and weathering in highland and mountainous areas, then transportation through linear, braided and meandering rivers and eventual deposition in water bodies. Soils with similar grading can form in in-situ materials of very different characteristics because of variations in the process of transportation and deposition. Thus, gravels can occur in a dense, low-porosity state when subject to repeated fluvial reworking, whereas rapid deposition can result in a high-porosity, open-work state. Such open-work gravels can also be the result of rapid reworking, deposition on the lee slope of a bar or post-depositional removal of fines by internal erosion. Finer-grained soils accumulate in bodies of still water, which may be ephemeral, or more permanent features such as lakes and the sea. The properties and lateral and vertical continuity of such soils will be determined by both the depositional process and post-depositional changes. Thus, normally consolidated clays are characterised by an increase in shear strength and reduction in moisture content with depth resulting from gravitational compaction. Greater loading and subsequent exhumation of materials with similar classification properties results in the formation of stiffer overconsolidated clays which are fissured, jointed and sometimes internally sheared. Pore-water chemistry has an important role in the post-depositional history of cohesive soils. Thus, clays deposited in fresh water will have a dispersed fabric, resulting in an anisotropic soil with a horizontal mineral parallelism encouraging drainage and improved consolidation. In contrast, salt-water clays will be less dense and isotropic as a result of the formation of a flocculated structure created by edge to face mineral bonds within the electrolyte. Such clays will be more permeable, and less affected by directional strength and consolidation differences.

Climatic conditions result in the creation of particular associations of soil types resulting from arid or tropical conditions, glaciation and periglaciation. Similarly there are soils wholly or largely formed by chemical processes and in which biological activity may have been dominant. These include, in particular, the shallow-water carbonates and evaporites.

The roles of mineral type, texture, pore-water chemistry and geological process need to be recognised and understood if the geotechnical properties and behaviour of soils and rocks are to be adequately appreciated.

### Mass fabric and properties

The processes that form rock and soil masses result in the creation of complexity and heterogeneity. The contribution made by mass fabric results from variability in material properties in three dimensions and the presence of structural breaks or discontinuities. Variation in the distribution of material properties is caused by the process through which the rock or soil has been formed. In sedimentary rocks, lateral and vertical variability, resulting from changes in environmental conditions in space and time respectively, are to be expected. If the environment of sedimentary deposition is retained without significant alteration over a large area and for a long period then distributions approaching large-scale homogeneity may exist, resulting in the formation of, for example, massive conglomerates, chalks and mudrocks. However, a more common situation results from the presence of frequent lateral variations caused by changes in bed thickness and continuity, or vertical variations resulting in the introduction of bedding planes and intercalations of different rock types. The tectonic deformation, associated with folding and faulting, of sedimentary rocks, and their subsequent metamorphism, results in transformation of the material rock type, and the further introduction of complexity through a redistribution of material types. The structural form of igneous bodies is determined by the intrusion process which may involve passive or active emplacement or replacement in situ. The larger, plutonic and hypabyssal intrusions tend to be homogenous, reflecting the presence of uniformity in enormous rock volumes during the crystallisation. Volcanic rocks accumulate through highly variable processes, and lateral and vertical variability results in the accumulated rock.

Discontinuities are present in rocks on all scales, ranging, with increase in scale, from microfissuring contained within individual mineral grains, through discontinuous microfracture systems, ordered sets of joints and general fracturing, shears and faults to large-scale through-going faults and fracture belts. Rocks of distinct material type (and soils where appropriate) are characterised by different discontinuity styles. Thus, granites are typified by an orthogonal joint system formed by successive stages of freezing and stress relief, whereas mudrocks contain a small-scale bedding-related fissility largely imposed during gravitational compaction, folding-induced bedding plane shears and subsidiary (and later) tectonic jointing. The traditional approach within structural geology has been to distinguish between the fracture systems on separate scales and types, dividing the rock mass into geometrically defined domains which are formed by particular rock types and bordered by major discontinuities. On the other hand, the approach in engineering rock mechanics has concentrated on data collection through line surveys, an approach that blurs or even ignores the underlying geological framework. The consequence is that there is a risk that the major, through-going discontinuities, of which there will be a few, will not be observed, or recognised as such, whereas it is exactly such a discontinuity that will have a large-scale influence on mass permeability and open-pit wall strength.

The mass properties of rocks and soil are related to scale. In general terms the permeability and deformability of such a mass will increase with volume and the mass strength will reduce (Price and Knill 1974). This arises because as progressively larger volumes are involved so the mass embraces new discontinuity types on scales that have an increasing influence on properties and behaviour. In the case of strength, for example, a rock specimen that is intact and not influenced by visible discontinuities will tend to have the highest strength. With progressive increase in specimen volume so will the unconfined compressive strength be reduced by the introduction of discontinuities. This situation can be represented on a very much larger scale in a rock slope where, using a height to slope angle relationship, it will achieve, or approach, a constant slope angle irrespective of height. This situation is illustrated in Fig. 4 based on multi-directional slopes in working and abandoned quarries in sheared high-grade metamorphic rocks in the UK (Malvern Hills) and low-grade metamorphic rocks along the Diba-Masafi road in the United Arab Emirates, as well as slopes in phyllite, schist and gneiss parallel to the controlling foliation in Scotland. Whereas the strength contribution from cohesion is important in lower slopes, with the increase in height the angle of shearing resistance becomes the dominant factor. In the case of mass permeability, the prospect of encountering large-scale, penetrative and water-carrying discontinuities becomes greater as the volume increases. The effect of discontinuities on deformability will increase, in particular, at the lesser increments of volume. Eventually, the scale will be such that the influence of new, longer discontinuities, with increase in volume, will be negated and any further reduction in bulk deformability with scale will only arise from the involvement of more deformable rock types.

### Environment

The main environmental conditions influencing the in-situ behaviour of soils and rocks include groundwater, stress, temperature and gas. Each of these may also be sources of hazard requiring control during engineering construction. The presence of groundwater gives rise to issues associated with pressure head distribution, flow, chemistry and temperature. Rock and soil masses are normally saturated below a particular level, referred to as the water table, and this will vary in depth below the ground surface dependent on geology, topography and climatic conditions. Above that level unsaturated or partially saturated conditions will exist, with groundwater held in transient bodies by aquitards. In certain situations groundwater may be confined below an aquitard, thereby generating heads with levels above the water table in overlying aquifers. In geotechnical investigations it is necessary to establish the distribution of groundwater and its head within the volume of ground which may be influenced by the construction. Below the water table the head will be influenced by geology, depth and groundwater flow; there may be locally confined conditions. The effect of engineering works on groundwater conditions can extend to considerable distances laterally and vertically. Preferred or potential groundwater flow pathways can be present. The chemistry of groundwater varies from effectively pure, with little contained mineral matter, to brines with salinities many times in excess of that of sea water. Elevated groundwater temperatures occur in active volcanic areas, or regions of past hydrothermal activity.

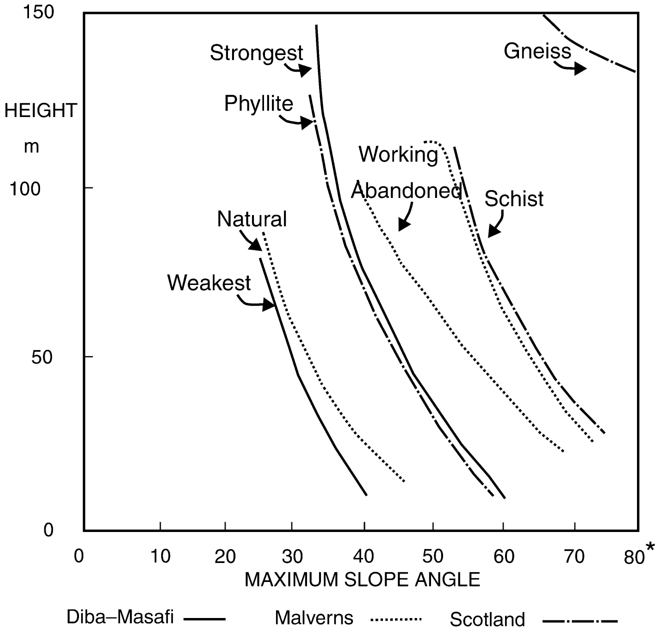


**Fig. 4**
Slope height/angle relationship for metamorphic rocks from the United Kingdom and United Arab Emirates

All soils and rocks are in a state of stress. Gravitational compaction of a soil takes place during progressive burial, and the stress state at depth is normally assumed to be derived from the vertical load of overlying sediment and the surrounding confined, unyielding condition. The horizontal stress, under such conditions, is about a third to a quarter of the vertical stress. If the sediment were then to be progressively exhumed by erosion there will be a systematic release of the vertical stress, but the horizontal stress will be constrained, being relieved more slowly because the soil is still laterally confined. As a consequence the ratio of horizontal to vertical stress increases from about 1:4 at depth to 5:1 or 10:1 close to the ground surface. The consequential shallow stress relief can result in deformation structures such as sub-horizontal shearing in overconsolidated clays.

If burial of the sediment continues so that lithifaction takes place, then a different stress regime can result from the tectonic stresses imposed during folding and faulting and the residual stress—arising from mineral recrystallisation and transformation. Tectonic stresses will be released close to, or at, the ground surface during seismicity which can normally be related to a specific fault zone. Residual stresses, which are locked into the rock material at depth, develop in igneous bodies and the higher-grade metamorphic rocks associated with melting and freezing. Burial is associated with elevation in temperature, so all these stresses are imposed at temperature levels greater than those at the ground surface. Erosion will result in unloading and cooling with progressive stress release, the effects of which vary with rock type and topography. At depths less than about 2,000 m, worldwide studies have shown that the ratio between the horizontal to vertical stress can exceed unity; within 500 m of the surface the ratio is typically about 2, and may be in excess of 4 or 5 close to the ground surface (Brown and Hoek 1978). As a consequence it is commonly assumed for design purposes that relatively high horizontal stresses are foreseeable in underground excavations. Most rocks exhibit some form of stress relief by joint formation which may involve re-use of pre-existing structures such as bedding planes. Sheet jointing, paralleling the topography, develops in more massive, stronger rocks such as granites and conglomerates. Some very strong rocks demonstrate the presence of residual stress by fracturing or disintegration soon after recovery in drill core. Where there are sharp changes in topography, particularly near gorges or steep-sided hills, the natural stress field is deflected and stress concentrations will occur, resulting in near-surface sheet jointing in massive rocks. It is not unusual for relatively low, or even negative, horizontal stresses to occur in massive rock (e.g. granite) adjacent to high valley sides, where global experience (Brown and Hoek 1978) would suggest that much higher horizontal stresses should exist. This situation can have important implications on the design of tunnelled penstocks and surge chambers. In bedded sedimentary rocks, particularly where low-strength mudrock layers are present, more complex associations of shallow faulting, near-vertical toppling joints, lateral shear on mudrock layers, cambering of hillsides, valley bulging and folding can occur. The role of stress relief in influencing rock conditions within valleys and the lateral extent affected is generally insufficiently appreciated.

The typical geothermal gradient is of the order of 2–3 °C per 100 m, and values several times this figure occur in situations where elevated groundwater and rock temperatures are encountered. In general, temperature profiles are undertaken too infrequently in boreholes that are in excess of 100 m depth, resulting in a lack of prior appreciation of elevated temperatures at shallow depth.

Gases encountered at depth include methane, carbon dioxide, hydrogen sulphide and radon, all of which carry significant hazards when encountered above specific limits. Pressurised gases can occur either as a free gas or in solution. If hydrocarbon reservoir conditions are present below the project area there can be a possibility that reduction in groundwater head by drainage into tunnels could release gas as a result of distressing the reservoir.

A multi-fatal accident occurred on the Lune–Wyre Tunnel well after completion following progressive release of methane from a very small gas reservoir in a reef structure about 1 km below the tunnel (Knill 1991) (Fig. 5). The only plausible cause of this release was the lowering of the water table by drainage into the tunnel, the consequential reduction in groundwater head at depth and release of gas from under the reservoir cap rock.

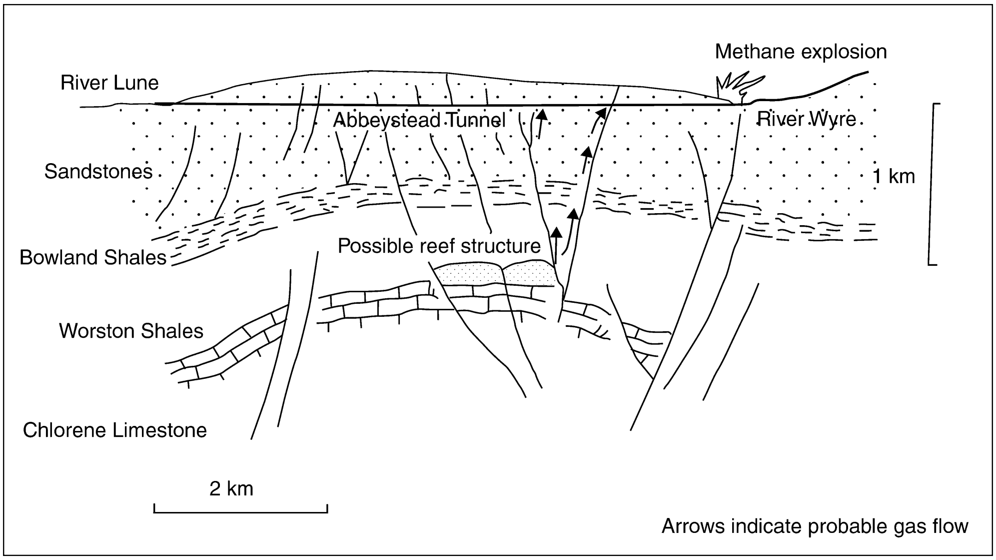
Radon, a radioactive gas, occurs particularly associated with granites. However, all gases may migrate and be trapped some distance from the site of formation. As a result, investigations into environmental conditions must extend well beyond the physical limits of a project, in both lateral and vertical terms.

### Imposed change

In construction the imposed change results from a stress change which can involve the addition of load by overlying structures such as buildings and embankments, the removal of lateral support in slope excavation and by the removal of both lateral and vertical support in underground excavations. The stress change may also result from modifications to groundwater head distribution which can occur directly as a response to excavation or by an increase in water head associated, for example, with reservoir impounding or a pressurised tunnel. Unlined underground gas storage chambers will impose stresses on the surrounding groundwater system.

### Ground response

The engineering response of the ground is demonstrated by deformation resulting from either consolidation associated with a mass volume decrease or bulk or progressive displacement which may be associated with some volume change. The deformation could take the form of downward movement associated with settlement and/or subsidence, lateral displacement (with some downward movement) associated with landsliding, and upwards movement associated with heave. During the process of deformation the



Arrows indicate probable gas flow

**Fig. 5**
Geological section through Abbeystead Tunnel, UK, showing mechanism of storage and release of methane

properties of the displaced mass will themselves be subject to change. If there is constraint, then the more cohesive soils in particular will consolidate, and gain strength, as a result of pore-water drainage. However, if there is no constraint, then the mass will increase in volume through dilation or softening, disintegrating in the process and developing new fractures in rock masses. During the deformation process, therefore, there may be a modification to the mass properties which will adjust the factors controlling overall stability. The mass properties of soil or rock masses that have been influenced by human interference, such as shallow mining, dewatering or waste disposal will have been modified.

Some natural geomorphological processes simulate the consequences of engineering construction. Thus load is added through sedimentation, lateral support is removed by toe undercutting of slopes by rivers, lakes and the sea, and vertical collapse may be induced by enlargement of solution-induced caverns. Such processes can form valuable examples of active models simulating conditions that could be relevant to the project engineering.

## Uncertainty and risk

### Uncertainty

Engineering geology is concerned with the resolution of geological uncertainty. Central to the engineering geology process to resolve such uncertainty is the establishment of a ground model as an integral and early part of the design process and prior to construction (Knill 1994). The established ground model needs to be verified during the continuing engineering process to ensure that design and construction procedure assumptions are valid. The validation process will inevitably result in adjustments as more information becomes available. Differences between the actuality and the ground model need not result in changes to the design or construction method and so do not necessarily give rise to additional costs, delay or reduced safety. Divergences in geology, or geological interpretation from the ground model, although interesting in themselves, do not always result on their own in changes in the anticipated ground response. However, if a new ground model is required to be developed because of significant modifications in geological interpretation, or to the assigned geotechnical parameters, which will result in different engineering performance and/or sequence, giving rise in turn to altered design or construction, then contractual variation is to be anticipated. Structural failures are typically followed by the discovery of new information and the redefinition of the ground model. The iterative change inherent to the geological/ground model concept must recognise that such change is not simply academic; the consequences can have massive contractual implications.

The geological and environmental factors that contribute to the ground model cannot be instantly portrayed in engineering terms by single numbers. Variability is a consequential characteristic of geological processes, and a particular engineering property is likely be represented by a distribution of values resulting from laboratory and field tests. Such a property is most simply represented within the ground model by a single operational value, which may be selected by a variety of methods including precedent experience, a judgmental process or some form of a probabilistic parametric analysis. Ideally the investigation should establish a series of geological and geotechnical benchmarks which define the ground conditions, and provide numerical definition of the ground model. More sophisticated models may incorporate Monte Carlo simulations in which a range of parameters are tested. During the construction process the design benchmarks can be verified, thereby providing for validation of the design. If, however, there is variation from the benchmark parameters then there may be the case for design adjustments and contractual compensation if unexpected cost is incurred.

Geological variability observable within the ground regime arises from a range of different processes which can be classified in an extension of those set out by Morgenstern and Cruden (1977):

Geological situations may have arisen from more than one of these processes and may, therefore, be complex. An adequate ground model must represent the consequences of the appropriate geological processes on the resulting soil and rock masses. However, geological complexity does not necessarily imply the presence of geotechnical complexity. A rock mass that is lithologically inhomogeneous may also contain a random distribution of discontinuities. A geological map or section illustrating such a situation will inevitably contain much intricate detail. However, irrespective of the direction in which the rock mass is excavated for a cut slope, it will perform in exactly the same manner. Such a rock mass is, therefore, homogenous in geotechnical terms and lacks elements of geotechnical complexity. Geotechnical complexity arises where "*geotechnical properties vary rapidly across a wide range within an engineering site*" (Morgenstern and Cruden 1977). A flat-lying marine clay which has been subject to post-depositional uplift, erosion and weathering provides an ideal example of geological simplicity. However, such a clay, having been overconsolidated, is likely to be weathered, fissured and could contain shears resulting from shallow stress release. There will be a considerable range of strength extending from that of intact soil to polished and slickensided shear surfaces. The operational strength of the soil mass will depend not only on the material strength range but also upon the distribution and preferred orientation of the fissures and shears within the soil mass. In such circumstances a site that is geologically straightforward can certainly be geotechnically complex.

Geological processes result in rock and soil masses that are inherently inhomogeneous, orthotropic and discontinuous. In addition, as engineering projects vary considerably both in lateral size and extension with depth, there may be significant differences in the manner in which the ground regime is influenced by the engineering process. As a consequence, variations in scale can also introduce uncertainty. If a series of unit volumes of a rock mass sequentially increasing by orders of magnitude are considered, then the greater the unit volume the greater will be the probability that new, potentially undiscovered ground conditions will be encountered. However, in general, the larger the rock or soil volume, then the probability is that the mass strength will be lower and the mass permeability and deformability will be higher. It will be of considerable importance to establish the limiting value of a rock or soil property where very large volumes are involved, for example, in major slope excavations or in reservoir watertightness.

Considerable limitations arise from the physical inability to fully observe and adequately sample in a representative manner the ground conditions during project investigation. The greater the uncertainty that remains at this stage, then the greater will be the probability that differences from the foreseen conditions will arise during construction. Any investigation must be designed to maximise the information that is obtained. The assessment of the adequacy of the completed investigation and its reporting is probably the single most important procedural function of the engineering geologist. It is good practice for the uncertainties associated with such an investigation to be formally evaluated by independent review or an auditing process during its progress in such a manner that reliable contingencies can be applied both during design and in construction. It has been common practice to assess the adequacy of the investigation by relating the investigation cost as a percentage of the project cost. For typical investigations, figures of 0.2–0.5% of the project cost have been quoted as confirming adequacy However, such a method can be unreliable as it ignores the geological and geotechnical complexity of the project, with the inevitable uncertainties, together with its scale and setting. An alternative approach (Price and Knill 1974) has been to relate project size, in terms of the soil or rock volume subject to stress change, to the volume of material sampled during the investigation. Where the ratio of material sampled to mass loaded is less than 1:500,000, there is an enhanced risk of unforeseen conditions being revealed during construction because of insufficient investigation. It is of relevance that the same ratio has developed, quite independently, from the exploration of shallow coal seams.

The distribution of an investigation cannot fully encompass the space occupied by an engineering project. Geology and engineering structures are three-dimensional, in contrast with most investigation techniques which are one-dimensional (e.g. boreholes, adits) or are based on point observations (e.g. natural exposures, trial pits). As a consequence, interpolation of ground data to a defined three-dimensional ground regime must be used to counter uncertainty.

To the dimensional factors of space and scale must be added time as another factor that introduces uncertainty. Geological processes have occurred during geological time and, built into the ground model, will be the milestones that have caused variability, and thereby uncertainty. Thus, folding and faulting as a result of tectonic activity, bedrock erosion resulting in the formation of rockhead and surface weathering will all have taken place at different periods, at different rates and will have different consequences. The rate at which a process takes place, the range of processes involved at any stage, the frequency at which an event is repeated and the extent to which a process will be active during the life of the project are all important questions which require to be answered. Evidence of continuing displacement, or recent movement, associated with landsliding, subsidence or faults requires to be established at a very early stage in the project as it is likely to have a significant influence on site selection. Continuing weathering, within the life of an engineering project, will result in loss of rock and soil durability and potential changes to mass properties, notably in soluble rocks.

### Risk

Uncertainty in ground conditions, whatever the origin, contributes to the jeopardy that the project will not meet cost or programme targets, prove on completion to be inadequate, or that it could fail. Such risk can be simply defined as the product of the recognised hazard to the project and its probability of occurrence. The consequence of such a hazard is the product of the nature of the hazard and the vulnerability of the system that it influences. Risk, when related to specific hazards such as slope instability or dam failure, can be determined through a formal process of quantitative risk assessment. However, many of the geological uncertainties that occur throughout construction are less amenable to numerical treatment and may arise from some form of mistake in the engineering process. The fact that an investigation has been carried out and reported on can offer a false sense of confidence unless the information base is of high quality. Indeed, the fact that an investigation has been carried out has been commonly regarded as an adequate insurance that the ground regime has been anticipated correctly.

Uncertainty within the ground model arises therefore from both inadequacy and error. Inadequacy as related to the ground investigation will embrace representability in terms of quantity and interpretation and completeness in terms of geometrical and geological sufficiency. Error will include faults in fact and interpretation and flaws in judgement and ignorance.

A statement of the potential sources of geological uncertainties, and their evaluation through conventional geological logic, can provide a potentially sound basis for identifying where doubt may remain in the ground model. For example, a statement of the professional qualifications and experience of the individuals with key tasks can provide both reassurance and a record of the originator of any flaws. Similarly, formal auditing of factual records such as borehole logs is important as a single error in depth location may underpin the liability for an expensive construction claim. It should not be forgotten that Hans Cloos concluded some of his scientific papers with a statement of their limitations. Both factual and interpretative site investigation reports would benefit from an obligatory requirement for the authors to include a concluding statement of the "predictive quality of the investigation" ranging say from 99% for "virtually certain" in a series of gradational steps to 33–66% for "moderate likelihood". The answers given to such a self-assessment would be challenging even for the most high-quality and comprehensive investigations where there was considerable cause for confidence.

Engineering geology has a contributory role to play in formal quantitative risk assessment at the time when a project has been formulated or even constructed. However, at the very earliest stages of a project it is difficult to provide a comprehensive evaluation of geological risk even though it will be known that, at the later design stage, such risks can be defined. Geological risks can be identified within natural landscape where active geomorphological processes are present such as unstable slopes and karst terrain. In addition, ground conditions that are generally regarded as demanding, such as thick normally consolidated clays, swelling soils or chemically deleterious rocks, all offer a potential for risk although no actual risk can be defined. Until the project is formulated in terms of the type and location of the component structures the anticipated ground response cannot be predicted. Only then can the formal concept of risk be introduced. The very purpose for the initial involvement of engineering geology in a project is to ensure that risk is minimised. Where there may, for example, be different alternative routes to a road it is possible to identify, at least in qualitative terms, the potential ground response that would result from construction of each alternative. However, at such an early project stage it will be impossible to judge which factors may in due course prove to be sources of risk. Thus variations in thickness of a particular soil layer, differences of proportions of specific rock types within a rock mass, or variations in groundwater head are simply observations which may, or may not, have geotechnical importance and so be risk-generating at a later stage in the engineering process.

Once the design begins to be formulated and investigation is proceeding it is possible to develop geotechnical risk registers (Clayton 2001) which will be constructed from the geological risks that are then perceived. At an earlier stage and before the project location and design has proceeded far, benefit can be gained by the development of geological uncertainty schedules (Knill 2001b) which can provide a simple listing of issues that may, in due course, make a formal contribution as entries in risk registers.

Geological uncertainty schedules would be built up from information of different types including recognisable geological hazards, active geomorphological processes, recognisable difficult soil or rock conditions, locally variable or complex conditions, areas with inadequate information or investigation and inaccessible areas. Such schedules can then be used as a basis for development of the project location and preliminary design and for further design investigation. During the project design the schedule will be overtaken and replaced by the geotechnical risk register, although it will remain open until all the issues have been dealt with or shown to be irrelevant.

## Ground profiles and models

### Profiles

Most ground investigation is concerned with the generation of one-dimensional geological, geotechnical or geophysical ground profiles derived from boreholes, trial pits (which are effectively point observations), occasional shafts and trenches and adits (providing horizontal profiles). Probably more time is spent by engineering geologists in the recording of data through the geological logging of borehole cores and samples and trial pits than any other task. Most boreholes are vertical, although, occasionally, inclined boreholes may be drilled to add a multi-dimensional aspect within a vertical borehole cluster, to explore a steep or vertical feature, or because of difficulties of access. Inevitably most sub-surface geological interpretation of ground conditions is based upon vertical boreholes. Logging procedures have been established and are published in national standards, and in textbooks (Geotechnical Control Office 1987, 1988; Clayton et al. 1995; British Standards Institution 1999). In the main, these procedures and descriptive methods are internationally compatible. Prior to the 1970s there was no national or international consistency in the logging of rock core for engineering purposes, but guideline procedures introduced at that time (Geological Society of London Engineering Group 1970) became increasingly widely accepted. It is essential that standardised methods should be used, particularly where the parties involved in a project operate in different languages, as is now common in international contracting. This becomes even more important when contractual claims occur and the geological documentation is open to misunderstanding. Investigation data should be subject to audit before finalisation and this can be carried out in a most practical manner after the draft log is prepared and during the selection of samples for laboratory testing. Alternatively, a dipstick approach to audit is recommended whereby a sample of the logs is checked. In view of the importance of the in-situ nature of soils, audit of trial pits should be carried out before backfilling and may need to follow closely on from logging.

The main disadvantage of the descriptive methods available for cores and samples is that, whereas they can provide an excellent record of material characteristics, they need not be placed within their in-situ context. The argument in favour of such an approach is that the record should be entirely factual, thereby avoiding subjective clarifications. As discussed previously, the geological model is built up from both a knowledge of the material and the mass characteristics as well as the geological process. Most site investigation records concentrate on material aspects but omit any reference, or implications, as to the process whereby the soils and rocks have been formed. This is a major deficiency because commonly the logger is not involved in the subsequent interpretation and so not all the information that is potentially available is collected.

This flaw can be overcome by classifying geological profiles, or their sub-sets, into their basic generic type as defined by the process (Knill 1994) by which they were formed. The depth of the profile will be limited by the vertical extent of the potential engineering influence of the planned structure. This approach recognises (Fig. 6) that a ground profile will potentially consist of overburden and bedrock commonly separated at rockhead with a gravel horizon. The potential menu of materials within the geological profile will include overburden composed of residual soil and a potential range of transported soils and fresh bedrock overlain by weathered rock. The nature of the bedrock surface will be dependent on the erosional process by which it has been formed (Knill 1978) and is an important indicator of the process by which the profile has been constructed during geological time There are, in principle, only seven variant generic profiles and three sub-variants as follows:

| | |
|---|---|
| A | weathered crust |
| B | weathered crust resting on transported soil. |
| C | transported soil |
| D | weathered crust resting on transported soil overlying rockhead with weathered rock. |
| D′ | as for D but weathered rock is absent and fresh rock occurs at rockhead |
| E | weathered crust resting on transported soil overlying rockhead with weathered rock and fresh rock below |
| E′ | as for E but weathered rock is absent and fresh rock occurs at rockhead |
| F | weathered rock |
| G | weathered rock with fresh rock below |
| G′ | fresh rock only |

Each of these generic profiles is a simplified product of a sequence of distinct geological and geomorphological processes. The actual ground conditions will normally be more complex because they represent a more involved geological history than indicated by the simplified representations.

Rockhead may not be a product of any of the processes that have caused the accumulation of the superficial materials within the profile. Thus a glaciated surface of metamorphic rocks may be overlain by marine clays. For this reason the nature of rockhead and its potential origin have to be recorded carefully. The concept of rockhead introduces the further complication in that there may be some practical advantages in it being also classified in engineering or geophysical, as well as geological, terms. Misunderstanding can arise, for example, in generic profile E where the weathered rock immediately below rockhead can be mechanically excavated as easily as the overlying transported soils. It is only when excavation reaches down to core stones or less weathered rock that the engineering performance changes so that alternative, more costly, excavation methods are required. Similarly, geophysical rockhead will be encountered within the less weathered rock. On such sites careful distinction between rockhead defined in different ways is required.

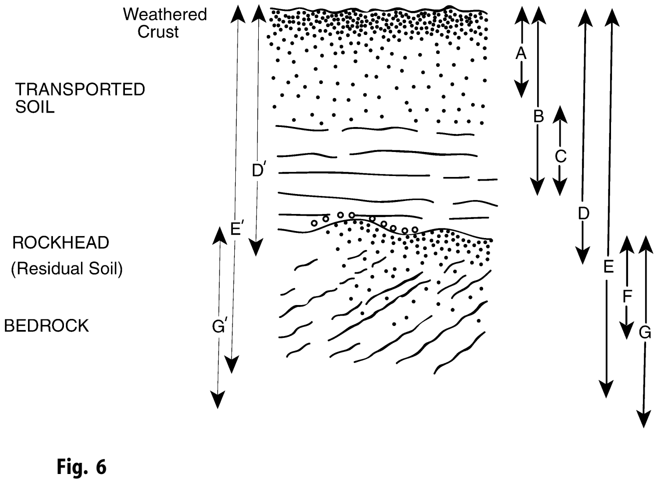


**Fig. 6**
Generic ground profiles

Although the bulk of geological and geotechnical interpretation of ground conditions is based upon one-dimensional profiles, there is remarkably little advice given in national investigation standards or textbooks on target depths for investigations for particular engineering structures. This raises important questions during investigation planning.

## Sections

Geological sections, which provide a two-dimensional vision of the geology present, can only be directly observed in section in cliffs and hillsides. Geological mapping is, of course, a means of two-dimensional representation but essentially in the form of a horizontal plan. Ground conditions can be directly observed in two dimensions in deeper trenches and may be interpreted by various geophysical methods, including shallow ground-reflecting radar, reflection seismics (refraction seismics involve a considerable interpretative element) and cross-hole seismic borehole tomography. Sections can, of course, also be built up from the different types of data source including point observations (exposures, trial pits), one-dimensional profiles including boreholes, trenches, adits and shafts, and two-dimensional mapping. However, such sections require interpolation and interpretation, so that accuracy and reliability are dependent on the extent and quality of the investigation. Confidence in such an approach is justified when the knowledge is such that geological boundaries can be extended laterally and vertically. Interpretation can be further refined by recognising geological change within individual layers or zones which can be used to enhance the quality of the section. Thus lateral changes in sedimentary facies, or the presence of particular igneous associations, can be used respectively to recognise variations in layer thickness and proximity to the margin of an igneous intrusion.

The process of section-drawing has traditionally been based on experience and a judgmental approach. The decision-making process can now be assisted by computer programs which, nevertheless, risk the production of stylised products which are geometrically precise but intellectually defective. Such an approach is, however, very valuable where there is a large borehole data set, as may occur in an urban area, so that refinement of interpretation can be obtained by modifying the section lines chosen.

## Models

Profiles and sections provide a limited one-dimensional or two-dimensional view of the geological conditions and most geological information is presented in this form in geotechnical documentation. However, engineering structures are three-dimensional and there can be significant geological variations within the scale of most structures. Many engineers find difficulty in understanding three-dimensional relationships from two-dimensional geological drawings and other records. Thus geology is best understood, and presented where possible, in three dimensions. This is carried out most effectively, for practical purposes, by the use of contour plans of particular boundaries (e.g. bedrock) or isopachytes of individual layers which may vary in thickness across an engineering site. It has been common practice for case histories to be illustrated by block diagrams or physical models which provide a simple representation of the site geology. For example, in the case of the Roseires Dam in the Sudan I used such an approach (Fig. 7) to provide an explanation of the different types of granite emplacement (early migmatitic granite and gneiss with pegmatite, late granite sills and late pegmatite) that were present which, up to that time, had been grouped into one association (Knill and Jones 1965). This distinction was very important because granite sills were much less susceptible to weathering and there was a risk that the concrete buttress dam excavation could cease within a sill while there was still highly weathered, older migmatitic granite below the sheet at some distance below the placed concrete. Such models should be developed in a stepwise manner in an evolutionary process during the progressive stages of investigation, design and construction as more information becomes available. Three such models constructed in association with the left bank of the 112 m high Latiyan Dam in Iran are illustrated in Fig. 8 (Knill and Jones 1965). The first model was based on the original, pre-investigation field mapping and demonstrates that the left bank ridge was composed of red moderately strong to strong sandstones of Devonian age faulted against the Oligocene volcanic Alborz Formation on the upstream side. Following a borehole programme, adits and a seismic survey, more detail was revealed. The dip of the sandstones was observed to be generally upstream and variable, thin red mudrocks were present, there was local internal faulting within the sandstone, the fault contact on the upstream side dipped downstream, the steep downstream slope of the ridge was partly underlain by granular colluvium and there was well-developed seismic velocity layering despite the complex rock structure. At the final stage the situation was fully revealed during excavation for the buttress dam foundations. The sandstones were in fact isoclinally folded, but only anticlines were present, the synclines having been sheared out and a persistent shallow downstream dipping joint set was found to be present in the sandstone. Even a very extensive, conventional investigation had failed to identify all the details within the rock structure until completion of the excavation. Two contributory factors were the difficulties in recovering satisfactory rock core and the range of variation within a relatively small rock volume. As the ridge was above the water table only limited perched water tables were identified. In this case the appreciation of the poor rock foundations was conservative so the exposed rock was not worse than had been allowed for within the design.

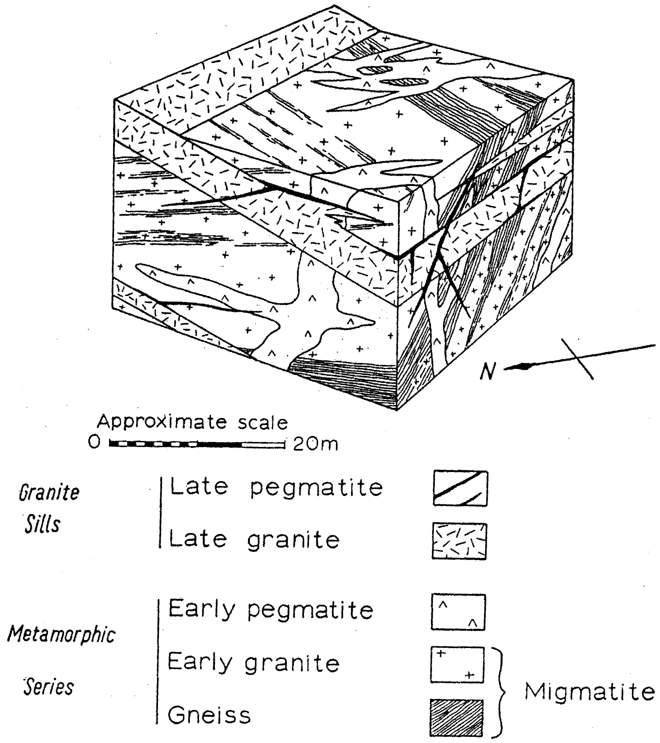


**Fig. 7**
Geological model of Roseires Dam bedrock, Sudan

The use of generic three-dimensional models has been advocated by Fookes et al. (2000) who recognised that "*the conditions and geotechnical characteristics of the ground are the product of the geological and geomorphological history of the site, including past and present climatic conditions, in short, its total geological history. The engineering performance of the site results from the influence of the engineering works on the total geological history*". Early knowledge of a preliminary geological model "*guides the planning of the investigation and the design and construction of the project*" and this is taken forward to

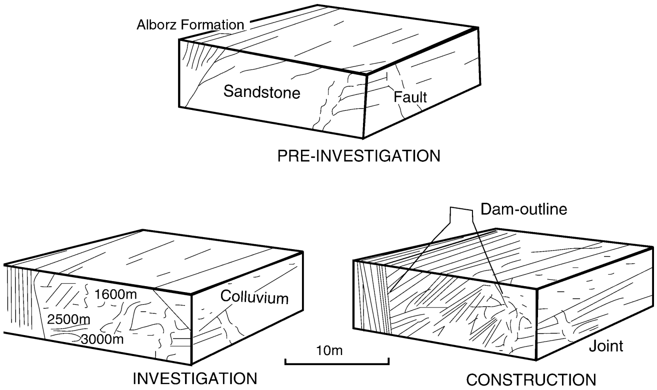


**Fig. 8**
Sequential geological models for Latiyan Dam, Iran

develop a site-specific model as knowledge of the project geology improves. This approach is illustrated by ten two-dimensional "*global scale tectonic models*", seventeen three-dimensional initial "*site scale geological models*" and eight three-dimensional "*geomorphological landform models*" illustrating past and present superficial processes. Some thirty-one case histories taken from the literature are presented which are intended to demonstrate the contribution made by total geological history to construction history. These models are based upon the type of geological and geomorphological principles that form the standard content of first-degree geological training, and so will be familiar ground to engineering geologists; much of the information will, however, be new to geotechnical engineers. In the main, information on environmental controls such as groundwater, gas generation, or rock stress is omitted. No three-dimensional geological models of actual construction sites are presented, as it would have been of value to see the illustrations of an actual iterative development of a geological model during investigation, construction and, possibly, remedial works as advocated by the authors. This comprehensive restatement of an established procedure is helpful in that it underlines the inherent complexity of geological situations.

The geological model must do more than visually illustrate the physical distribution of rocks and soils, their structure and currently active geomorphological processes. The model must also provide an indication of the inferred or actual distribution of environmental controls, such as groundwater, gas and temperature.

Once information on the geotechnical properties becomes available from in-situ or laboratory testing, a ground model can be developed which draws in the available geotechnical information. In that process it is possible that aspects of the geological model may have to be revised or simplified as engineering parameters are allocated to individual lithological units and discontinuities. The ground model will need to be further simplified before it can be subject to mathematical analysis for the purposes of calculations or modelling.

In summary, therefore, the three-dimensional geological model can be seen to have four functions: (1) an enhancement and easing of the visual representation of complex geological situations, (2) an opportunity to place the site geology within an historical process recognising scale, time and space together with the resulting environmental framework, (3) a demonstration of variability as shown by the distribution of material and mass properties and (4) an evolutionary record of the geological understanding of a site from investigation, through design to construction. The geological model must provide a clear indication of the degree of uncertainty that exists.

## Recording, analysis and reporting

### Geological recording

Most time spent by engineering geologists is devoted to recording information. This may involve geological mapping in natural terrain, mapping of excavations, logging of trial pits, trenches, adits and shafts, the logging of borehole core and samples and the interpretation of aerial photographs or satellite images. Many of these tasks are routine and can be very repetitive. They are, now, materially assisted by the use of computers which are hand-held and portable when applied in the field. The development of systematic procedures and automation through the application of computers requires that for each element that needs to be recorded there will be a menu of potential responses. Geology has traditionally been viewed as an observational science which requires a measure of interpretation, whereas most engineering geological procedures have now evolved into basic recording from which any opportunity for personal bias or misinterpretation has been removed. Thus, in needing to describe a rock as being "green", the menu will offer a range of possible shades. What the menu almost certainly will not do is provide the opportunity to record the fact that the green colour is distinctive enough to indicate the presence of green-coloured minerals such as epidote, chlorite or serpentine. The existence of such minerals may not, however, go unrecorded if in the form of large crystals, but their distribution within the rock matrix, which can be of greater importance for engineering purposes, may go unrecorded. Rock fractures may be precisely described in terms of parameters such as orientation or separation, but there can be a lack of ad hoc information such as would be recorded by a structural geologist. Similarly, the use of formal soils descriptions methods can severely restrict the information collected and the record will be deficient in terms of process. The recording of coarse gravels in a trial pit will be factually accurate, but it will fail to indicate whether the soil structure is open-work and subject to an elevated permeability.

Therefore, the consequence of seeking to achieve consistent, reproducible standards in order to ensure accurate design information and to minimise eventual contractual misunderstanding has tended to create systems whereby some of the background geological detail will be omitted, leading to risk. It is normal practice for sample or borehole loggers not to be familiar, other than in a general way, with the anticipated geological conditions. Thus, the desk study summarising the geological knowledge of the site and prepared for design engineers is not made available to such individuals. Borehole core can, therefore, be logged without taking into account other information obtained during drilling. So the presence of open joints in a borehole, and their significance, may not be recognised even though the drill water failed to be returned. Similarly, borehole deterioration may be associated with an increase in fracture frequency for which a tectonic cause may be sought whereas the actual cause may be hydrothermal or another deleterious form of alteration. There can be a failure to recognise buried weathering effects, notably palaeosols, which can result in significant desiccation of underlying cohesive soils. Reliance should not be placed, therefore, on the borehole log alone and, unless the full set of cores is inspected independently of the formal logging as a standard practice, at least sample cores must be re-logged.

In order to accelerate procedures, computer developments now permit the instantaneous transfer of field data to the design office. Whereas such an approach may be regarded as enhancing efficiency, it omits recognition that point observations are linked into a continuum in the field, the significance of which is lost if each point observation is treated individually and interpreted mechanically. The thought process of the field observer should be integrating successive observations into a comprehensible whole, which may conflict with the computer-driven interpretation. Indeed, many experienced field mappers would argue that much understanding of the underlying geology is achieved during the process of walking from one exposure to the next.

### Analysis

The analysis of the data collected during the investigation process is an essential method of maximising the benefit that can be gained from the factual information base. This is standard practice for the automatic handling of laboratory test data whereby relationships can be readily plotted out (e.g. plasticity chart) on a routine basis. However, it is commonly less obvious in what manner geological data (e.g. RQD, assessed rock strength) or large sets of field tests (e.g. packer tests) should be analysed. For example, boreholes may be drilled in an area to be piled for the purpose of determining the unit side friction values. In such circumstances thickness-weighted values for the descriptive rock strength must be generated in order to calculate the lengths of rock sockets required; a simple depth plot would be of no value. In-situ packer permeability tests, if carried to sufficient depth, commonly show a reduction that is related to an increase in natural stress (Knill 1990) which is of value, for example, in predicting grouting performance or leakage. However, some test data may not show such an ordered arrangement. For example, data from limestones may be more readily interpreted if related to depth below the palaeo-ground surface rather than the present-day ground surface. In the case of layered rocks with very different material properties, there may be little structural change to permeability with depth. However, separation out of test sections that are dominated by particular rock types may introduce some order as is illustrated (Knill 1972) in a case history for a reservoir overlying closely alternating mudrocks and sandstones in south-west England. By dividing the data into that which had more or less than 75% mudrock in the test section it was possible to demonstrate that the mudrock permeability was depth controlled, whereas the higher values in the sandstones at least to depths of about 100 m were not implying the overriding control of fractures at that depth. Many engineering geologists will be aware of similar types of correlations between quantitative data and geological situation which have assisted in providing an engineering answer or establishing a relationship that would not otherwise have been obvious. Most engineering geological case histories are not published, irrespective of their quality, and this type of analysis might be expected to be generally retained within reports that are project-specific. However, it is clear from many project reports that such an investigative approach is by no means general, and on some occasions no attempt is made to analyse a wealth of geological information which is available to enhance the engineering context.

### Synthesis

There has been a general lack of adequate and up-to-date synthesis in engineering geology whereby published and unpublished information is drawn together. An early cause of this situation was that case histories published in the earlier text books (e.g. Legget 1962) tended to be classified under type of construction so that any synthesis of experience on, say, mudrocks was distributed rather than concentrated. There have been significant advances, for example, comprehensive reviews of the engineering geological context of characteristic rocks such as granites (Dearman et al. 1978) and limestones (Fookes and Hawkins 1988), soils environments such as glacial (Fookes et al. 1975) and residual soils (Fookes 1997b), and natural hazards such as karst (Milanovic 2000). However, the coverage of all the relevant topics is by no means comprehensive because they concentrated on weathering, classification and properties, rather than practical construction-related issues. Some reviews have become somewhat dated in that the more recent primary source material remains unsynthesised. For example, much of our understanding of the engineering behaviour of mudrocks is based on some benchmark papers (Morgenstern and Eigenbrod 1974; Taylor 1988) which set out fundamental principles of weathering, behaviour and classification. Nevertheless, in the subsequent decades, although many papers have been published on a wide variety of mudrocks, there has been no in-depth, fundamental review of the engineering geology of mudrocks recognising their diversity of origin despite the known importance and wide distribution of this rock type. The importance of this issue cannot be underestimated as engineering geology is based, to a large degree, on integration of case history experience. Some 40 or 50 years ago the experience gained by many engineering geologists was broadly based, commonly being derived from projects in several countries, on a range of soil and rock types and in different climatic and topographic environments. Individuals were able to achieve their own engineering geological synthesis derived from experience, publications and networking. The wealth and breadth of personal experience that was gained at that time, much of which was not published, is not being replicated at the present day.

### Reporting

The preparation of reports as a result of site investigations represent, with logging, the most significant tasks carried out by an engineering geologist. Without a record the investigation need not have been carried out. Project reports can be divided into multi-stage hierarchical structure, set out below in relation to current UK practice, to which some US terminology is added (Essex 1997; Brierley 1998):

Desk studies are carried out prior to any physical investigation and involve the review of all the available published and unpublished information together with a walk-over survey to ensure site familiarisation. The walk-over survey may contribute significantly to the understanding of the influence of ground conditions on the project area. For example, the locational options for the project can be reduced by avoiding unstable areas and potential sites for construction materials can be established. An effective walk-over survey, by an experienced engineering geologist, can result in considerable economies at a later stage. The desk study is used for the planning and design of the subsequent investigation.

As discussed earlier, the literature contains remarkably little guidance as to the scale of an investigation in relation to particular project types. Effectively the number of boreholes and their depth, the area over which mapping is required or the frequency of testing are left very largely to experience and engineering judgement. The geological information available at the design stage will fall into two classes: (1) data collected by investigation carried out in relation to and in the vicinity of the particular development and (2) information collected as part of the desk study. Whereas drilling may be carried out to a depth of, say, 25 m below the base of a structure, geological extrapolation from other sources may provide some level of knowledge to a greater depth.

The depth or lateral extent of investigation must at least cover the ground or groundwater that may be affected by the structure and the influence of its construction or operation. The limits of the eventual structural foundation will be much smaller than the zone of ground that could be influenced by excavation or dewatering. Investigation should take place through soils or rock that would not provide founding conditions and should, in general, penetrate at least 5 m into rock to prove the presence of bedrock, unless it is known that boulders of some form could be present or the existence of bedrock is irrelevant to design. For structural foundations, the depth of investigation will be a function of the height of building, the area of the foundation and the effect and intensity of loading. A conservative approach is to ensure that some investigation is carried down to a depth equal to the building height below the founding level. Such an approach can be relaxed if adequate geological information or experience is available from other sources. Once a general founding level is determined, then the specific investigations below actual foundations for footings or piles should be 5 m or two-and-a-half times the foundation width or pile diameter. Deeper investigations will be required where hazards are present, such as cavities in limestone, mine workings or confined groundwater. In the case of very large structures, such as concrete or embankment dams, sufficient investigation should be taken to a depth that is not less than the height of the dam and in complex cases significantly more because the groundwater effects will extend far wider than the structure alone. For excavated slopes the investigation should extend below the depth of any potential failure surface or confined groundwater body, which may involve drilling to at least a third of the slope height below the level of its toe. For shallow structures, such as pavements or pipelines, investigations of 1–3 m below founding level would normally be adequate. Investigation for tunnels should take place some distance below the invert level. Applying the 1:500,000 ratio (discussed earlier) to tunnelling would imply a need for the total length of HX (circa 100 mm) diameter exploratory drilling for a tunnel below mountainous terrain to be equivalent to the length of the tunnel. The lateral extent of investigation will vary with the scale and type of structure. For buildings in an urban environment, site-specific knowledge within a range of hundreds of metres would normally be adequate unless groundwater conditions were relevant, in which case the investigation would be more extensive. In the case of slopes, mapping should extend uphill to at least the topographic crest and some distance beyond and for an equivalent lateral distance beyond the toe. Mapping should be carried out within a 2 km strip for a major tunnel in hilly or mountainous terrain. The actual area mapped will have to be adjusted in relation to the large-scale rock structure. In the case of smaller reservoirs, mapping to a distance of 1 km out from the proposed margin is normally adequate, but this will have to be extended with increase in reservoir size to possibly 5 km or more for very large reservoirs, or where leakage and induced seismicity are issues. In the case of all investigations, search should be made for situations that could represent precedent experience such as slope instability in quarries, old adits or sink holes. Particular attention should be paid to the extent of both lateral and vertical investigation for any structure where the construction process will contribute to settlement, loss of support or heave.

The factual report (British Standards Institution 1999) is the record of the results of the investigation which may be carried out in distinct stages. For large investigations, the report will be multi-volume, involving borehole and trial pit logs and photographs, field and laboratory test results, monitoring records and geophysical results. It is common practice for monitoring boreholes, to record variations in water level or ground movement, to be installed during the investigation so that observations will continue during the design process. The factual report is commonly prepared by a site investigation contractor, with sub-contractors reporting on specialist work. This situation ensures that the record can be regarded as an independent document which has not been subject to adjustment by other parties; this can be important in the event of subsequent contractual claims. However, it is also important to ensure that the factual report is audited to ensure that the record is accurate, comprehensive and that all the necessary information is presented. For example, the stratigraphical position of known geological formations encountered in boreholes should be recorded on logs, thereby reducing the risk of misinterpretation at a later stage. Agreement on stratigraphic designation could be assigned to an audit process. The detail of what is contained in the factual report can vary and there may be advantage, for example, in interpolated geological sections being presented at this stage. However, the preparation of geological sections involves interpretation and, unless such sections can be agreed by all parties, they should not be included at this stage.

The interpretative report is generally presented in two main sections, is normally not written by the author of the factual report and there is commonly more than one contributor. An interpretative report will contain a general account of the local geology together with a detailed site-specific statement of the formations encountered as based on the investigation results. Other information on regional seismicity or hydrogeology, as appropriate, will be presented. Active geomorphological processes will be identified. This account will be illustrated by maps, sections and photographs of the major rock formations. The geo-environmental conditions will be described and illustrated, including groundwater, rock stress, gas and temperature. This information will be summarised in one or more geological models, normally presented as three-dimensional isometric drawings. The next part of the interpretative report addresses broad geotechnical issues and may be subdivided into two parts, one that deals with information that tends to describe soil and rock mass properties and behaviour, and another that has a more strictly engineering content. However, the way in which the report may or may not be subdivided and presented will be very dependent on the project, the ground conditions, the engineering issues involved and the staff involvement. Quantitative geological information (e.g. RQD, assessed rock strength) and in-situ (e.g. packer permeability) and laboratory (e.g. classification, shear strength) test data will require summarising, tabulation and analysis in an appropriate format. This will be followed by an interpretation of the ground conditions recognising both the design and construction requirements. The extent to which design is covered in depth may be a matter of choice dependent on a decision as to whether there will be a separate development of a geotechnical design report. Where a relatively sophisticated geotechnical structure is involved (e.g. embankment dam) then a specific design report is always to be preferred. The interpretative report will commonly address the engineering issues in relation to specific structures. Thus, in the case of a rock tunnel, the report will cover: excavation method (referring to strength and abrasivity tests) in relation to the rock types likely to be encountered (the proportions of which will be computed); need for temporary support and, if so, the type, which may require issues such as convergence and rock durability to be addressed; groundwater inflow in terms of location, rate and temperature; and potential gas entry. Geological and engineering issues must be integrated together. Thus, the design of a dam cutoff must combine protection of the structure, its foundation and general reservoir watertightness.

The geotechnical design report will provide the specialist analysis of engineered structures, including embankments, cut slopes in soils and rocks, foundations and underground excavations.

A recent development within the report sequence has been the baseline or benchmark report intended to identify the key geotechnical parameters that are to be used for design or applied as foreseeable limits in construction (Essex 1997; Brierley 1998). When applied in design the baseline can be presented as a single figure, as in the case of the frictional and cohesive components of shear strength applied in slope stability analysis. By stating the geotechnical assumptions used in design so transparently it is relatively straightforward during construction to check whether there is any deviation from the base assumption. Alternatively, the baseline may be a range covering, for example, a rate of settlement or the pore-water pressure developed under specific loading conditions. The concept of baseline conditions has also been advanced because it provides a means of predicting conditions that might reasonably be anticipated during construction by a contractor. Put simply, the baseline is the best guess that the design engineer can make on the basis of the available information. This provides a short-cut for a contractor at the tender stage in evaluating the ground-related information and then subsequent protection during construction if different conditions are found to exist. The baseline conditions set for excavation in a rock tunnel could include rock type, joint and bedding separation, rock strength, quartz content, abrasivity and durability, which would give an indication of cutability, drillability, rock block size and spoil properties. The figures quoted would probably be within a specified range supported by evidence obtained during the investigation. If different figures were encountered during construction, and these differences contributed to engineering difficulty which had not been allowed for, resulting in additional costs or delay, then the contractor would have gone some distance in establishing the technical case to support a claim. Such a procedure avoids sterile technical argument which may only be resolvable through a time-consuming and expensive formal process. An argument against setting such baseline conditions is that the owner and designer might select a range of conditions set unjustifiably wide which could not be justified on the basis of the investigation, so that the contractor would be very unlikely to encounter conditions outside the baseline. One approach to counter that situation would be to ensure that the ground reference conditions (Construction Industry Research and Information Organisation 1978) are agreed between the contractor and owner at the time of contract signature.

A further contractual issue is the extent to which information obtained during the investigation is provided to contractors at the tender stage and whether that information is deemed to be within or without the contract. A traditional view was that the contractor should be given no more than the actual records, such as borehole logs, and even then there was an attitude that no information should be provided to contractors. However, the evolution of the factual report within the industry has been such that this report has been specifically designed so that it can be given to contractors without the suggestion that the document contains any statement of opinion on behalf of the owner. In many cases contractors are also provided with the interpretative report partly because it will save time during the limited period available for tendering; otherwise the contractor will have to evaluate the site conditions within a matter of a few days or weeks. Baseline or benchmark reports would be provided to contractors as part of the contract documentation because that is their purpose. In view of the bulk of material that requires review by the contractor, a summary geotechnical report may be provided, as an information document, which focuses on the most important background data regarding the natural setting of the project, including rainfall and hydrological records, seismic history maps, geological sections and photographs of illustrative outcrops or core, with locations of outcrops where typical geological conditions can be seen. In urban or other areas where there has been development, mining or other human interference such information would be included. It is now regarded as good practice for as much information to be provided to a contractor as possible as a part of the contract documentation, within the framework of carefully devised baseline conditions.

## Construction practice

### Design

The site investigation is normally closely merged with the design process. The desk study will have provided guidance on site layout and location, with alternatives if appropriate. Areas with obvious geological hazards would be identified and either avoided, or recognised by use of an uncertainty schedule. The location, scale, depth and type of investigation can be decided and an exploration programme planned. By staging the investigation with periods for design review, which may be modest in length, there is an opportunity for adaptation of and extension to the investigation process. Indeed, in the case of all but the smallest investigations there should be a provisional financial allotment which would permit extension of the investigation in response to the initial results. The earlier stages of the investigation may be more general in character, being related to the establishment of the basic ground conditions. As the design matures and the location of the component parts of the project becomes more firmly fixed, it is necessary to ensure that each component structure is subject to at least a minimal level of physical investigation. Such an arrangement will ensure that a contractor cannot make a possibly spurious claim based on a lack of site-specific information. Indeed, such an issue underlies a fundamental defect in investigation designs in that they tend to be design-focused without providing sufficient parallel information relevant to construction practice and operations. Contractors require information, such as the permeability of superficial deposits which will require dewatering or rock hardness data where there will be extensive rock excavation. If this is not provided, then the contractor may be able to offer little more than an educated guess.

The interpretative report should provide sufficient information to permit basic engineering design to proceed to completion. Extensive engineering geological input will be required during decisions such as the depth and shape of excavation, detailed interrelationships between the permanent works and ground conditions, temporary works, temporary and permanent ground treatment, permanent support requirements and the presence of suspect or deleterious ground conditions. Engineering geological approval should be sought for all design drawings where the structure and ground interface.

### Promotion

Once design is complete the appropriate statutory or other powers need to be sought to enable permission to be provided so that construction may proceed; finance may have to be sought. The promotional stage will require documentation and may involve hearings at which evidence is formally given on the nature of, and need for, the project. Public opposition to engineering projects must be accepted as a standard feature, even though public benefit will result, so that geological evidence regarding the proposal is commonly required to demonstrate the feasibility of the scheme in terms of cost, environmental impact and safety. For example, a reservoir may be challenged because it could be subject to leakage and thus the economics of the scheme will be affected; the siting of borrow pits and quarries may be questioned because of long-term visual intrusion; and the presence of unstable slopes may be argued to increase local hazards. The introduction of such issues should be recognised during the investigation and design phase and appropriate steps taken before promotion. In the circumstances that such opposition to the project is anticipated then the additional investigation should be carried out so that it is adequate to provide the level of necessary evidence, although it may not be strictly required for design and construction purposes. For example, in the case of a reservoir that might be argued not to be watertight, it will be necessary to be able to demonstrate continuity in the groundwater body below the assumed water table, a situation that would be normally assumed. The matter becomes even more difficult where the project is extremely controversial such as a toxic or radioactive waste disposal site.

Engineering geologists commonly give both written and oral evidence in such circumstances, being subject to aggressive cross-examination on their factual observations and interpretation (Knill 1987).

### Tendering

Once design is complete, and approvals are anticipated, contract documents will be prepared on behalf of the owner, normally by the designer, which will set out the terms of the contract in relation to general conditions, specifications, bill of quantities and drawings. These documents form the basis upon which the contractor will cost the project. Before this stage it will have been necessary to determine in what form the ground information, including the desk, factual, interpretative and baseline reports, is made available to contractors. It would be quite exceptional, at the present day, for no information whatsoever to be made available, but the interpretative report may be retained under special conditions, or for inspection only. In addition, if reports are made available, it is essential for their contractual status to be determined; will they be a part of the contract documents or not? If there is any omission in the information given to contractors which could give rise to misunderstanding at a future date, then the potential implication should be understood. For example, a map of ground hazards, if prepared as part of the ground report suite, should not be withheld from the contractor. It is not unusual for the contract documents to state that contractors are expected to satisfy themselves as to the ground conditions, by carrying out investigations, in the period between the start and end of the tender period. Such a requirement is unreasonable because, even for contracts with a long tendering period, it would mean the expensive establishment of a drilling programme on a short timetable.

Nevertheless, pre-contract geological inspection by contractors can be highly rewarding in that new facts are commonly recognised. There can be limited time available for engineering geologists working for contractors to carry out an independent interpretation of the ground conditions. The input is normally limited to a site visit, inspection of cores and type outcrops and a review of the documents supplied. In the case of a 6-week tender period, information available more than 10 days into the tender period is normally too late to influence the billed price. Only if the information fundamentally changes the construction approach will it have a significant influence on the contract, and the contractor may choose to regard the matter as a potential claim for the future rather than adjust the bid price. Engineering geologists will be looking for misinformation or gross errors in the tender information which might form, in due course, the basis of a successful claim; such conditions are more frequent than might be thought possible.

If the contract defines baseline geotechnical conditions then these may be subject to formal agreement between owner and contractor as part of the contract settlement process. As this reduces the options that the contractor has with regard to disputing the reasonableness of the conditions at a later stage it is essential that the baseline data are checked by the contractor's geotechnical staff. This subject can be further complicated by more modern forms of contract such as design-and-build, or the involvement of an overall project manager. Current contractual practices also allow for alternative procedures such as the appointment of engineers to supervise construction who may not have been involved in the earlier stages of the project.

### Construction

It is now general practice for engineering geologists to work for both the engineer supervising construction and the contractor. The engineer requires confirmation that the anticipated design and/or baseline conditions have been encountered. In addition, a record needs to be made of all exposed geological conditions as these may provide the basis for eventual ground-based claims. The contractor's engineering geologist is also responsible for maintaining a geological record of ground conditions in view of potential claims, as well as the design and installation of temporary works. Unfortunately it is unusual for a single agreed geological record to be prepared and attempts by one party to achieve such an objective are normally rejected on tactical grounds. It is not unusual for the engineer's engineering geologist to declare that the conditions revealed are as predicted, at which point any debate on the issue is deemed to be closed. The consequence is that non-contemporary records can be manufactured at a later date in order to form the basis upon which to support or reject a claim. The engineer's engineering geologist may choose to limit the owner's involvement to a simple acceptance of record drawings without comment, may reject the presentation of certain information being recorded, may refuse to accept the inclusion of certain data (e.g. assessed RQD), or may refuse to agree to records unless the engineer's position is unilaterally accepted. Claim situations can reveal the adoption of quite unsatisfactory professional practices leading to sterile argument. Ideally, a single set of all geological record drawings or logs which includes the information required by all parties should be prepared. No party should have the right to exclude relevant information which another party wishes to include. An early task on any site, where extensive visually recorded ground records are to be made, is to agree the format in which such recording will be carried out.

Engineering geologists working for both the supervising engineer and contractor are normally responsible for recording monitoring data; the owner may also have a representative geologist. Commonly the contractor's engineering geologist is also responsible for installation of monitoring equipment (e.g. convergence, displacement, groundwater), technical supervision of geotechnical engineering processes such as grouting and special research studies into construction performance (e.g. drillability, excavation). The contractor's engineering geologist would be expected to be alert to potential claim situations and also be involved in situations where the rate of performance of engineering plant or success of engineering processes was less than that predicted.

In the case of large projects, where the funding is from the World Bank or a Development Bank, it is normal practice for a Review Board of about three individuals to be appointed who are expert in the particular engineering issues associated with the project. It is normal for an engineering geologist to be appointed as a member of such panels where dam, underground and associated surface works are involved. The Board has the responsibility to review the design and tender documents and then to report at regular intervals during construction. The Board comments on technical issues and would only rarely become involved in financial matters associated with the contract. Although the Board will meet with the contractor, normal liaison will be through the engineer and so the Board may not necessarily have a balanced view when contractual arguments arise. Further, the Board will carry a measure of implied responsibility in the circumstances when there is inadequacy in the contract documentation. Ad hoc panels may be set up to resolve disputes by mediation, such as the review of underground conditions at the Kariba North Bank Underground Power Station in Zambia/Rhodesia in

1972 where flat-lying, isoclinally folded seams of biotite mica schist were encountered in the machine hall roof (Fig. 9). The contractor claimed that these were unforeseen and, furthermore, that as the borehole logs (which showed no such schist) were warranteed, there was a valid claim. Although the panel adjudicated in favour of the contractor, the dispute was not resolved, resulting eventually in the requirement for the contractor to go into liquidation (Morrell 1987).

Monitoring is commonly integral to the construction control process and this has evolved into the "observational approach" (Peck 1969; Nicholson et al. 1999). The conventional design-and-construction process adopts a specific design based upon selected geotechnical parameters which permit limited flexibility during construction. The factor of safety in such circumstances will tend to err on the conservative side. Construction control can be provided by pre-established baseline performance conditions set, or largely set, before construction begins. The construction of prototypes such as fill embankments or the excavation of cut slopes carried out during the investigation or early in construction can provide some prior indication of ground performance. The observational method has been applied for some time in the construction of temporary linings for tunnels, thereby permitting the incremental addition of support (e.g. shotcrete, rock bolts, netting, steel arches, floor struts) in response to the interpretation of convergence measurements. The added support is all that is required to achieve the required level of performance; further support can be added if excessive deformation takes place. The observational approach has been extended to larger-scale earthworks involving progressive placement or staged excavation, particularly where previous movements have taken place. The location of monitoring instrumentation will commonly be supervised by engineering geologists to ensure that the zones that are at risk with regard to displacement, or could give rise to excessive groundwater pressures, are given particular attention.

### Monitoring

Long-term monitoring equipment will be installed in those circumstances where there is a possibility of response to the completed, operational structure such as impounding of a reservoir, foundation settlement or slope deformation. During construction it is normal practice for the contractor's engineering geologist to be closely involved in the installation of the longer-term monitoring equipment which will be used to confirm, or otherwise, the satisfactory performance of the structures during the operation of the project.

### Remedial works

The need for ground-related remedial works may be recognised from the results of monitoring, by unanticipated fluid release, or from observations of excessive deformation in a completed structure. The evidence on non-performance is commonly observed by a sudden change in conditions such as subsidence depressions or settlement, ground cracking or bulging, cracking and deflection in concrete and changed (normally increased) water flow possibly associated with suspended sediment. The Symvoulos rockfill dam was constructed in Cyprus on the carbonate Pakhna Formation in the early 1990s; two phases of remedial grouting did not alter the situation. Leakage started soon after impounding was initiated and increased yearly at constant reservoir level as the flow path was progressively opened up (Fig. 10). A different approach to interpreting the rock mass geology and geomorphology was adopted and some low-cost investigations identified a probable preferential flow pathway. A further programme of excavation, concrete backfill and specialist grouting encountered and sealed the leakage zone, resulting in the reservoir holding water, reaching top water level in the winter of 2001–2002 (Fig. 10). Such situations arise either from unanticipated behaviour or from anticipated behaviour but at levels beyond those expected. Although a monitoring system will provide some information on the cause of the failure and the means by which it may be treated, additional investigations are generally

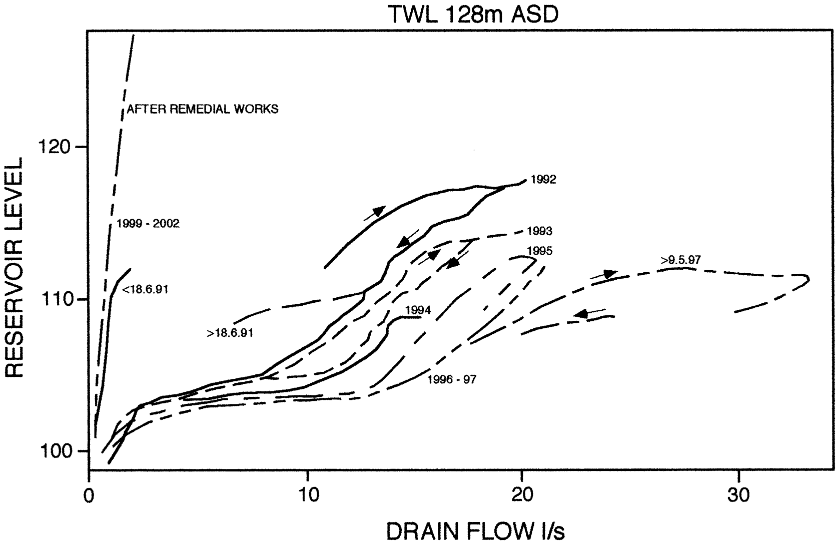


**Fig. 9**
Geological section through Kariba North Bank machine hall, Zambia/Rhodesia, showing isoclinally folded gneiss with biotite schist layers. Machine hall is about 30 m across

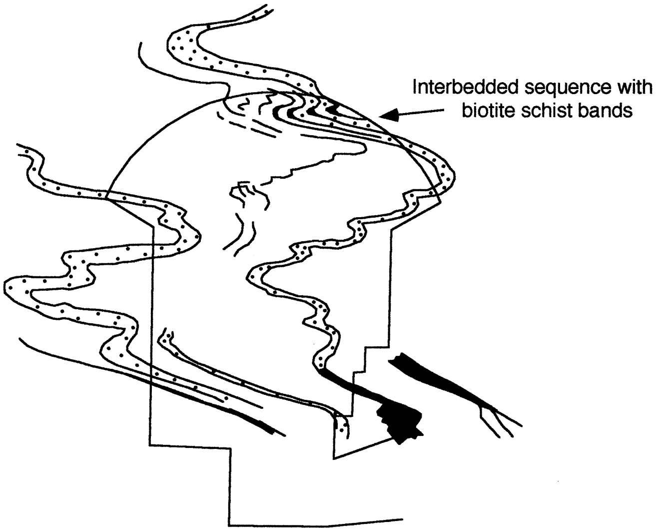


**Fig. 10**
Leakage from Symvoulos dam, Cyprus, showing effects of remedial works

required before any redesign and construction of any further works. There is normally a close engineering geological involvement throughout these stages.

## Verification and validation

### Verification

The process of verification is built into most engineering processes where, for example, design assumptions and calculations are checked and confirmed. This has been formalised into the application of Quality Assurance (QA) procedures which generate a document-certified set of protocols through which certain individuals confirm that the particular work (e.g. interpretative report) has been fully checked. Although the QA system is in wide usage it has potential flaws, particularly when geological information is being reviewed. This arises for a number of reasons. For example, in the case of borehole logs, or geological maps, the original source of data is difficult to check without returning to the field or the core. In many engineering organisations there may not be enough engineering geologists in the position of being able to carry out the independent review to adequate levels. However, where the geological material under review is interpretative, such as in the case of geological sections or the relationships between ground conditions and engineering behaviour, QA may have some validity if the operational reviewer is of sufficient quality and experience.

The lack of formalised review procedures for geological data and interpretation has to be regarded as a serious issue in view of the frequency in which claim situations are ascribed to errors in documents, or to a lack of adequate understanding of ground conditions. A common method of handling this situation is the involvement of a consultant engineering geologist, who may be in-house, with the responsibility of maintaining a continuing review of the project geology as it evolves from the desk study. Where logging or mapping are involved a formal audit procedure should be devised so that, for example, the core of one borehole in ten is relogged. All completed draft logs and maps should be checked in detail by an engineering geologist. Where engineering drawings indicate the presence of a ground-structure interface, then there should be a formal review by an engineering geologist even though the production of the drawing may have involved geological/engineering collaboration.

Whatever the methods adopted, a procedure for any project with an engineering geological input should be devised for the data and interpretation verification procedures that have been adopted. A transparent statement of this procedure should be contained in any reports or relevant parts of contract documents.

### Validation

Validation of a project can only be demonstrated by the satisfactory performance of the project and its components, the lack of need for remedial works, or by the demonstration of its economic, safe and timely construction. If the project, or a component part, fails validation then one or more parties will attempt to seek compensation from others. The most common situation is a claim by the contractor to cover additional costs associated with unforeseen conditions and delay. However, failure or some other deficiency within the project will result in the owner seeking compensation to cover the costs of remedial works. In such circumstances the engineer will need to defend a case of professional negligence. In general, there is now a greater tendency for cost recovery to be sought, and ground-related issues are amongst the most common that give rise to some form of litigation. Engineering geologists have a critical role in protecting their employer's or client's financial interests.

Hoek and Palmieri (1998) reviewed geotechnical risk in heavy civil engineering and recognised, through an analysis made in 1996 of 71 World Bank hydroelectric projects, that actual construction costs and schedules were on average about one quarter higher than those that had been originally estimated and that "*projects have been abandoned or where cost and schedules have escalated to several times the original estimates*". Unforeseen geological conditions and the associated geotechnical problems were accepted as contributing to such "*overruns*". Many of such "*disasters*" were seen to be caused by inadequate geological information, inappropriate geological interpretation and incompetence. Such experience is mirrored throughout construction experience and is dealt with through a number of processes (Gould et al. 1999).

Civil engineering contracts contain a protective clause, or clauses, covering the situation where the conditions encountered are not those foreseen. The traditional "Clause 12" generally deals with such circumstances and Clause 12.2 of Part I of the Federation Internationale des Ingenieurs-Conseils (FIDIC) "Conditions of Contract for Works of Civil Engineering Construction" states that "*If, however, during the execution of the Works the Contractor encounters physical obstructions or physical conditions,* *other than climatic conditions on the Site, which obstructions or conditions were, in his opinion, not foreseeable by an experienced contractor, the Contractor shall forthwith give notice thereof to the Engineer, with a copy to the Employer. On receipt of such notice, the Engineer shall, if in his opinion such obstructions or conditions could not have been reasonably foreseen by an experienced contractor, after due consultation with the Employer and the Contractor, determine: (a) any extension of time to which the Contractor is entitled under Clause 44, and (b) the amount of any costs which may have been incurred by the Contractor by reason of such obstructions or conditions having been encountered, which shall be added to the Contract Price, and shall notify the Contractor accordingly, with a copy to the Employer. Such determination shall take account of any instructions which the Engineer may issue to the Contractor in connection therewith, and any proper and reasonable measures acceptable to the Engineer which the Contractor may take in the absence of specific instructions from the Engineer*". The FIDIC clause is widely applied internationally, although there may be variants adopted of the same "foreseeability" principles by governments, their agencies and large international organisations.

Contractual claims, notably associated with ground-related issues, can give rise to a considerable escalation of cost. The frequency of such claims has led to the development of alternative clauses which try to restrict the opportunity for a claims-based culture. For example, the contractor may be required to carry out the project on a fixed price basis accepting the full risk associated with cost escalation, or there may be a cap on the total contract price which would include some allowance for any claims that may be constrained to particular issues where uncertainty remains. The Hong Kong Government, for example, adopts an "impossibility" clause in its General Conditions of Contract for construction which states "*Save in so far as it is legally or physically impossible the Contractor shall execute the Works in strict accordance with the Contract to the satisfaction of the Engineer and shall comply with and adhere strictly to the Engineer's instructions on any matter related to the Contract whether mentioned in the Contract or not*".

Because of pressure on design engineers to come forward with tight project estimates, intense competition between contractors and the general policy of awarding contracts to the cheapest bidder, a contract may start in an environment in which a contractor must find and win claims to avoid a financial loss. This situation has created a litigious atmosphere arising from the fact that claims are relatively common but settlement cannot be achieved by simple discussion between contractor, engineer and owner. The engineer regards it as a matter of pride that the conditions encountered are the same as those foreseen; a claim is a criticism of the engineer's professionalism. The owner, unless well-attuned and prepared, would rather not know. The Review Board will have commonly had too little opportunity to spend enough time on the project to have adequately appreciated the ground conditions and anticipated design errors sufficiently early in the project; in any event the Board is normally not responsible for financial considerations. So time-consuming argument develops between the contractor on the one hand and the engineer and owner on the other. Eventually recourse has to be made to a formal resolution procedure. There are two groups of such procedures, one that introduces external parties to assist in the process, and another that invokes a legal or quasi-legal method of determination.

In the case of larger projects, or where the possibility of claims is envisaged, a Dispute Review Board is commonly appointed (Matyas et al. 1995). Such a Board is typically composed of three individuals, certainly comprising engineers but possibly lawyers who are expert in contract law as well. The contractor and owner will each appoint one member, and the chairman will be jointly appointed. The Board is established at the time that the contract is signed, and thereafter is available to review disputes that are referred to it. The function of the Board is to work with the other parties through meetings and discussions to achieve consensual agreement and not by imposing a decision. The Board's reports will reach definitive decisions and provide recommendations which it is anticipated will achieve acceptability amongst the parties.

More informal procedures operate through mediation and conciliation where, typically, one individual (normally an engineer) is appointed to review the evidence submitted by the contractor and on behalf of the owner after claims have been established. The process is semi-informal and the reports are advisory, not mandatory. It will be up to the parties to decide whether this process has achieved a proposed resolution which is both fair and far less costly than that which would result from proceeding to arbitration or litigation. Such a process is very dependent on the mediator achieving confidence amongst the parties.

Arbitration is a legal procedure, for which provision is made in the contract, in which the decision on a claim is made by an arbitrator or an arbitral panel, typically composed of engineers, with a lawyer as chairman. Having identified and recorded the circumstances of the claim, the contractor's advocates prepare a statement of the grounds of claim and the redress sought on behalf of the contractor as claimant. This is responded to through the owner's (respondent) advocates, thereby progressively defining the issues at dispute. Documents, correspondence, site records and reports that relate to the project history and to the defined issues are collected together. Statements are prepared by the individuals involved in the project (witnesses of fact), and by expert witnesses, who had no prior involvement with the project. The expert witnesses will deal with liability, which relates to the technical issues involved, quantum which covers issues of cost, and programming. Evidence is given to the arbitrator or arbitral tribunal in a formal setting on behalf of both parties, with opportunities for cross-examination by an advocate acting on behalf of the opposing party. The procedure is formal although there is some internal flexibility as to how the hearing proceeds. For example, it may be agreed that the expert evidence is tested by the expert witnesses for liability cross-examining the opposing team instead of this task falling to the advocates. The arbitrator or arbitral tribunal then writes a report which is, normally, binding on the parties involved; only exceptionally can it be appealed against. If the issue is taken to litigation, then a trial is held before a judge with a similar but more formal procedure than is adopted in an arbitration. In order to reduce the opportunity for time-wasting technical debates it is possible, both at arbitrations and in court, for joint single witnesses to be appointed who will provide a definitive view on the technical aspects of matters under debate.

The claims process begins with the recognition of the grounds for claim by the contractor which needs, as soon as possible, to be formally reported to the engineer and to the owner according to the terms of the contract. Because the conditions that justify a claim may appear over a period of time this process is not always clear-cut and so can give rise subsequently to some dispute. Thus, in the driving of a tunnel very different conditions to those foreseen may be encountered over the first tenth of the tunnel. This may not constitute a valid claim because it could be argued on behalf of the owner that the conditions in the remaining nine-tenths of the tunnel may alter the balance back to those foreseeable. Even though the observed geological conditions indicate that such a premise is unlikely, the engineer may maintain such a view for months and years, giving rise to intense frustration on behalf of the contractor. The owner, as advised by the engineer, will recognise that an early decision on a claim, even though it is valid, may introduce a precedent which could open the door to claims at a later stage. As a result, the resolution of a claim may be delayed for a considerable period and this tends to lock the parties into set positions. At the same time the contractor is faced with an increasingly difficult cashflow situation in that inadequate financial resources are available to service the contract as it has now evolved. This is the point at which a Dispute Review Board (if appointed) or a mediator could take the matter forward to a resolution. The contractor will nevertheless still have to proceed with preparing formal claim documents and this will involve appointing an expert or experts who will be able to provide an independent view of the case for the claim. Engineering geology has a central role in either winning or defeating a ground-related claim. Good-quality site records, as discussed previously, are extremely important and, on many large projects, there will be a team working for the contractor on what is effectively preparation for claims submission.

The expert engineering geological witness has a key role in validating the technical case for the claim, and needs to have sufficient site familiarity, based upon a number of visits during construction (Knill 1987). If a geotechnical baseline approach has been adopted in the contract, then the starting point is relatively straightforward in that the predicted baselines can be compared directly to measurements or observations made during construction. In such circumstances one would not expect that a claim could be justified and approved without major debate, although the owner may be reluctant to settle at too early a stage in view of the risk of creating a precedent. There may be disagreement over the validity of sampling or interpretation, which would require resolution; this underlines the importance of maintaining good records. Most commonly, the basis of a geological claim may have a very simple origin. For example, rockhead may have been misinterpreted, rock mass permeability may have been underestimated, the presence of hydrothermal conditions in granite with geothermal water may not have been recognised, the properties of superficial deposits could be misdescribed, or there may have been inadequate site investigation. Many such claims typically arise from a poor quality of geological understanding commonly caused and exacerbated by the involvement of inexperienced engineers in essentially geological tasks.

This discussion has concentrated on contractual claims arising from the conditions being encountered during construction which were different to those foreseeable. A different basis for dispute, based on professional negligence, arises where the engineer is the source of the error and the owner seeks reimbursement for additional costs that have had to be paid to a contractor (possibly following an arbitration), or compensation for the failure of a project to meet its purpose, as might arise in the case of a leaking reservoir. The procedural arrangements are similar to those discussed previously and, not uncommonly, can be subject to settlement before arbitration or litigation.

## Strengths, weaknesses, opportunities and threats

### Strengths

Engineering geology is soundly based on the broad understanding and application of the science of geology, reinforced by an appreciation of the mechanical principles influencing the engineering behaviour of soils, rocks and fluids. Engineering geology is not restricted to a particular geological situation, formation or issue but ranges through rocks and soils of all ages, formed and occurring in all environments. This universality of awareness and comprehension is unique within geology and its applications. The subject is applied throughout all stages of the engineering process, although most intensively during investigation and design. Successful engineering geology gains little publicity and as a consequence acquires too little credit. The recognition of adverse ground conditions in site selection ensures that unnecessary investigation is avoided and the risk of costly failures reduced. Well-presented evidence in arbitration or litigation can gain or protect very large capital sums. Working as an engineering geologist can be highly rewarding, providing opportunities for employment on construction sites in remote locations or centres of urban population while avoiding being bound to a desk. There are leading-edge opportunities to be involved in the handling and interpretation of data through information technology and state-of-the-art geophysics. Good opportunities exist for the establishment of small consultancies by entrepreneurs which offer niche expertise in the engineering geology of a region, or in a particular subject area. Specialist postgraduate qualifications can be obtained. There are considerable exciting research spin-off arising from construction experience, as well as fundamental research. The teaching of civil engineers, through higher education, offers opportunities to publicise the manner in which geology can be best applied in the construction industry. There are strong, well-developed learned society and professional body activities for engineering geologists in many countries, with influential over-arching international activities provided through the IAEG and conferences.

### Weaknesses

Engineering geology, being concerned with the applications of geology, is regarded with some disdain and lack of understanding by the academic geological community on the grounds that it is related to industry and is concerned with a simple form of the subject which is not intellectually challenging, or respectable. As a result, national and international influence within geology is vested in individuals who, on the one hand have no knowledge of engineering geology or civil engineering and on the other are all too willing to accept commissions to provide advice on matters related to engineering geology. This situation is not aided by geotechnical engineers who supplant the need for engineering geology within their own work even though they do not have comprehensive geological experience or background. Although engineering geologists work as equal colleagues within industry, the institutional system, as reflected by national and international organisations in geotechnical engineering, does not appear to give a balanced position to engineering geology. Engineering geology can be perceived to fall into a second-class role. Engineering geologists are regarded, in industry, as the junior members of the geotechnical engineering team. Although the subject is accepted in civil engineering, because it is recognised that good engineering geological advice is essential, it is the exception rather than the generality for engineering geologists to be seen as strictly equal to engineers. Many engineering geologists accept that situation, seeing their roles as data collectors and interpreters with a somewhat routine and essentially descriptive technician role. Indeed, that independence is often encouraged to the point at which a quasi-scholarly role has been achieved, detached from the practical reality of the job. The lack of numeracy in basic geological education and consequential lack of mechanical understanding is commonly not overcome so that some engineering geologists can find even the most simple mathematics challenging. The position has been further weakened by a lack of any well-defined discipline to engineering geology with inadequate synthesis of data collected through case history experience. Opportunities for university training in engineering geology are being reduced as a consequence of funding restraints and lack of champions within conventional geology and civil engineering departments. Research at a fundamental level is exceptional, being more commonly related to the documenting of case histories and the assembly of soil and rock properties. Research-funding bodies, being dominated by classical geological thinking, are unsympathetic and lack forward vision. The public funding available for postgraduate training in engineering geology is under threat and the possibility exists that industry will no longer have a supply of well-trained staff. Industry is not responsive to the need for financial support for training and research.

### Opportunities

The lack of an accepted discipline, supported by an integration of experience, provides an enormous opportunity for the subject to move itself to a new position through which its role in relation to other fields of geotechnical engineering can become better acknowledged. At both international and national levels there are active working groups studying and reporting on issues, many of which involve a reprocessing of familiar ground and achieve little real advance. In their place, a new series of professionally directed study groups should be encouraged. More fundamental topics such as the role of uncertainty and risk in engineering geology, how the proper application of engineering geology adds value, the development of protocols for the establishment of geological and ground models, the challenge of global environmental change and the formalisation of information and data validation processes for increasingly large data sets throughout the engineering process require development to the point that they are widely introduced into day-to-day practice. Research priorities, in terms of work that will achieve fundamental advance, require definition and encouragement. Professional recognition, achieved through full geological training and engineering geological experience, should be strengthened and enhanced particularly where status can be endorsed through legal and statutory bodies.

### Threats

Threats include a continuing environment where the subject is given a limited, second-class status within geology, geotechnical engineering and civil engineering with a lack of career progression; the loss of a university postgraduate base which provides a reliable supply of skilled engineering geologists through training and focused research; and replacement of the engineering geology function at all levels by engineers and some geologists who do not have the broad competence to address the needs of the subject as a whole.

## Prospect

In looking to the future, engineering geology faces three choices:

1. There is the simple option of “business as usual”, no new initiatives would be taken, and the outcome would be the maintenance of the status quo. The subject has been successful but has not been as flourishing as some would prefer. Such a stance would not restrict engineering geology from being pro-active in the exploitation of new opportunities where preferential standing

would be achieved by those who understood geological processes and the natural environment.

2. Engineering geology could seek a restructuring of geotechnical engineering which might place the subject in a new, and potentially beneficial, light. Morgenstern (2000), at GeoEng2000, advocated such a move through the creation of an "*International Geotechnical Union*" which would "*contribute to both current and future industrial and environmental needs, particularly in the context of sustainable development*" by building on the "*integrated and holistic approach*" which characterises geotechnical engineering. Most, if not all, engineering geologists would applaud such sentiments because the training and experience of our subject makes us well able to contribute to the changing world (Knill 2001a, 2001c). However, little publicity has been given in the last 2 years to progress in achieving accord in such an endeavour.
3. Finally, we should appreciate that, as recognised by Terzaghi, Müller-Salzburg and Morgenstern, engineering geology has still to find itself through metamorphosis from the chrysalis. Our role within geotechnical engineering would be better recognised, and rewarded, if we were to acknowledge and exploit the core values of our subject as presented in, this, the first Hans-Cloos lecture.

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