ENGINEERING GEOLOGY AND ROCK ENGINEERING

JACK, Christopher D., PARRY, Steve & HART, Jonathan R.
GeoRisk Solutions Limited
Hong Kong SAR, China

Abstract

Engineering geological input is critical in rock engineering projects, such as tunnels and caverns, where it can have significant positive impacts. Ground information for such projects is often limited and the engineering geologist is ideally placed to assist. However, the engineering geologist must have the correct skills and experience and these are discussed in the paper. Through discussion of case studies the paper then examines common failings in rock engineering projects where engineering geological input is lacking, and provides recommendations for future best practice.

Keywords
Geological models, rock characterisation, kinematic assessment

1. Introduction

Timely, high quality engineering geological input is critical to the success of any undertaking in rock engineering, particularly those involving tunnels and caverns.

The aim of this paper is to show, through case studies and discussion, that engineering geologists can have significant positive impacts on the safety, performance, serviceability, cost, programme and maintenance of underground projects involving rock engineering. Conversely, the omission of, or provision of poor quality engineering geological inputs will likely have negative effects including over-design, cost overruns, unnecessary maintenance requirements or even failure.

Typically, only limited ground data is available for the tender and design of tunnels and caverns. Consequently, the engineering geologist is theoretically ideally placed to assist with understanding and characterising the rock mass. This is because they have expertise in evaluating and more importantly predicting multidimensional geological variations including rock formations, tectonic modification, overprinting of weathering and hydrogeology.

This paper first provides a description of an 'ideal' engineering geologist, with particular regard to the attributes required for rock engineering projects. Observations on current practice are then made, with reference to case studies, which highlight the common problems that occur where there is insufficient engineering geological input.

2. The engineering geologist in rock engineering projects

The IAEG Statutes (1992) define engineering geology as *'the science devoted to the investigation, study and solution of the engineering and environmental problems which may arise as the result of the interaction between geology and the works and activities of man as well as to the prediction and of the development of measures for prevention or remediation of geological hazards*.'

However, as discussed in depth by Parry *et al.* (2011), to make an effective contribution to projects an engineering geologist must have the correct training, knowledge, philosophy, approach, understanding of their responsibilities and appropriate skills. So, what attributes should a good engineering geologist have?

Firstly, they should have the right philosophy, i.e. that they are first and foremost scientists.

Secondly, they should use engineering geological models in their approach to refine their understanding of a particular project. The scheme proposed by the IAEG (2011) that divides models into *conceptual*, *observational* and *analytical* engineering geological models is one such approach.

Thirdly, they must have a correct understanding of their responsibilities. Baynes (2003) considers that these are:

- Observation and investigation of the geology in engineering projects
- Engineering geological model development
- Establishing standards and scope for the engineering geological activities
- Engineering geological information management
- Communicating the geology to engineers

Fourthly, the engineering geologist must have the required technical knowledge and skills to carry out their role. These will naturally vary from practitioner to practitioner although a list of the baseline knowledge and skills might include the following (modified after GSL, 2008):

- Undergraduate level geology

- Ability to collect and collate the relevant existing engineering geological data
- Engineering geological mapping
- Ground investigation
- Soil and rock description
- Soil and rock mechanics
- Interpretation of engineering geological data
- Production of engineering geological models
- An appreciation of geo-engineering design
- An understanding of construction methods
- Recognition and management of uncertainty
- Recognition and management of geo-engineering risk
- Effective communication with engineers and other professionals

Critically, given that geology is possibly the most observational of all the sciences, it is difficult to imagine a good engineering geologist who does not have extensive experience of geological fieldwork. In particular, the engineering geologist should have skills in factually recording and subsequently interpreting engineering geological information from a wide variety of sources including exposures and core.

To make a successful contribution to a rock engineering project, the following particular attributes will also be required:

- Experience in rock engineering projects
- Good understanding of the principles of rock engineering design
- Ability to carry out rock mass characterisations appropriate to the feasibility, investigation, design and construction stages of a project
- Experience in GI methods important to rock engineering projects (including orientated core, televiewers, plate bearing tests, dilatometers, hydrofracture tests, borehole jack tests, cross-hole tomography, petrographic description, index tests, unconfined compressive strength, point load tests, slaking tests, direct shear tests, full-scale loading tests, geophysics etc.)

The term *engineering geologist* as used for the purpose of this paper describes an individual who consciously strives towards the level of professionalism that has been discussed. The reason this definition has been provided is that it is an implicit assumption of this paper that efficient rock engineering design and construction in tunnel and cavern projects requires that an engineering geologist has significant involvement.

3. Case Studies

The following case studies illustrate common problems that occur without or with only limited use of engineering geological input. Recommendations are made where appropriate.

3.1 Case Study A

Introduction

This involves a deep excavation for a large cut and cover underground space with near vertical sides, predominantly in competent plutonic rock in Hong Kong. The project was part of a larger tunnelling project that was at the tender design stage. The tendering contractor was looking to optimise elements of the design, including the rock support.

This section examines a number of issues that became apparent during the attempted optimisation and how these affected the project. These issues are related to desk studies, site investigation, rock mass assessment, discontinuity strength, kinematic analysis, block sizes and communication. Where appropriate observations are made on wider rock engineering practice, recommendations are made for future improvement.

Desk study issues

The desk study for this project should have included the consultation of existing tunnel records, but this was not done.

Whilst it is a requirement for construction tunnel logs to be provided to the Hong Kong Government, the accessing of this data is not straightforward and a Geographical Information System (GIS) system, similar to United Kingdom Highway Agency Geotechnical Data Management System (HAGDMS), with a link to a scan of the tunnel records would be highly beneficial. Incidentally such a system could be used to manage all geo-engineering information in the Special Administrative Region (SAR) including ground investigation, registered slope and Landslip Preventative Measures (LPM) and Natural Terrain Hazard Assessment (NTHS) reports. Such a system would help to make this information much more accessible, allowing more useful desk studies for underground projects.

Site investigation issues

In Hong Kong, in addition to recently constructed tunnels where recorded data exists, there are numerous disused tunnels throughout the SAR relating to mining and civil defence from the Second World War, and these provide extremely valuable large-scale exposures. Despite this these are rarely inspected and were not for this case study.

In addition to existing tunnels there were also nearby cuttings with significant rock exposures. However, similarly the opportunity to inspect these exposures was not taken.

As with the majority of projects, the emphasis was on ground investigation (GI) rather than site investigation (SI). Unfortunately, in common with the majority of drillhole logs examined by the authors, the discontinuity descriptions were inconsistent, lacking in detail and no attempt had been made to attribute the discontinuities to individual sets.

Issues related to the assessment of the rock mass

Acoustic televiewers were used to obtain discontinuity orientations. However, no assessment of aperture and roughness was made from this information. Optical and acoustic televiewers have a number of benefits, including the speed with which discontinuity data can be obtained and prepared for analysis. However, they also have a number of shortcomings, chief of which are:

- The number of discontinuities identified by core logging and by a televiewer can differ significantly. Therefore caution must be exercised in assigning values such as Rock Quality Designation (RQD) on the basis of televiewer information alone (Maybee *et. al.* 2002).
- Often it is not possible to tell the difference between features such as a joint, a dyke, an incipient discontinuity or a clay infilled joint from a televiewer.
- It is not possible to obtain discontinuity information other than orientation, aperture and a broad sense of roughness from a televiewer.

As was the case on this occasion, there appears to be a worrying trend of using televiewer data as a substitute for detailed rock mass characterisation, such as detailed discontinuity descriptions of exposures and core. This approach results in an enormous amount of discontinuity orientation data and an impressive looking (and easily produced) stereonet, but does not provide sufficient information for a full rock mass characterisation.

In contrast, where the investigation is based on drillholes alone it is important to note that there are a number of discontinuity characteristics that cannot be reliably recorded in core such as persistence, aperture, wavelength and infill. This is why exposures such as natural outcrops, cuttings and unlined tunnels are preferred.

When detailed discontinuity descriptions from core and televiewer logs are used in conjunction, then this is valuable information. However, if the project engineering geologist does not log the core and inspect the televiewer logs, there is no opportunity to undertake a sense-check of the data and develop a 'feel' for the rock mass.

Drillhole core for rock engineering projects should be orientated wherever possible. Failure to do this means the possibility of linking detailed discontinuity descriptions of core to those from exposures, televiewer and impression packer data is much reduced. In this case study, the core was not orientated and no attempt appears to have been made to record detailed discontinuity information from the core, let alone relate it to the televiewer data.

With respect to GI and discontinuity evaluation, the standard approach for rock mass description and the logging of core for rock mass assessment is that they are undertaken by GI contractors. However, despite the often extensive GI that is undertaken, the core is logged by individuals with little or no engineering geological training or rock mechanics expertise and who are provided with no background to the project. It is the authors' opinion that engineering geologists should undertake this work. Whilst the initial cost may be higher, the improvement in the quality of the data will facilitate the selection of the most suitable design - easily offsetting this cost later.

At the tendering stage, the time constraints meant that the tenderers had to accept the discussed inadequate data for their tender designs. Consequently this meant that conservative assumptions had to be adopted for the analysis and design of the excavation. However, even with the quality of data provided, it is considered that improvements with respect to the parameters adopted for tender design could have been made. However, rather than evaluating the existing data from an engineering geological perspective to determine which parameters could be adopted based on experience, the design engineers adopted conservative values for each assumption. This resulted in a highly unlikely ground model. For example, a conservative estimate of the angle of friction of the joints was made based on shear box testing of core. However, such testing already gives very conservative values due to the limited size of the sample. Also, no normalisation of results was undertaken and no allowance made for joint roughness, waviness, amplitude etc. The assessments of joint persistence and spacing were also absent or inadequate.

Issues related to the assessment of discontinuity strength

The angle of friction of joints should include considerations of joint roughness, infill, wall strength etc. As noted for plutonic rocks in GEO (2007): *'Where shear box testing of a joint is undertaken the natural roughness of the surfaces should be taken into account by normalising the data to account for dilation during testing (Hencher & Richards, 1982). A basic friction angle of 40° has been proposed by Hencher &*

Richards (1982) regardless of the decomposition grade'. Hencher & Richards (1982) note that a roughness angle should also be applied, and an example of this approach is provided by Richards & Cowland (1982). This suggests that a joint angle of friction of 40° could be considered as conservative for Hong Kong granites in the general case, yet angles of friction of much less are regularly seen in rock engineering designs for Hong Kong granite.

Every effort should be made to select appropriate parameters for analysis and design. An example of an appropriate basis for selecting these is the definition of a *characteristic value* as defined in Eurocode 7 (BSI, 2004) which defines it as a *'cautious estimate of the value affecting the occurrence of the limit state*' or statistically as *'the calculated probability of a worse value governing the occurrence of the limit state under consideration is not greater than 5%.'*

The discontinuity orientations were also analysed in very simplistic terms by assuming that a concentration of poles to the planes (derived from televiewer data) plotting within a failure envelope on a stereonet equalled the risk of failure, rather than being used as a prompt for further analysis.

Issues related to kinematic analysis and block size determination

Kinematic analysis is only the first step in block stability analysis (Wyllie and Mah, 2004). The plotting of a pole, or the intersection of two planes, within a failure envelope merely indicates the possibility of failure. This is a prompt for further detailed investigation and analysis, not an immediate indication of risk.

Unrealistic assessment of joint persistence and spacing for this case study meant that the block sizes adopted in the analysis were generally smaller than those expected to exist in reality and were unrealistic geometrically. The assessed block sizes required less force to support than the actual likely block sizes, but in some cases were assessed as more likely to fail, as less friction was mobilised on the joints. Therefore, the assessment was simultaneously over and under-conservative. Whilst blocks of this size and shape might exist, they were unlikely to represent the general case.

Ranges of realistic block sizes, taking into account joint persistence and spacing are required. Whilst it is difficult to estimate this from drillholes alone, it can be done with detailed work. This could have been undertaken relatively easily if the available exposures were inspected.

Unfortunately in this case, due to the shortcomings in original GI and consequent lack of the required basic data, it is unlikely that significant optimisation of the tender design could have been carried out effectively.

Communication issues

The case study also involved two significant failures of communication. The first was that the designer did not provide a quantification of the hazard posed by potential rock instability, meaning the tenderer found this aspect difficult to account for. The second was that the designer failed to explain their design to the tenderer in a way that was understood. This meant that there was a lack of confidence in the design, for reasons not simply attributable to the shortcomings already discussed. Clear communication of the potential geological hazards and risks is critical otherwise misunderstandings and errors can occur.

However, it is difficult to put values onto geological features and risks. It is one of the main responsibilities of the engineering geologist that they quantify that which sometimes seems unquantifiable, by putting numbers to soil and rock masses and assigning percentages to hazard and risk (Hoek, 1999). Without this the engineering geological input becomes greatly limited.

An effective way of communicating the key points to other geo-engineers is through the use of uncertainty and risk registers (Knill, 2001). An uncertainty register provides a rigorous, transparent and documented method of managing, investigating and reducing geological uncertainty.

A geo-engineering risk and opportunity register is a similarly transparent, rigorous and documented tool with which to record, manage and communicate risks with other geo-engineering professionals. This is sometimes done but there are problems including failure to keep the register current and poor communication of the risks to the project team.

One additional impediment to communication seen in this case study, and many others, was the misuse of effort on summarising data that has no or minimal relevance to the project. This is an issue that has been discussed elsewhere (Parry and Hart, 2009) and rock engineering projects involving underground space are no exception to this. This is not to say that sources of potential useful information should not be consulted. Rather, that only the important points are summarised, otherwise the key information is swamped and communication is impeded.

Consequences

These missed opportunities, misconceptions and errors meant that any chance of developing an efficient rock support design prior to construction was effectively lost. This resulted in three possibilities:

a) A safe, but considerably over-conservative design.
b) A design that has missed a critical hazard, such as a large, weak, through-going discontinuity.
c) An efficient design that is not necessarily based on the provided data, but is safe and appropriate due to the application of the engineering geologist's knowledge and experience.

Generally it is a) that is the most likely result. However, b) continues to occur in engineering projects, both large and small with regularity. Outcome c) is rarely seen in today's litigious culture. Therefore the importance of the engineering geologist providing the data that the designer needs to produce an efficient design is clear.

In this case study the tender design of the rock support adopted for the excavation consistently used conservative parameters. This was partially as a result of the data provided and partly due to of the approach of the tenderers' design team. The result was that the likelihood of failure was probably overestimated and the consequent support was likely overdesigned. As a result the tender was probably overpriced.

The most notable aspect of this case study is that the information required to carry out the analysis properly was available, or could have been acquired relatively easily. Certainly the modest additional cost of these measures would be saved many times over in efficiencies on the rock support design or significant failures avoided. It is suggested that many of these problems could have been avoided or reduced had an engineering geologist been involved throughout the project.

3.2. Case Study B

Introduction

A contrasting example is provided by a tunnel and cavern construction project through tectonised volcanic rock. This project was at the early stages of construction when discussed.

This section discusses issues related to engineering geological models, *unforeseen* and *unforeseeable* ground conditions, faults and quartz veins. Again, reference to broader practice and recommendations are made where appropriate.

The original investigation appears to have been undertaken without an adequate geological model and a nearby existing tunnel was not inspected. The contractor's designer realised that a considerably improved rock mass characterisation was required for a proposed optimisation of the design, to replace two parallel tunnels with a single cavern, and in particular two key issues arose:

- Were features logged as faults in drillholes really faults?
- Would large inflows of water occur in association with the 'faults'?

To address these issues the following work was carried out by engineering geologists:

- Re-logging of drillcore.
- Engineering geological mapping for rock mass characterisation in the nearby tunnel.
- Improvement of the engineering geological model.

Engineering geological models

For all engineering projects the development, from the desk study stage, of a robust, defensible and evolving engineering geological model is of paramount importance. This is the foundation on which all the geo-engineering aspects of the project should rest and where there is the most scope to make savings and reduce risks to the project. Unfortunately many engineering geological models are overly-simplistic or simply incorrect.

The Total Geological History approach (Fookes *et. al.* 2000) and published geological data suggests that the following geological conditions could be applicable to this case study:

- Tectonic model – convergent plate boundary – magmatic arcs.
- Geological model – igneous – acid volcanic.
- Geological model – structural – strike-slip faults.
- Geomorphological model – hot wet climate.

These models provide a 'check list' of the potential geological conditions, geohazards and engineering challenges that may face a site and consequently the risk of unforeseen ground conditions is reduced or eliminated. In this case study these models predict the following geological conditions that were subsequently encountered during the project:

- Acid volcanic (rhyolitic) rock.
- Pyroclastics and tuff.
- Hydrothermal mineralisation/alteration.
- Faulting.
- Aplite/pegmatite dykes.
- Faults and joints displaying consistent pattern.
- Extensional pull-apart features.
- Deep weathering profiles.

These are discussed further below.

Unforeseen and unforeseeable ground conditions

Related to engineering geological models, there is a general misunderstanding and misuse of the terms *unforeseen* and *unforeseeable* with regards to ground conditions. It is often the case that these ground conditions are perfectly foreseeable to a competent engineering geologist. As noted by Baynes (2010).

'There is very little geology or geomorphology that will be unforeseen on a site if the investigation is carried out properly. This means that if a project is managed in a way that implements all of the established techniques developed to mitigate geotechnical risk, and the work that is carried out is high quality, then the probability of an 'unforeseen' condition being encountered during construction should be reduced to negligible proportions.'

'Nevertheless, there are some geological conditions that are 'unforeseeable', and when those conditions are encountered (they will have been anticipated) there will inevitably be some undetectable variations in the geology that can never be completely investigated within practical limits; for example, cavernous ground as a result of karst may be recognized but it may be impractical to attempt to investigate the details of every single cavity; the details are 'unforeseeable''.

Quartz veins and faults

In this case study, features originally identified as 'faults' were reinterpreted as hydrothermal quartz veins on the basis of the re-logging and the consideration of an appropriate engineering geological model. As such, unlike faults, they were not formed by shear with an associated reduction in strength, but were formed in tension and subsequently the discontinuities were largely 'healed' by hydrothermal minerals, in this case quartz. Some faults were encountered but these were very minor and might have been more appropriately described as joints associated with accommodation movements.

Whilst the mechanical strength of such zones is considerably higher than faults, in certain locations related to this case study the veins are associated with significant groundwater flow. This is because the metalliferous minerals in the quartz veins are easily decomposed, forming a preferential flow-path for groundwater.

One of the reasons for the misidentification of the quartz veins as faults was poor descriptive practice. It is the authors' experience that the description of weak zones, such as faults and shear zones are generally inadequate for rock engineering purposes. The United States Department of the Interior method for describing such zones is recommended as a suitable descriptive method (USDOI, 2001), and was adopted for the re-logging in this case study.

Had an appropriate engineering geological model been developed at an earlier stage of the project then mapping could have been carried out at the surface. A focus of the mapping would have been establishing the location, orientation and nature of faults and hydrothermal veins. The from mapping of nearby exposures such as natural outcrops, cuttings and quarries information could have been used in conjunction with the drillhole data to estimate the spacing and location of these features and to begin to build a 3D model. This would have allowed prediction of where these features would be encountered in the proposed tunnel. Mapping allows early access to detailed and potentially valuable information and is a much more efficient use of project budget than relatively costly ground investigation. It is noted that surface mapping is particularly underused in Hong Kong practice.

3.3. Case Study C

This case study involves a tunnel that is approximately 150 years old, driven through limestone. There had been several small rockfalls in the tunnel and a number of potentially unstable blocks were observed in the tunnel walls. An investigation of the tunnel was carried out which included a desk study, tunnel mapping, ground investigation and interpretive reporting.

However, there were a number of significant shortcomings in both the tunnel mapping and ground investigation. Firstly, the discontinuity descriptions were not sufficiently detailed. The joint descriptions only included orientation data (a common problem) along with general comments of varying use. Critical aspects such as persistence, spacing, roughness, aperture, infilling and wall strength were not recorded. Merely having orientation data only allows a rudimentary analysis, generally leading to conservative and occasionally unsafe design. Furthermore, the drillholes were not orientated and no televiewer, impression packer or *in-situ* tests were carried out.

In addition, standard rock engineering classification and analysis approaches were used inappropriately. For example, it is good practice in rock engineering to compare the findings of empirical design tools (such as Q, RMR and RMi) with calculations (such as the results of hand calculations and software packages including UNWEDGE and UDEC) to check that the approaches used provide a similar result. Generally the more conservative result is chosen as the basis of design. However, such classification systems and analytical methods were formulated to assess new excavations in rock. These methods are appropriate for such purposes provided that the engineering geological input is of high quality.

However, such an approach may not be appropriate for analysing and designing rock support for tunnels that have existed for many decades, as many of the failures that are likely to occur in these tunnels will have already occurred or been mitigated since construction. Ongoing failures will likely be due to rock mass deterioration.

In this case Q and RMR classifications were compared with the results of an UNWEDGE analysis. The result was an inappropriate and extremely conservative design which proposed pattern bolting for extensive sections of the tunnel.

Whilst this may have been appropriate for a new tunnel, a more appropriate design for this old tunnel would have been spot bolting of those blocks assessed to be potentially unstable combined with light scaling and mesh in areas where ravelling might occur. This work, if guided by an engineering geologist, would have been much cheaper, quicker and appropriate.

One factor that may have led to the over-design in this case is the relative lack of guidance on the assessment, maintenance and design for existing unlined rock tunnels and caverns. The vast majority of current guidance and standards relates to new and proposed works.

3.4. Case Study D

This final case study involves a cavern and several related tunnels and adits in plutonic rock. This project was at the construction design stage and the contractor wished to optimise the design. The preliminary and tender designs were based on a combination of empirical design methods and computer modelling and further investigation of the assumptions, parameters and analytical models used in the design was required.

An increasingly common approach in rock engineering projects, including this case study, is that rather than obtaining data to characterise the rock mass, the investigation focuses on obtaining data simply to input directly into rock mass classification systems such as the Q and RMR systems. This may be in an attempt to save time, but the authors consider such an approach to be technically constrained. If instead a rigorous rock mass characterisation is carried out, then the data required for the classification systems will have been collected as a matter of course. Furthermore, such an approach has the added benefit that a model of the rock mass will be developed and understood, against which the recommendations derived from the classification system can be evaluated.

A second issue related to the Q system is that inadequate rock mass characterisation often leads to significant underestimation of the Q values and hence underestimation of the rock mass quality. It appears that the Q value had also been underestimated for this case study, allowing significant potential for optimisation of the design. However, this could have been incorporated at an earlier stage of the project.

Evidence of this is given in GEO Publication No. 1/2007 (GEO, 2007), Table 6.7.3 which is reproduced below.

Total Length of Bored Tunnel (1,609 m)			
Q-value range	< 0.3	0.3 – 4.0	> 4.0
Pre-construction estimate	14.7%	60.6%	24.7%
As-built records	7.5%	43%	49.5%

Table 1 – Sha Tin Heights Tunnel Q-value ranges estimated at the pre-construction stage and from as-built records

What this table and several others in the source document make clear is that Q-value is being significantly underestimated at pre-construction stage in Hong Kong. While some underestimation is to be expected, the size of the difference is of concern. This suggests that the rock support designs upon which tenders are won are likely to be overdesigned and hence overpriced. It is considered that this discrepancy could often be significantly reduced if an engineering geologist carries out a thorough rock mass characterisation at the pre-construction stage and then refines this throughout the project.

Finally, numerical analysis software such as FLAC, PLAXIS and UDEC are increasingly being used and both were adopted in this case study to assess movements related to the excavations. However, the analytical models that were adopted for this project were, from an engineering geological perspective, very unrealistic. The following points were observed:

- PLAXIS and other finite element codes (such as FLAC) only realistically model massive unjointed rock masses. These are relatively rare, and these conditions did not apply to this case study. For instance there are no such rock types in Hong Kong. That is not to say that these methods should not be used but that their limitations should be realised.
- UDEC and other discrete element codes are more appropriate for jointed rock masses, such as the rock found at the case study site.
- Discrete element modelling will not help analysis and design if an unrealistic discontinuity model and parameters are used.

It was considered that the parameters used for joint friction in this case study were overly conservative.

- The discontinuity model should include realistic discontinuity lengths, spacing and variations of orientation. The joints modelled for this case study were quite unrealistic as they were analysed as having great persistence and very close spacing, which did not reflect the predicted geological conditions. This results in unrealistic and conservative results.
- Factored design parameters should not be used in numerical models unless an extremely conservative result is sought.

5. Summary and Conclusions

It is considered that there is still considerable scope for improvement in engineering geological practice and its application to rock engineering projects, particularly in the development of realistic engineering geological models, collection of rock mass data, rock mass characterisation and kinematic stability analysis. It is suggested that if an engineering geologist meeting the description provided in Section 2 of this paper was sufficiently involved in these case studies then the majority of these issues would have been removed or their impact reduced. The four case studies illustrate common problems in underground rock engineering that lead to inappropriate and overly conservative designs.

The key factors that underlie any analysis and design are the assumptions. A single conservative assumption may be defensible. However, the cumulative effect of many conservative assumptions can lead to a significant divorce from reality. Rock is a structural material and in many cases will be stable or meta-stable. If this is accepted, then it is logical that less conservative design should follow. The tendency in Hong Kong to over-design may also be influenced by insufficient incentives for efficiency, particularly for large well-funded projects. As a result there is little incentive to optimise design in a market where funding is ample, and where there is little desire to accept responsibility and even the lowest levels of risk.

Many of the recommendations made in this paper are in line with guidance contained in Geoguide 4 'Guide to Cavern Engineering' (1992) and so these are not new issues.

The range and scale of the underground rock engineering projects taking place in Hong Kong means that there is an excellent opportunity to establish our engineering industry at the forefront of international practice. Good engineering geological input will help us achieve this.

6. References

BAYNES, F. J., 2003. Generic Responsibilities of Engineering Geologists in General Practice, *Geotechnics on the volcanic edge.* NZ Geotech. Soc. Symp. IPENZ Proc. Tech. Groups Vol. 30, Issue 1 (GM).

BAYNES, F. J., 2010. Sources of Geotechnical Risk, *Quarterly Journal of Engineering Geology and Hydrogeology.* Vol. 43, p321-331.

BRITISH STANDARDS INSTITUTION (BSI), 2004. Eurocode 7, Part 1, BS EN 1997-1.

FOOKES P. G., BAYNES F.J., and HUTCHINSON J. N., 2000, Total Geological History: A model approach to the anticipation, observation and understanding of site conditions. *Geoeng 2000 Conference*, Melbourne Australia.

GEOTECHNICAL ENGINEERING OFFICE, (GEO), 1992. *Guide to Cavern Engineering,* Geoguide 4.

GEO, 2007. *Engineering Geological Practice in Hong Kong*. GEO Publication No. 1/2007.

GEOLOGICAL SOCIETY OF LONDON (GSL), 2008, *The Geological Society Training Guide for Engineering Geologists.* Second Edition.

HENCHER, S.R. & RICHARDS, L.R. (1982). The basic frictional resistance of sheeting joints in Hong Kong granite. *Hong Kong Engineer*. p 22-25.

HOEK, E. 1999. Putting Numbers to Geology – an Engineer's Viewpoint. The Second Glossop Lecture, *Quarterly Journal of Engineering Geology*, Vol. 32, No. 1, 1-19, 1999.

INTERNATIONAL ASSOCIATION FOR ENGINEERING GEOLOGY AND THE ENVIONMENT (IAEG), 1992. *IAEG Statutes.*

IAEG, 2011. *Part 1: Introduction to Engineering Geological Models*, Report of IAEG Commission C25 – Use of Engineering Geological Models.

Knill, J. L., 2001. Geological uncertainty and geotechnical risk determination. *Proceedings of the Fourteenth Southeast Asian Geotechical Conference*, Hong Kong, p129-134.

MAYBEE, W.G., CAI, M., KAISER, P.K., MALONEY, S.M. and MCDOWELL, G.M., 2002. Televiewer Logging of Exploration Boreholes for Mine Design; *Proceedings of the 8th International KEGS/MGLS Symposium on Logging for Minerals and Geotechnical Applications*; Toronto, Canada.

RICHARDS, L.R. & COWLAND, J.W., 1982. The effect of roughness on the filed shear strength of sheeting joints in Hong Kong granite. *Hong Kong Engineer,* p 39-43.

UNITED STATES DEPARTMENT OF THE INTERIOR (USDOI), 2001. *Engineering Geology Field Manual*. Chapter 5.

WYLLIE, D. C. and MAH, C. W., 2004. *Rock Slope Engineering*. 4th Edition, Spon Press.