Geotechnical risks on large civil engineering projects

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Keynote address for Theme I – International Association of Engineering Geologists Congress, Vancouver, Canada, September 21 to 25, 1998

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ABSTRACT: Unforeseen geological conditions and the associated geotechnical problems are a major contributor to cost and schedule overruns on large civil engineering projects. In spite of numerous attempts to deal with these situations by the incorporation of various clauses in contract documents, the problems persist. The best solution is to define the geological conditions as early and as accurately as possible so that surprises are minimised. This paper explores methods for predicting these geological conditions.

1. INTRODUCTION

In recent years a number of innovative approaches have been adopted in contractual arrangements for large civil engineering projects. The traditional Owner-Engineer-Contractor arrangement with fixed price or target price contracts are being replaced by Design-Build, Build-Operate-Transfer and other arrangements that involve all the partners in a contract in the design and financing of projects. While these changes have removed some of the constraints on financing large projects they have done little to minimise one of the principal sources of financial uncertainty – the risks associated with unforeseen geological conditions.

This paper explores some of the geotechnical risks on large civil engineering projects and suggests some of the options that can be considered for minimising these risks.

2. WORLD BANK STUDY ON COST AND SCHEDULE OVERRUNS

The World Bank's Energy Department recently carried out a study of power generation projects in developing countries (World Bank 1996). The database assembled for the study includes 64 thermal and 71 hydroelectric plants financed with IBRD (International Bank of Reconstruction and Development) and International Development Association (IDA) credits. The actual project total costs cover a wide range – between US $3.2 million and US $1,782 million in 1996 price terms. The project schedules also cover a wide range – between 1.2 and 14.4 years. The projects were implemented in 35 developing countries**.** The majority of these hydroelectric projects were located in Latin America, the Caribbean and in Sub-Saharan Africa.

The results of this study are summarised in Figures 1 and 2 that show actual versus estimated costs and schedules. Note that these plots are for total costs and the cost overrun component due to geotechnical factors cannot be isolated from the data presented. In practice cost overruns, as well as completion delays, may occur due to a host of technical, managerial, financial and political factors. These factors can often overlap, thus, establishing the level of cost overrun, based on any one factor, is almost impossible.

In commenting on their findings the authors of the World Bank report concluded that actual construction costs for hydropower projects were on average 27% above estimated costs, whereas schedules were on average 28% longer than estimated. Past experience in hydro preparation costs indicate that, on average, less than 1% of the total project cost is spent on feasibility, pre-feasibility, reconnaissance and hydrological studies before the engineering design is undertaken (World Bank 1985). This is a remarkably low number compared to the potential cost overruns.

Regarding geological risks, the World Bank report authors state:

> *Changes in project scope during implementation can have a significant impact on the project cost and schedules. Such changes can arise, for example, from the inability of design-stage investigation to eliminate risks from unknown geological conditions for construction of underground works, particularly for many hydropower projects. In addition, for first-of-a-kind projects in developing countries project estimators do not have a track record of similar projects as a basis for carefully analysing major construction risks and deriving reliable contingencies for them. Instead, they often rely on unreliable rules of thumb for such contingencies.*

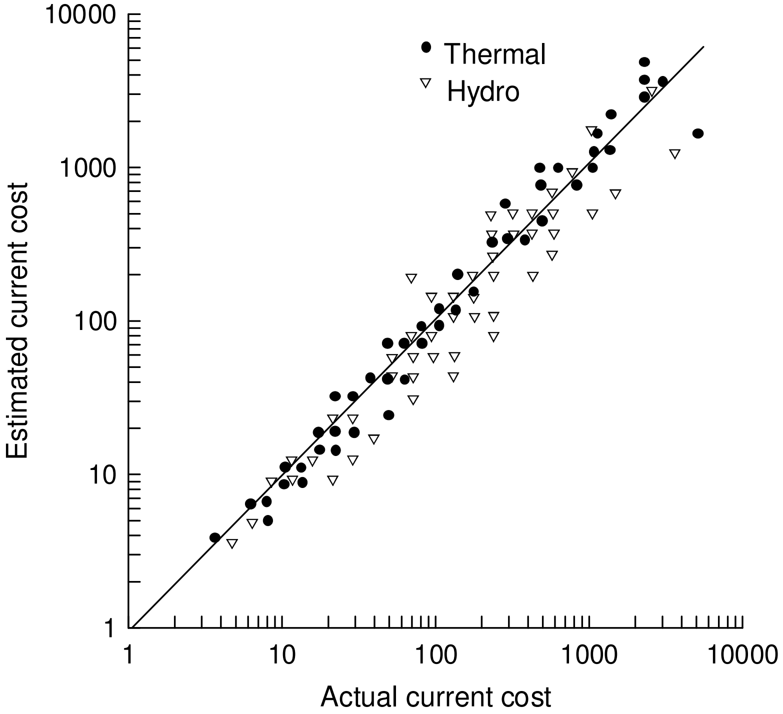

Figure 1: Comparison between actual and estimated total costs for 125 energy projects studied by the World Bank.

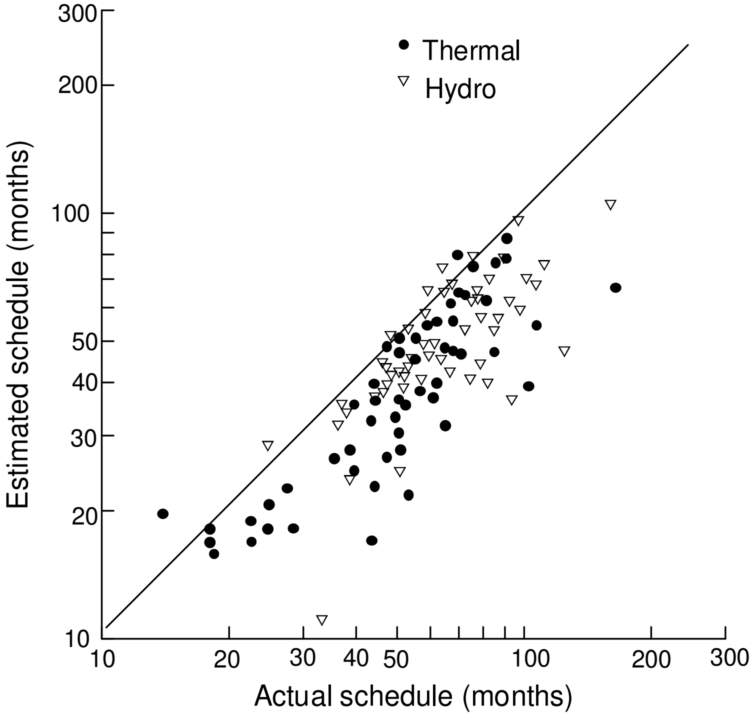

Figure 2: Comparison between actual and estimated schedules for 125 energy projects studied by the World Bank.

In plotting Figures 1 and 2, the authors of the World Bank study omitted 10 projects on the grounds that they faced genuinely unpredictable major risks that resulted in very large cost and schedule overruns. Some of these risks were associated with unpredictable geological conditions.

Figures 1 and 2 present rather a sanitised view of project cost and schedule overruns in the overall civil and mining industries. Comparable figures are difficult to obtain since, in many cases, these are not published. However, on the basis of their personal experience, the authors are aware of projects that have been abandoned or where costs and schedules have escalated to several times the original estimates. Unforeseen geological conditions cannot be blamed for all of these cost and schedule overruns. Many of these disasters are the result of inadequate geological data, inappropriate interpretation of available data and incompetence in dealing with the problems once they have arisen.

3. GEOLOGICAL INFORMATION COLLECTION

The basic problem faced by a designer in attempting to predict the geological and geotechnical risks in the construction of a highway, a long tunnel, an underground powerhouse or a dam foundation is the adequacy of the information obtained from the site investigation program.

Figure 3 is based on data collected by the U.S. National Committee on Tunnel Technology (USNCTT 1984) by interviewing the Owners, Engineers and Contractors on 84 tunnels. This plot shows variations in the cost versus the ratio of exploration borehole length to tunnel length. The plot suggests that inadequate core drilling for geological investigation results in significant project cost increases. These increases are clearly associated with difficulties that have arisen as a result of unforeseen geological conditions.

These conclusions are particularly true for long tunnels through mountainous terrain where it is generally neither physically nor economically feasible to drill a sufficient number of boreholes or excavate a sufficient number of exploration adits to investigate all the rock units along the route. In addition to the requirement to interpolate the geological conditions between widely spaced boreholes or adits, there is the problem of estimating the geotechnical parameters for these interpolated geological conditions. The net result is a very approximate picture of the construction problems and resulting costs that will be associated with the excavation of the tunnel.

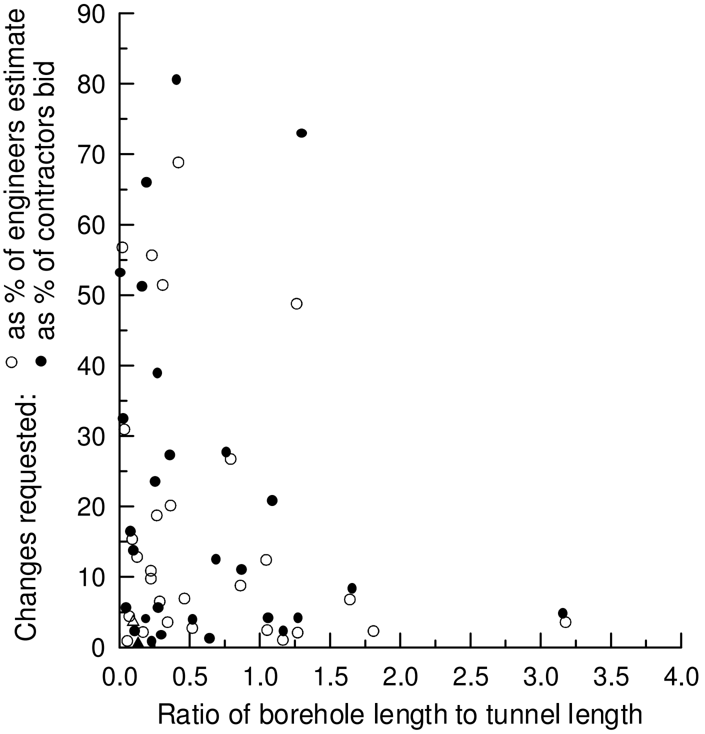

Figure 3: Variation in contract costs as a function of the length of exploration boreholes drilled.

In contrast, the information available from site investigations for dam foundations, underground powerhouses and similar sites of limited extent is generally much more comprehensive than that for long tunnels. This is because the overall investment in each cubic meter of excavation is very high and there is both the motivation and the justification for conducting comprehensive site investigations. Carefully placed boreholes, exploration adits and geophysical surveys provide an accurate three-dimensional picture of the geological conditions. All of this information does not guarantee that construction will be entirely free from problems but the chances of encountering unexpected geological conditions are greatly diminished.

From this discussion it is clear that the greatest potential for geological and geotechnical surprises, and the consequent cost overruns, is associated with construction projects of significant linear extent such as highways, tunnels and long dams. Dam abutments, reservoir slopes, spillway and plunge pool excavations, which fall outside the area of intense site investigations for dam foundations, power house excavations and tunnel portals, are also at risk because of lack of geological and geotechnical information.

The remainder of this paper is devoted to a discussion on how these geological and geotechnical risks can be minimised on large projects.

4. USING LOCAL GEOLOGICAL KNOWLEDGE

All developed countries and a number of developing countries have a highly developed geological data base for most of their land masses. For example, the Indian Geological Survey is an organisation that has been in existence for over 100 years and it has carried out detailed geological investigations for most of the subcontinent. It would be foolhardy and irresponsible for any external agency to attempt to develop or to assist in the development of a major project in a country in which such a data base exists without taking full advantage of the services offered by the local agencies. In many cases, sites for potential projects will already have been investigated as part of a national development plan and relatively little additional work will be required to bring the existing information up to an acceptable level for initial project design.

Where no national geological data base exists or where such a data base is not yet fully developed, excellent local knowledge is sometimes available in geological departments at local universities, government mining departments or other agencies which have had some responsibility for the development of infrastructure and resources in the country. Admittedly, it is more difficult to find relevant information in such cases but it is generally worth the effort to make the attempt.

Where no local source of geological information is available, there is no option but to mount a geological and geotechnical site investigation program that will identify the overall conditions of the site and give some indication of potential problem areas. It has to be recognised that such a program will be more time consuming and expensive and that the information obtained will be less reliable than one which builds on an existing geological data base. Wherever possible, it is prudent to break the site investigation program into two or three separate packages, each with its own program and budget and with sufficient time between each component to allow the information to be fully interpreted and digested before embarking on the next phase. Very careful planning of each stage of the site investigation program is essential and a recipe-book approach which requires one borehole every x meters should be avoided at all costs.

When financing organisations plan to invest in a number of projects in a country with no established geological data base, consideration should be given to providing financial assistance for development of or the enhancement of existing national organisations with an obligation to provide geological information for major projects. Such assistance programs or, in some cases, training programs, do not fit comfortably into normal project budgets and grants usually have to be made from unallocated funds. While it is always difficult to justify such funding, there is a reasonable chance that the investment will be repaid by lower cost overruns on future projects.

In planning the site investigations and in interpreting the results of these investigations, there is great benefit to be gained by using the services of a senior engineering geology consultant with experience in the area under investigation or in areas with comparable geological formations. Based upon their wide experience and their understanding of the mechanisms of formation and associations between different rock units, these persons can short cut many of the lengthy processes required to build a geological model. Such a model is of fundamental importance in the rational development of any major construction project (Fookes 1997).

The services of such an engineering geologist can be even more valuable when he or she is a member of a small consulting board or panel of experts set up by the owner to advise on the technical aspects of the project (Hoek and Imrie 1995). Ideally such a body should be set up very early in the development of the project so that it can help in establishing the site investigation program and in detecting and eliminating costly mistakes before they are built into the project design.

The following quotation is from a recent review on geotechnical engineering by Professor Ralph Peck (Peck 1997):

> *Nature did not follow standards in creating the mass of rock or soil in question. A defect or a field condition potentially fatal to the performance of the project may exist that escapes the standard investigation. Experience leading to judgement is the best defence against the consequences of such a possibility, and the course of action leading to an appropriate solution will differ amongst individuals of different experience. That is, judgement is an essential ingredient in geo-engineering, and it cannot be standardised.*

5. THE ESSENCE OF A GOOD GEOLOGICAL SITE INVESTIGATION PROGRAM

The prime purpose of any site investigation should be to obtain the maximum amount of relevant engineering geology information on rock mass characteristics, faults, structural systems and groundwater conditions. This information is important in estimating the rock mass properties and in assessing the stability of tunnels, slopes and foundations in the project. The information is also important to the contractor in that it should provide a basis for establishing the optimum construction method and the type of services that will be required in order to meet the construction schedules.

As discussed earlier, the limited extent of a dam foundation, a bridge foundation or the rock mass surrounding an underground powerhouse complex means that an adequate number of boreholes and exploration adits can be used to investigate the overall geological conditions and specific features such as faults. Consequently, it is neither difficult nor prohibitively expensive to develop an adequate geological and geotechnical database for such projects.

In the case of a project of significant linear extent, the question is how much site investigation can the project afford? Consider, for example, a 25 kilometer long tunnel to be driven at an average depth of 300 meters through a young mountain chain such as the Andes in South America. Local experience suggests that there is likely to be a fault or significant contact between different rock types every 500 meters. Suppose that it is considered reasonable to drill boreholes to tunnel depth every 250 meters to explore these faults and contacts and the rock in between. A total of 30,000 meters of drilling will be required, assuming that access is available to the drill sites. The cost of mobilising equipment and carrying out such a drilling program will run into several million dollars and this, together with the time required, may be far in excess of any preliminary budget estimates. Even more disturbing is the probability that, even with a site investigation program of this intensity, some significant features will be missed and the tunnel will run into the sorts of problems which the investigation is designed to eliminate.

Anyone who has had experience in planning major civil engineering projects knows that this is not a hypothetical example. There are many cases where projects have been designed and constructed with a geological and geotechnical data base which can only be described as totally inadequate. With luck and the help of an experienced and co-operative contractor, it is possible that the project can be completed with relatively few disruptions and cost overruns. However, as discussed earlier, comparisons between estimated and actual project budgets and schedules suggests that this is not usually the case and that many projects run into cost and schedule problems because of unanticipated geological conditions.

What can be done to alleviate these problems? There is no single simple answer to this question and it is necessary to consider a number of parallel approaches and to determine which combination of these will be most appropriate and cost effective for a particular project. The following discussion centres on techniques that can be used to construct a site specific data base to be used for project design.

5.1 Surface mapping

The basis for any geological map is surface mapping based on satellite and air photo images, which provide information on major structural features and lithological boundaries, and mapping by field geologists to fill in the details. In many cases, excellent regional geology maps are already available and it is only necessary to add site specific features in order to provide an excellent starting point for the project planning.

In considering the geological information required for tunnel design Robinson (1972) has discussed the accuracy of geological projections from surface maps in different geological environments and his comments are summarised as follows:

- *Sedimentary rocks:* Mostly, these rocks are formed under relatively uniform conditions over large areas. Subsequent metamorphism, folding and faulting, even though relatively complex, do not change the sedimentary rock to the extent that its original composition and areal extent cannot be recognised. Hence, relatively accurate interpretation between data points and projection to the depth of a tunnel is possible.
- *Extrusive igneous rocks:* Like sedimentary rocks, but with more lithological variation, these layered rocks permit interpretation between data points and projection to depth with an accuracy related to the origin of the feature. Hence a basaltic flow may be expected to retain homogeneity between widely spaced data points and can be projected to depth with considerable accuracy. On the other hand, a rhyolitic ash flow may be of relatively limited extent and projection to depth may be much less reliable.
- *Intrusive igneous rocks:* These are less predictable than extrusive igneous rocks and the accuracy of projection is of the same order as their areal extent. Consequently, a dyke can be interpreted between data points and projected to depth to the approximate extent of its surface expression. The least reliable feature of an intrusive igneous rock mass is the contact of a cross-cutting intrusive body. Robinson quotes an example from the Roberto tunnel in which the intersection of intruded igneous Montezuma Stock was about 3 km more than projected from surface information (tunnel depth 1000 to 1300 m).
- *Structural systems:* In general, the extent of rock formations and their composition can be interpreted between data points and projected to depth with more accuracy than can structures or structural systems. A major fault formed at shallow depth may be projected horizontally and vertically over considerable distances while small faults and shear zones can only be projected over limited distances. As a general rule, the dimensions and characteristics of a structural feature, such as a fault, can be projected into the vertical dimension with no more accuracy than they can be interpreted at the surface. Shallow dipping structural features comprise a particularly complex problem since they are difficult to project vertically with any degree of confidence and because they are a frequent cause of stability problems in underground excavations.

5.2 Subsurface investigations

The best information on subsurface conditions is that which is obtained from exposures in trenches and exploration tunnels. Unfortunately, these are usually of very limited extent compared to the length of a typical tunnel and only a limited amount of information can be obtained from them.

In some exceptional cases pilot tunnels have been driven for part or all of the tunnel length and these provide excellent information as well as the opportunity to drain and reinforce the rock mass ahead of the tunnel drive. There can be no excuse for tunnel construction problems due to unforeseen geological conditions where such a pilot tunnel is available. In particularly difficult cases, the high cost of a pilot tunnel can be justified on this basis.

On most projects, subsurface conditions projected from the surface have to be confirmed by diamond drilling. Fortunately, diamond drilling equipment and techniques have been developed to the point where 100 percent core recovery can be obtained in almost any formation and where careful core logging can provide an excellent assessment of the character of the rock mass. In setting up a diamond drilling program it is very important that the percentage core recovery be used as a basis for payment rather than the traditional diamond drilling contracts in which the driller was paid on the basis of length of borehole. These latter contracts encouraged the drillers to aim for the highest possible drilling rates and practically guaranteed very poor core recovery.

Most diamond drilling programs are based upon vertical or steeply inclined boreholes but, in some cases, horizontal drilling has been used very successfully. This is particularly useful when investigating steeply dipping sedimentary strata or where access to drilling sites along the tunnel route is limited. Horizontal holes of several hundred meters in length have been used on some projects and there is merit in considering such holes to confirm features such as faults that have been projected from surface mapping. Note that borehole surveys are important in any drilling program but are essential for horizontal holes because very large deviations can and do occur.

Directional drilling techniques are commonly used for oil exploration and studies are being undertaken in France to evaluate the potential for utilising these techniques for geotechnical exploration. Consideration is being given to using directional drilling for long horizontal holes for tunnel investigations.

5.3 Geophysical techniques in site investigation

Geophysical techniques cannot replace surface mapping and diamond drilling as the primary site investigation tools, but they can be used to supplement the information available from these traditional methods. Techniques such as seismic reflection are useful in delineating boundaries between weathered surficial deposits and deeper bedrock or for defining the extent of alluvium in buried valleys. Cross-hole siesmic techniques and tomography are powerful tools for interpolation between boreholes and for exploring the extent of significant structural features or lithological boundaries.

Tunnel boring machine manufacturers are beginning to install seismic equipment on cutter heads of machines in order to provide a view of the rock mass ahead of the machines. Where significant features such as steeply dipping faults occur in the rock mass, these seismic tools have the potential for giving a clear signal that can assist the machine operator in deciding upon an appropriate course of action.

In assessing the potential for using geophysical techniques on a particular site, the question that has to be addressed is whether there are distinct boundaries which can be detected by the technique under consideration. The contact between overburden alluvium and bedrock will be clearly visible in a seismic reflection survey but the transition between two rock types of similar character will be invisible to all but the most sophisticated techniques. Hence, depending upon the information required, geophysical techniques may or may not be useful site investigation tools.

5.4 Presentation of information

Geological information for civil engineering projects is normally compiled on plans and sections and this form of presentation will remain the most important vehicle for geotechnical interpretation and the design of rock excavations.

For many years the mining industry has been using geostatistical techniques and three-dimensional computer modelling for the evaluation of mineral deposits. With the rapid development and decreasing cost of personal computers, it is foreseeable that these three-dimensional modelling techniques will be adopted by the civil engineering industry for the presentation of geological and geotechnical information. The advantages of using these three-dimensional solid models, which can be rotated and viewed from any direction and sectioned in any orientation, only becomes evident when working with them. The authors' experience is that the interpretation and understanding of the geological conditions on a site are greatly enhanced by the use of these models and they look forward to the time when these models are widely used in civil engineering.

6. GEOTECHNICAL INTERPRETATION OF GEOLOGICAL DATA

Once the geological information has been assembled and interpreted as described above, the next task is to estimate the geotechnical characteristics of the different rock masses. The rock mass strength, deformability and permeability are the primary geotechnical parameters required for design of deep tunnels, while the structural features and the shear strength of these features are required for the design of slopes and shallow tunnels. There are still many uncertainties in the estimation of these properties but existing techniques are probably adequate for preliminary design purposes.

The rock mass classification systems proposed by Bieniawski (1989) and Barton, Lien and Lunde (1974) have been widely accepted as tools for estimating likely problems and for providing initial estimates for tunnel support. These systems utilise information that can be obtained from surface outcrop mapping and from diamond drill core to construct a simple numerical characterisation of the rock mass. Because of their ease of use these systems have been used in all manner of construction projects including slopes, foundations, caverns, and for such tasks as estimating rippability and designing blasting patterns. These classification systems have also been incorporated into contracts and specifications and used as a basis for measuring payment. It is important to recognise that they were originally developed for use in estimating tunnel support. They should be used with caution for some of these other tasks.

The Geological Strength Index is a classification system developed by Hoek and Brown (1997). This classification and the methodology associated with the estimation of rock mass strength and deformation properties are increasingly being used for obtaining input data for numerical models. These models are important tools for assessing the stability and support requirements for all rock excavations.

Ideally, these classification systems should be used during preliminary site investigations for feasibility studies where they can be very useful for assembling the available geological and geotechnical data into a meaningful database. This will help to identify areas in which additional investigations are required to supplement available data and, in the case of tunnels, will provide a good first estimate of tunnelling conditions and support requirements.

It is advantageous to build sufficient flexibility into the contract so that refinement of the rock mass properties, and hence the final design, can be made during construction. These refinements can be made on the basis of back-analysis of measurements of excavation deformation and observations of excavation behaviour. The overall behaviour of the rock mass surrounding a tunnel is only fully understood when the construction has been completed. Hence a contract, which imposes rigid designs and inflexible construction methods, will almost certainly result in an inefficient and costly construction project.

Once the design moves on to a more advanced stage the estimates provided by the rock mass classification systems have to be supplemented with information which can be used in more detailed design calculations. This includes information on the permeability, strength and deformation properties of the various units which make up the rock mass as well as information on the characteristics of faults, shear zones or other significant geological features which can have a major influence upon the behaviour of the structure being designed. Estimates of the regional and local in situ stress field are required for the design of any underground structures. The construction of regional and local seismic risk maps is also important in areas of high seismicity.

It is seldom possible to obtain all of this information from boreholes and it may be necessary to construct a few exploration trenches or tunnels in order to gain direct access to the rock masses that are critical to the design. These excavations are expensive and it may be difficult to obtain adequate funding at this stage in the project design process. Consequently, it may be necessary to proceed with the design on the basis of estimated information, but it is necessary to make provision to confirm these estimates with more detailed investigations during subsequent stages in the development of the project.

A summary of the steps described above is presented in Table 1.

7. CONTRACTUAL ARRANGEMENTS

From the discussion presented above it will be clear that the elimination of all geological risks in construction project is unlikely, even with the most elaborate site investigation program. With ever increasing emphasis on cost cutting in highly competitive construction markets, trimming of site investigation programs is a reality that has to be faced. Consequently, in order to minimise costly disputes, it is essential to give very careful consideration to the contractual arrangements on major projects.

A concept that is worthy of consideration is the Geotechnical Baseline Report that aims to establish a contractual understanding of the subsurface site conditions, referred to as a baseline (ASCE 1997). Risks associated with conditions consistent with or less adverse than the baseline are allocated to the contractor and those significantly more adverse than the baseline are accepted by the owner. The more clearly defined the anticipated conditions, the more easily the encountered conditions can be evaluated. Therefore, the baseline statements are best described using quantitative terms that can be measured and verified during construction.

Where the baseline has been set determines risk allocation and has a great influence on risk acceptance, bid prices, quantity of change orders and the final cost of the project. The interpretations and statements contained in the Geotechnical Baseline Report should reflect the risk allocation attitudes and preferences of the owner.

The following measures are recommended by the American Society of Civil Engineers (1997) to reduce geological risks:

a) Provide an adequate budget to explore subsurface conditions.
b) Retain suitably qualified and experienced design consultants to investigate, evaluate potential risks, prepare drawings, specifications and a Geotechnical Baseline Report consistent with the risks.
c) Allocate sufficient time and financial resources to prepare a clear Geotechnical Baseline Report that is consistent with other design documents.

d) Develop unit price payment provisions that can be adjusted to the conditions encountered.
e) Review and discuss the baselines with the bidders before the bids are submitted. The authors recommend that this be done in the course of a pre-bid workshop following pre-qualification.
f) Maintain an appropriate reserve fund, depending upon the perceived risks on the project.

Table 1: Stages in a tunnel project development.

Stage in project	*Information required and design methods used*	*Sources of information*
Feasibility	Topography, geology groundwater conditions and seismic hazard estimates in project area. Rock mass classification and estimates of rock mass characteristics and in situ stress conditions, particularly along tunnel routes. Estimates of tunnel support from rock mass classifications.	Regional topographic, geological and seismic hazard maps, geological information from adjacent projects, possibly limited site investigations to confirm critical geological or groundwater conditions. The use of geophysics may provide useful information.
Basic design	Confirmation and refinement of estimates made during feasibility stage. Numerical and limit equilibrium analyses of excavation and slope stability. The quality of information available may not permit 'precise' calculations and sensitivity studies may be required to predict the range of rock mass behaviour.	Topographic survey, surface geological mapping and diamond drilling programs. Where funds are available, exploration trenches or tunnels can yield very high quality information. In situ stress measurements using hydro-fracture techniques. Laboratory tests of rock and soil properties, particularly of weaker units.
Detailed design and awarding of contract	As for basic design but with more refined analysis as better quality information becomes available. Particular care is required in the preparation of specifications and contracts to minimise the risk of creating problems due to inappropriate wording.	Exploratory excavations in which detailed geological studies and in situ tests can be carried out, if required. Pilot tunnels for particularly difficult short tunnels should be considered.
Construction	Confirmation of design assumptions and adjustment, if required, of design details. Measurement of excavation quantity and performance for payment and settlement of disputes.	Geological mapping of conditions exposed during excavation. Monitoring of excavation behaviour and back-analysis of excavation performance to permit refinement of designs. Measurement of tunnel profiles.

Sharing risks associated with unpredictable events can substantially improve the success of a contract both in terms of cost and schedule control. Where the overall financial and contractual arrangements permit, it may be possible for all parties to agree on some form of 'Risk Sharing Package'.

An example of a Risk Sharing Package for a tunnel in karstic limestone is given in Table 2. In this particular project, the general geological conditions indicated a potential for karstic cavities of considerable size. Site investigations had revealed some information, however the incremental investigation cost aimed at fully identifying them was not considered financially justifiable.

A set of limits, based upon experience in the construction of similar tunnels was worked out and agreed by both parties to the contract. Note that the rock mass classifications are used for general guidance on the conditions to be encountered in the tunnel but they are not used for measurement of limit quantities. All of the indicators shown in Table 2 can be measured by simple quantitative site observations. This is in line with the Geotechnical Baseline Report.

The provisions listed in Table 2 represent a reasonable risk package and it is probable that any international arbitrator would classify anything in excess of the limits defined in this package as Force Majeur conditions.

Table 2: Risk Sharing Package for a tunnel in karstic limestone

Tunnel length: 5020 m; finished diameter: 3.5 m; concrete lining to be provided.
Geology: Miocene Limestone and Jurassic Dolomitic Limestone, cover 80 to 200 m
Rock Mass Quality (RMR (Bieniawski 1989) and Q (Barton, Lien and Lunde 1974)):

Description	*RMR*	*Q*	*Extent (m)*
Massive to slightly jointed	68 to 79	30 to 75	2600
Closely jointed	44 to 59	1.3 to 18	1650
Weakly cemented	39 to 57	0.8 to 3	670
Fault zones, karstic cavities	Not applicable	Not applicable	100

Risk description	*Risk sharing*
Rock mass quality along the route	Since the main risk is associated with large karstic cavities and the average rock quality is fair to good, deviations from the assumed distribution can be included in the Contractor's risk.
Presence of groundwater	Inflows into the tunnel are within the Contractor's risk up to the following limits: a) 20 l/s at the tunnel face; b) 50 l/s at the tunnel portal; c) head of water not to exceed 50 m.
Karstic cavities	Limits to the Contractor's risk: a) cavity zone not exceeding the tunnel span, say 4 m; b) water inflows not exceeding 20 l/s and decreasing to less than 20 l/min within 3 days; c) the cavity does not contain soft soil filling that may flow when in the unconfined state; d) delays caused by the occurrence of cavities do not exceed 30 days.
Presence of gas	The possibility of the presence of inflammable or toxic gases is negligible; the Employer will carry the corresponding risk.

Because of the wide variety of contracts used on major civil engineering projects, general guidelines are difficult to formulate. However, the overall objectives are the same and the need to minimise cost and schedule overruns and the subsequent disputes is common to all of these contracts. The following quotation is from an excellent document on Contracting for Underground Construction, prepared by the US Academy of Sciences in 1976.

The Contract drawn between the owner and contractor seeks to define the requirements of the underground project, to assign the responsibility for its accomplishment, and to establish its cost. A good contract does not merely divide the responsibilities of the project; it is a unifying force, an agreement committing both parties to a single common objective. Every provision in the contract must be an acknowledgement not only of the legitimate interests of the individual parties but their common goal.

The system works best when the engineer, contractor, and owner establish the attitude through their organisations that each party is knowledgeable, fair-minded, co-operative, competent, and willing to see equitable payment made for the work.

8. CONCLUSION

Geotechnical risks, in the form of unforeseen geological conditions, are a serious factor in cost and schedule control on all major civil engineering projects. The amounts of money, involved in claims arising from these geotechnical problems, is enormous and needs to be taken very seriously by financing agencies and engineering organisations.

Inadequate site investigations rank as one of the major contributors to geotechnical risk. More realistic allocations of time and money have to be made to these site investigation programs. It is also important that geologists and geotechnical engineers make more efficient use of the resources allocated for site investigation. Traditional vertical boreholes may not be adequate to define the conditions on a geologically complex site and innovative use should be made of horizontal boreholes and exploration tunnels. Ongoing investigation during construction is also important and probe hole drilling ahead of tunnels or the fitting of forward-looking seismic devices to tunnel boring machines can help to define difficulties before they are encountered.

The use of experienced consultants in the early stage of a project can also contribute to the reduction of geological and geotechnical risks. The judgement of these individuals, built on their wide experience in similar geological environments, can help to put problems in perspective and to set priorities for the use of limited resources and time.

The preparation of a contract is a vital step in minimising cost and schedule overruns. The inclusion of a Geotechnical Baseline Report in a contract and the development of Risk Sharing Packages are amongst the contractual arrangements being explored to minimise the problems of unforeseen geological conditions.

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