GEOTECHNICAL HAZARD REVIEW

Dr Steve Hencher

Halcrow China Ltd.
23 rd Floor Central Plaza,
18 Harbour Road,
Wanchai,
Hong Kong
Tel 852 2802 9228
Fax 852 2827 8352
HencherSR@halcrow.com.hk

Halcrow Korea Ltd.
#508 Shin-A Building,
39-1 Seosomun-dong,
Joong-ku, Seoul
Korea
Tel 822 779 5437
Fax 822 779 5439

ABSTRACT

Engineering projects often run into "difficult" ground conditions which cause delays, failures, hugely increased costs or even abandonment with consequent disputes and claims. Pertinent questions are "what constitute difficult conditions?" and "how might they be foreseen?" and these questions provide the focus for this paper.

Geological, geotechnical and hydrogeological models for engineering projects (simplified representations of the ground) need to be developed in a systematic manner. Within these models, the potential hazards associated with material (small) and mass (large) scale attributes of the geology, the environmental setting and the influence of the engineering works themselves need to be considered individually and in a progressive, systematic manner. This paper introduces the concept of a *Geotechnical Hazard Review* with reference to examples from various engineering works.

INTRODUCTION

Disputes relating to ground conditions are often based on the premise that the conditions were unforeseen or unforeseeable. The questions of "what constitute difficult conditions?" and "how might they be foreseen?" are the focus for this paper. A systematic approach is introduced whereby the various geological and environmental factors that might conceivably affect the success of the project are considered.

WHAT CONSTITUTE DIFFICULT GROUND CONDITIONS?

Often in engineering projects, the extent of difficulties associated with ground conditions are not foreseen prior to something going seriously wrong. The difference between *unforeseen* (not predicted) and *unforeseeable* (outside common experience, not to be expected and without indications) is important.

It is important that ground conditions, which have the potential for causing problems, are recognised at the correct time and dealt with adequately by the designer. Following failures of designed works, it is often found that the model of ground conditions was inadequate, either because some geological feature or property had been missed or overlooked during investigation, or because its significance had not been recognised. It is apparent that the "unforeseen" condition might at least have been anticipated to some degree, had a more thorough approach been taken to weighing up the geology and environmental setting. Even where nothing major goes wrong in many projects, it is often a matter of good fortune (absence of difficult conditions) rather than the result of a proper process of assessment and focused investigation.

In practice, it is dangerous to disregard any property (e.g. chemistry, fabric, structure) of material or mass without careful consideration of its potential effect on the proposed works, both during and post- construction. Examples of the severe influence of apparently minor factors will be given later.

GEOTECHNICAL HAZARD REVIEW

A broad overview of the geological and environmental setting can provide many insights into the likely difficulties to be faced throughout an engineering project. DeFreitas (1993) suggests that, when dealing with works of any significant size, careful consideration should be given to three questions:

a) what do we know?
b) what do we need to know?, and
c) what do we not know?

Each question should be considered at an early stage with reference to possible design solutions and methods of working. The site investigation should be specified accordingly. This might seem obvious but, for many reasons, it is rarely done systematically or comprehensively.

It is suggested that potential hazards be considered in a formal way through which potential problems are identified so that they can be categorised and mitigated against as far as possible. Such a systematic way of approaching hazard and risk is becoming common throughout civil engineering (Godfrey, 1996; Brown, 1999).

An approach for carrying out a *Geotechnical Hazard Review* is described here with reference to three equations (Tables 1 and 2). The equations were originally conceived by Knill and Price (Knill, 1976) and subsequently used by Price and Lumsden as the framework for teaching advanced courses in engineering geology at Delft University (Holland) and Leeds University (UK) respectively (Hencher, 1994; 1996). The equations provide a useful way of and, essentially a checklist for, approaching geotechnical aspects of many engineering works. The equations focus attention progressively on *geological materials* (mineralogy, fabric, texture and hence intrinsic engineering properties), then more broadly to include *mass features* (discontinuities and overall geological structure), *environmental setting* and, finally, the influence of the *engineering work* themselves.

Examples of factors that should be reviewed systematically at the initiation of a project are listed in Tables 3 to 6 and discussed below. The relevance of particular factors will depend upon the specific nature of each project.

MATERIAL SCALE FACTORS

Nature of Problems

Many problems encountered during projects relate to the basic chemistry of the ground. For example, rocks with a high silicate content such as rhyolites, quartzites, sandstones and cherts often result in high wear or damage to equipment such as drills or tunnelling machines due to abrasiveness of the ground.

Salts such as gypsum, which are commonly present in sedimentary sequences, can be dissolved by groundwater leading to the creation of voids, settlement and damage to properties (e.g. Cooper & Waltham, 1999). Conversely swelling due to the growth of gypsum, partly as a result of oxidation of pyrite, can lead to heave and building damage (e.g. Hawkins & Pinches, 1987). Similarly swelling pressures in some mudrocks can seriously delay tunnel projects (Steiner, 1994).

Chemical reactions between different minerals can also cause problems. For example at Carsington Dam in the UK, the original dam was constructed largely from Carboniferous mudrock with a limestone riprap cover. Iron pyrites within the mudrock oxidised on exposure producing a weak sulphuric acid (with water) which polluted water courses. The acid also reacted with the limestone riprap producing carbon dioxide which, because it is heavier than air, accumulated in tunnels beneath the dam and led to fatalities.

Alkali silica reactivity in concrete can cause severe deterioration and yet is readily avoided if the mineralogy of the aggregate is considered properly and appropriate tests conducted (Smith & Collis, 1993). Figure 1 shows the crazing of the Pracana dam in Portugal caused by alkali-silica reactivity, which necessitated major repair works.

Intrinsic material engineering properties (e.g. looseness of silty sand, which could give rise to liquefaction) can dominate large-scale behaviour. An example is the slaking characteristic of completely decomposed rock (grade V, Anon 1995). This tendency of grade V to disaggregate in contact with water is reflected in distinctive types of slope failure and gulleying (see Figures 2).

Expecting Problems

An experienced engineering geologist should be able to predict many potential problems simply through general knowledge of the geology. For example, knowledge of the occurrence of valuable materials such as coal bearing strata, close to the surface, in a populated area, might allow the possible presence of mining caverns to be anticipated even if there are no records that mining has taken place. Figure 3 shows deep storage caverns being excavated in chalk. The original design was to use the illustrated road header to cut the caverns but the method had to be changed to drill and blast. The change was necessitated because of unacceptable wear to teeth in the road header from flints within the chalk. The flints were under-sampled in the ground investigation but might have been anticipated through general geological knowledge.

A site underlain by limestone, bought by a building contractor for house development, is shown in Figure 4. The irregular bed rock profile caused significant problems for constructing shallow foundations. Again this might have been expected through general review of the local geology, awareness that limestone is commonly associated with dissolution features, and could have been proved inexpensively by a few shallow trial pits.

MASS SCALE FACTORS

The most important mass scale features in geotechnical engineering are discontinuities – bedding planes, fissures, joints and faults. These typically reduce strength and stiffness and increase the permeability of the rock or soil mass. Discontinuities are generally approximately planar and there is often a regular pattern, which means that engineering properties of the mass are anisotropic. Therefore structural orientation relative to the geometry of the project is often extremely important. Cutting a slope into jointed rock with a particular aspect may be perfectly safe whilst cutting at some other orientation may result in failure. In Figure 5, the geological structural control of the discontinuities on the quarry faces is obvious.

Joints and other fracture systems are often consistent with the tectonic history of the site and it is useful to try to interpret the origin of the fractures rather than just measure them and treat them in a statistical sense (Hencher, 1987; Rawnsley et al, 1990; Pollard & Aydin, 1988; Hancock, 1991).

Care must be taken to sample carefully. For example in Figure 6 (Halcrow Asia Partnership, 1998), two stereoplots are presented for the same weathered rock mass. Figure 6a is based on field mapping, mostly on steep exposed faces. Joints measured are predominately steeply dipping. The second set, Figure 6b, were measured using a BIPS system (Kamewada et al, 1990) in vertical drillholes. In these drillholes, the steep fractures were under sampled and most of the disccontinuities recorded were shallowly dipping.

If vertical holes are used predominantly to investigate a site (as is common practice) then steeply dipping structural features may be overlooked. Figure 7 shows the site of the Pen-Y-Clip headland (Al-Harthi & Hencher, 1993). A tunnel through the headland encountered vertical fractures infilled with soil. The soil collapsed into the tunnel and a chimney extended up to the surface of the hillside above. The vertical boreholes had missed the fissures during investigation which therefore came as a surprise during the tunnel excavation. The vertical joints were probably unloading fractures which run roughly parallel to the coastline and as such, might have been anticipated and investigated using inclined boreholes.

A photograph of typical core from an investigation for a very wide span underground station, planned to be excavated in mudrock at a depth of about 50 m, is presented as Figure 8. The vertical, calcite infilled fracture is obvious. Faced with such evidence the designer has to consider the possibility of extensive roof failure (as per Figure 9), the difficulties in preventing such failure and the long term implications for rock load. This requires that the fractures be properly characterised in terms of their planarity, frequency and persistence. If joints are impersistent, and infrequent, the problem may be only minor. Similarly if the joints are wavy at the field scale, then the rock mass will dilate and may lock up as movement occurs towards the tunnel so that the volume of failure will be restricted. These are, however, serious questions which demand careful consideration of the geological mass features.

Faults often cause problems for engineering works. Faults are rarely simple breaks through the rock but are often associated with other shear zones and poor quality rock. The collapse of a tunnel, which buried a TBM, is illustrated in Figure 10. The tunnel had encountered a fault zone, the extent and weaknesses of which had not been anticipated even though it was known from ground investigation that a fault occurred at that location.

Figure 11 shows a major rock slope failure in Repulse Bay, Hong Kong that occurred due to sliding within a zone of fractured rock and pink clay (probably a fault). The zone was about 700 mm thick and persistent throughout the hillside. Because of the thickness of the zone, the rock did not contribute to shear strength.

The importance of lithology contrasts in controlling hydrogeological patterns is well established but sometimes not looked for or the significance is not appreciated in design. Figure 12 shows a landslide on Tuen Mun Highway, HK where failure was interpreted as having been caused by perching of water above a gently dipping dolerite dyke (Hencher & Martin 1984). Similarly, dolerite dykes within the weathered granite contributed to the complex hydrogeology and system of pipes which were an integral part of the failure mechanism of the major landslide affecting the Ching Cheung Road, HK in 1997 (Halcrow Asia Partnership, 1998). A cross-section across the failure showing the interpreted dyke structure is shown in Figure 13.

Other examples of geological control of landslides are given in Hencher et al, (1985).

ENVIRONMENTAL FACTORS

Environmental factors include natural factors such as seismicity, rainfall, flood and in-situ stresses together with man-induced problems such as contaminated groundwater, blast vibrations and gases and disturbed ground due to mining activities.

The natural factors to be considered will depend upon geographical setting and the nature of the project. Quite often the factor will have to be considered on a risk basis. For example, in Hong Kong there is quite a high probability that structures will be affected by ground vibration, induced by nearby earthquakes of magnitude up to say 4.0 over a 100 year period, but a very low probability that they will be affected by a nearby earthquake of, say 7.5 magnitude. Earthquakes therefore are generally discounted for design in Hong Kong. In Taiwan the proximity to active, major faults makes the risk significantly higher and dynamic loading must be allowed for in design.

An important environmental consideration is variation in groundwater levels, naturally due to rainstorms or drought, which results in changes in effective stress and hence possibly reduced strength or settlement.

In-situ stresses can cause major problems, especially to underground structures. Where stresses are high, support systems may be insufficient and unacceptable deformations may take place. If stresses are low (area of extension), joints can be open and high groundwater inflows may occur.

Harmful gases occur naturally in rocks. The major explosion of methane in finished tunnels and associated underground structures at Abbeystead, UK in the early 1980's, provided a warning to the industry (Health & Safety Executive, 1985; Orr et al., 1991). Radon gas can be found, not only in materials normally thought of as radioactive, but in sediments such as mudstones and shales and needs to be investigated (e.g. Talbot et al., 1997).

Tunnelling through or close to contaminated land has its own special problems as reported by Barla & Jarre (1993)

ENGINEERING WORKS

The final stage is to consider the effects of the works themselves. Obvious aspects include changes in stress – unloading by excavation or loading due to the construction of a building. For example, tunnelling often causes ground settlement and the potential for damage needs to be accounted for in selecting the route. Figure 14 illustrates the undesirable effects of tunnelling for the Singapore Subway.

More subtle changes include the effect on groundwater regime. For example, in cutting a slope, the well-established groundwater flow paths and patterns will often be disturbed. New and very active flow paths may be developed as the groundwater system reacts to the changed geometry, and stresses and may result in piping and movement of materials (e.g. leaching and redistribution of clays). This will be exacerbated by stress relief and opening of discontinuities in the mass. Constructing a dam and impounding a reservoir will cause rises in groundwater in adjacent slopes and possibly initiate landslides due to reduction in effective stress. Drainage into tunnels can result in settlement of the overlying ground and may result in damage to existing structures.

The effects of the works during construction should be considered as carefully as the integrity and performance of the final structure. It is often during construction that problems occur. For example, Figure 15 shows some of the 20,000 piles driven to support the 2nd Phase of Drax Power Station in Yorkshire, UK. The piles shown were driven to various depths (the holes in the front are where piles disappeared below carpet level). This was not through design or choice. The variable penetration achieved was totally unexpected and due to varied grading in the sand-rich horizon that the piles were founding in. Where the clay/silt content was relatively high, high temporary pore pressures were generated during driving of the piles, resulting in low shear resistance and deep penetration. This caused major difficulties in predicting pile length and added perhaps 10% to the cost of pile production (Hencher & Mallard, 1989).

DISCUSSION

It is clear that site investigation will rarely provide a comprehensive picture of ground conditions to be faced. This is particularly true for tunnelling because of the length of ground to be traversed, the volume of rock to be excavated and often the nature of the terrain. Instead reliance must be placed on engineering geological interpretation of available information, prediction on the basis of known geological relationships and careful interpolation and extrapolation of data by experienced practitioners. Factors crucial to the success of the operation need to be judged and consideration given to the question *what if*? It is generally too late to introduce major changes to the methods of working, support measures etc. at the construction stage without serious cost implications.

Site investigation must be targeted at establishing those factors most likely to be important to the project. This requires careful *Geotechnical Hazard Review* as advocated in this paper. Even then, one must remain wary of the unknowns. In tunnelling, which is often one of the riskiest types of engineering project, probing ahead to establish the position of structures likely to cause difficulties may delay operations but that is better than simply driving on in the hope that everything will be all right. Instrumentation can be of great benefit in identifying problems before they become too severe (the Observational Process), but the use of advanced electronic devices may prove inefficient because of a lag time between measurement and interpretation back in the site office. This was highlighted as a possible contributing factor in the severity of the collapse of tunnels at Heathrow, in the UK (NCE, 1994).

CONCLUSIONS

Many geotechnical problems for engineering works can be anticipated through general knowledge of the geology and environmental setting. It is recommended that a review of the possible difficulties is carried out syatematically, starting from the small scale (such as chemistry of the soils and rocks), leading to geological structure and then environmental constraints. All this must be considered in the context of the changes to be brought about by the engineering works themselves.

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Table 1 Engineering geology expressed as simple equations
(after Knill, 1976)

Equation 1

Material properties + Mass fabric ⇒ Mass properties

Equation 2

Mass properties + Environment ⇒ Engineering geological situation

Equation 3

Engineering geological situation + Influence of engineering works
⇒ Engineering behaviour of ground.

Table 2 Commentary on Knills Equation

Equation 1	GEOLOGY	The first equation includes the geology of the site and concerns the physical, chemical and engineering properties at small and large scales. It essentially constitutes the soil and rock ground conditions.
Equation 2	ENVIRONMENT	The second equation describes the geological setting within the environment. Environment includes factors such as climate, groundwater, stress, time and natural hazards.
Equation 3	WORK	The third equation relates to changes caused by the engineering works. It is the job of the engineer to ensure that the changes are within acceptable limits

Table 3 Examples of Material Scale Factors that should be considered for a project

FACTOR	CONSIDERATIONS	EXAMPLES OF ROCK TYPES/SITUATIONS
mineral hardness	abrasivity, damage to drilling equipment	silica-rich rocks and soils (e.g. quartzites, flints in chalk)
mineral chemistry	reaction in concrete	olivine, high temperature quartz etc.
	oxidation –acids	pyrites
	swelling, squeezing dissolution	mudrocks, salts, limestone
	low friction	clay-infilled discontinuties, chlorite coating
loose, open texture	collapse on disturbance or overloading, liquefaction, piping, low shear strength	poorly cemented sandstone, completely weathered rocks (V); loess; quickclays

Table 4 Examples of Mass Scale Factors that should be considered for a project

FACTOR	CONSIDERATIONS	EXAMPLES OF ROCK TYPES / SITUATIONS
lithological heterogeneity	difficulty in establishing engineering properties; construction problems (plant and methodology)	colluvium, unengineered fill, interbedded strong and weak strata, soft ground with hard corestones
Joints/natural fractures	sliding or toppling of blocks	slopes
	deformation	foundations
	water inflows / collapse	tunnels
	leakage	reservoirs
	radionucleide migration	nuclear repository
faults	as joints; sudden changes in conditions; displacement, dynamic loads	tunnels, foundations, seismically active areas
structural boundaries, folds, intrusions	heterogeneity; local stress concentrations; changes in permeability – water inflows	all rocks / soils
weathering (mass scale)	mass weakening; heterogeneity (hard in soft matrix); local water inflow; unloading fractures	all rocks and soils close to earth's surface especially in tropical zones; ravelling in disintegrated rock masses.
hydrothermal alteration	as weathering, minerals low strength	generally igneous rocks

Table 5 Examples of Environmental Factors that should be considered for a project

FACTOR	CONSIDERATIONS	EXAMPLES OF ROCK TYPES / SITUATIONS
in-situ stresses	high stress: squeezing, overstressing, rockbursts	mountain slopes and at depth, shield areas, seismically active areas
	low stress: open fractures, high inflows, roof collapse in tunnels	extensional tectonic zones, unloaded zones, hillside ridges
natural gases	methane, radon	coal measures, granite, black shales
seismicity	design loading, liquefaction, landslides	seismically active zones; high consequence situation in low seismic zones
influenced by man	unexpectedly weak rocks, collapse structures	undermined areas
	gases and leachate	landfills, industrial areas
ground water chemistry	chemical attack on anchors/nails foundations/materials	acidic groundwater, salt water
groundwater pressure	effective stress, head driving inflow, settlement if drawn down	all soils and rocks
ice	ground heave, special problems in permafrost/tundra areas, freeze-thaw jacking and disintegration	anywhere outside Tropics
biogenic factors	physical weathering by vegetation; rotted roots leading to piping;	near surface slopes
	insect attack	causing tree collapse

Table 6 Examples of the Influence of Engineering Works

FACTOR	CONSIDERATIONS
loading /unloading – static / dynamic	settlement, failure, opening of joints increased permeability in cut slopes, blast vibrations
change in water table	increased or decreased pressure head, change in effective stress, drawdown leading to settlement, induced seismicity from reservoir loading
denudation or land clearance	increased infiltration, erosion, landsliding

List of Figures

그림은 원고의 명도가 낮아 인쇄를 생략하였습니다.