Hazardous Ground Conditions: Reducing the Risks

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Abstract: Engineering geologists would generally agree that ground conditions should be predictable (or could have been, in hindsight, once something goes wrong) but projects still regularly have major problems because geological conditions have not been properly recognised or accounted for. This paper addresses the question of how to carry out focused site investigation – to avoid wasteful ground investigation and testing at non-demanding sites (most of them) yet focus attention and expertise at those sites where there are potential difficulties. The paper considers how to spot the problem, how to carry out investigations and who should be involved. The importance of thorough geological training and experience for those who develop and interpret ground models is emphasised.

1 INTRODUCTION

When someone talks about geological hazards they normally consider the obvious natural hazards such as earthquakes, volcanoes and natural landslides that cause tremendous loss of life and economic damage each year. This paper however concentrates on less obvious geological hazards that may be overlooked during the geotechnical engineering process yet can still result in considerable danger and economic impact if not addressed and dealt with - the paper is aimed at identifying where projects go wrong due to geotechnical problems and how such problems might be avoided.

One difficulty in addressing this issue is that geotechnical engineering is very diverse and covers a wide range of skills and processes including geology, hydrogeology, and soil and rock mechanics. Tools include site investigation, testing, instrumentation and numerical simulation. Specific project types such as tunnelling, slope engineering and foundations have particular requirements critical to their successful achievement. There are therefore many potential candidates when things go wrong. There are also often many possible explanations - things might have been done incorrectly (e.g. wrong modelling), important aspects of the site might have been missed (e.g. poor ground investigation) or ignored (i.e. inadequate training or lack of experience). There may have been, and often were, financial and contractual constraints. Finally, there may be fundamental management and contractual issues as highlighted by Muir-Wood (2000 & 2004).

Conditions can be genuinely unpredictable in that certain behaviour has not been previously identified or recorded but the chances of claiming such an excuse diminishes with time. This a good reason to make sure that the team for the design of any major geotechnical project includes specialists that cover all the relevant aspects. In the author's opinion, this must include a properly trained engineering geologist who has a fundamental knowledge of geological sciences and understands the options for engineering structures and the constraints for construction.

2 SOURCES OF HAZARDS IN GEOTECHNICAL ENGINEERING

The Burland triangle (2006) is a useful way of representing the geotechnical engineering process schematically with the apices representing:

- Ground Profile
- Observed Behaviour, and
- Appropriate Model

These three aspects are discussed by Burland as linked and interdependent with the whole process being dynamic and based on experience and empiricism. Burland argues the necessity to keep the triangle balanced - all aspects are important to good ground engineering. Burland's description of ground profile is however as a simplified representation. He states: *"Establishing the ground profile is the key outcome of the site investigation. In this context, the ground profile is the description in simple relevant engineering terms of the successive strata together with the groundwater conditions and their variation across the site."*

Figure 1 is a modified version of the Burland triangle and is a good starting point to consider where things may and do go wrong with projects. The top apex of this modified version of the triangle includes *all* geological and hydrogeological aspects of a site together with the environment factors affecting that site (including in-situ stresses and seismic hazards), prior to any judgment of what is or is not important which differs from Burland's definition. This is not a trivial point because over-simplification or incorrect characterisation of geological conditions during the development of a geological model is a key aspect of many geotechnical failures as discussed later.

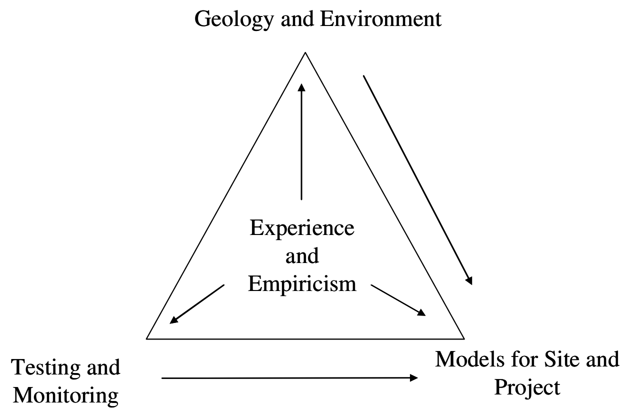

Fig. 1. Geotechnical process, based on the Burland Triangle (Burland, 2006)

Figure 1 is presented as a process (rather than a group of interactive activities in Burland's triangle. The final outcome of site investigation should be a geotechnical or ground model that can be analysed adequately and which allows prediction of the ground response reasonably accurately. The predicted behaviour can then be monitored during construction and operation to ensure that performance is with the tolerance of the structure.

In terms of risk, there are hazards at every stage of development of the ground model including errors in testing, monitoring and modelling that can contribute directly to poor performance or even failure of a project. Such hazards are however outweighed by errors in assessing geological conditions or by missing key aspects of the geology. Burland (2006) reports that: *"nine failures out of ten result from a lack of knowledge about the ground profile - often the groundwater conditions"*.

The process by which that site geology is assessed, simplified and presented within geotechnical models is the main focus of this paper. It is obviously correct that we will never know all aspects of the ground profile even after extensive ground investigation but the engineering geologist must initially take a holistic view of the geological history at a site and the nature of materials that can be expected so that the investigation can be focused, not only on providing broad geotechnical parameters for design, but also on the less obvious hazards that might adversely impact the project.

3 SITE GEOLOGY AND ENVIRONMENTAL FACTORS

One of the difficulties for site investigation, as discussed by Baecher & Christian (2003), is that major consequences sometimes arise from minor geological defects that are difficult to detect. One of the key tasks therefore for the engineering geologist is to predict and search for the defects, however "minor" relative to the mass of other data that may be available for a site, and that will cause the problem. Most sites have no serious problem and even a poor investigation may not end in disaster. Now and again however, there is an intrinsic problem at a site and the skill is in predicting, investigating and recognising the significance of that problem so that it may be mitigated. Investigation must be focused on those aspects that are important. To do this requires careful thinking about a site prior to specifying any ground investigation.

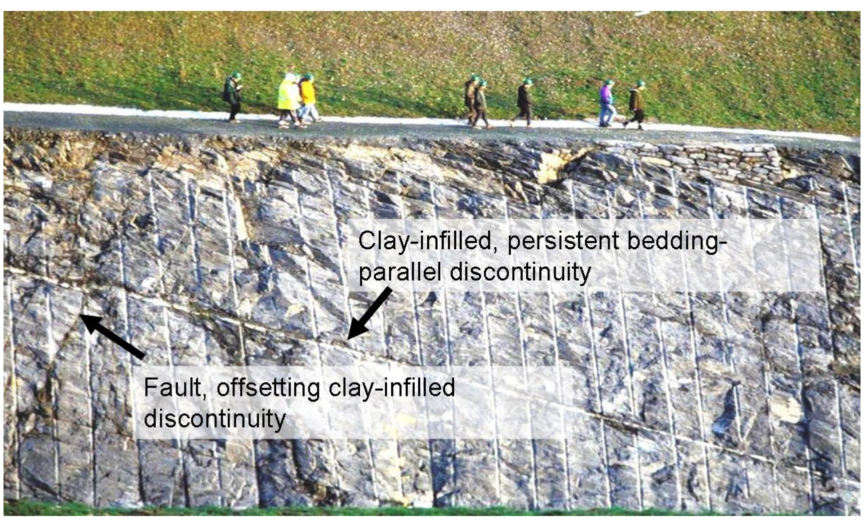

Fig. 2. Road cutting in North Wales. Dip of the beds is into the page and to the right. The photograph was taken from the opposite, failed slope (with similar structure)

For example, during cutting a rock slope, a large unforeseen wedge failure occurred on clay-filled discontinuities parallel to bedding dipping at 25 degrees, in conjunction with faults (Figure 2). Gordon et al (1996), describing the failure, note the difficulty of identifying faults and bedding plane shears in hard rocks by conventional site investigation despite using relatively sophisticated drilling techniques and this is true as a general statement as discussed in some detail by Baecher & Christian (op. cit).

Nevertheless, in this relatively simple geological situation, where the structure was not complex, wedge failure was certainly predictable given the general dip of bedding, the low shear strength and persistent nature of the obliquely dipping clay-filled joint (unusual) and the presence of cross cutting faults. The failure might have been avoided if the ground investigation had been targeted on that wedge mode, which was actually the only credible mechanism for failure for the cutting. Putting it another way, one wonders what information the ground investigation did reveal that was of any use in judging the stability of the cutting.

4 CHECKLIST APPROACH

The problem is how to create an appropriate geological model to which can be assigned design parameters and which allows identification of all the hazards that might adversely affect a project? One approach is to adopt a checklist approach to consider all hazards one by one that have any possibility of occurrence at the site, based on a general review of site geology (say from desk study). This is akin to setting up a risk register for a project (Brown, 1999) but focused specifically on the likely geology and environmental factors. The adequacy or not of the potential hazards list will depend of course to a high degree on the experience and knowledge of the team for the project.

Having reviewed various ways that this might be approached the author believes that the clearest method is to consider, in turn and systematically:

- Geology (with small and larger scale characteristics addressed separately)
- Environmental Conditions at the site, and
- The Project Constraints - what is to be constructed, how this is to be achieved and the interaction of the construction process and project operation with the geology.

These headings are interpretations of a “verbal equation” approach which has been used in analysing the engineering geological process and is discussed in some detail by Knill (2002), Hencher (1994) and Hencher and Daughton (2000).

An experienced engineering geologist should be able to predict many potential hazards at any scale and under each of these headings through general knowledge of the geology. For example, knowledge of the existence of shallow coal-bearing strata, in a populated area, would mean that the presence of mine workings should be considered even if there are no records that mining has taken place. Contrast this with an actual occurrence during the construction of the High Speed Rail in Korea in 1996. Tunnels for the railway, south of Seoul, were under construction when they ran into old mine workings. Embarrassingly for those who planned the route, not only should it have been recognised that the geology predicated the possibility of such mines, abandoned mine buildings were still to be seen on the hill above the tunnel where it encountered the workings. A long section of the route was relocated at great cost and delay.

5 MATERIAL SCALE FACTORS

Material Factors are at the scale of hand-held samples or pieces of core. It is the scale of most laboratory and borehole tests. Hazards at this scale are associated with the physical and chemical nature and properties of the various geological materials making up the site. Hazards include:

- Chemistry: potential solubility, abrasivity, reaction of aggregates in concrete and chemical reaction with other rocks and fluids. Heave, rapid weathering and pollution can result.
- Density and strength: potential for collapse, bulking, piping and liquefaction
- Other material scale attributes that should be considered include durability and permeability.

One example of the significance of material scale hazards is from the construction of Carsington Dam in the 1980s. The dam was constructed of locally-derived rock fill. The fill included black shale with pyrite (FeS) and the riprap was limestone ($CaCO_3$) (Figure 3). The various chemical reactions and processes are discussed in detail by Pye & Miller (1990). Sulphuric acid was generated as a result of the geological materials present and polluted local stream courses. Carbon dioxide collected in underground chambers and workers died as a consequence.

Another example of a material scale factor that should have been anticipated is shown in Figure 4 which shows a cavern under construction for the storage of liquified gas beneath South Killingholme, Yorkshire. The road header pictured had been specified for the excavation of the caverns but this proved economically impractical because of wear caused by the presence of bands of extremely strong and abrasive flints in the chalk. Blasting had to be used instead to excavate the caverns (Anon, 1985). It is suggested that the presence of bands of flint should have been anticipated in the chalk, even if it had not been sampled or logged during site-specific drilling (probably due to inadequate sampling methods).

Fig. 3. Carsington Dam, post failure in 1984. Scar has exposed the rock fill including dark, Carboniferous shale. White rock is limestone rip rap.

A third example of a problem derived from a material scale property is shown in Figure 5. The gulley shown was caused by water discharging from a raking drain in a nearby slope straight on to the ground, below the slope, without proper channels to take the water from site. The ground comprises uniform, completely decomposed granite (Grade V) which by definition slakes (disaggregates in water).

6 MASS SCALE FACTORS

Mass Scale Factors include the distribution of different materials in different weathering zones or structural regimes, as successive strata or as intrusions. It includes structural geological features such as folds, faults, unconformities and joints. Mass strength, deformability and permeability may bear almost no relationship to those of the composite materials which means that laboratory tests may be unrepresentative and not to be relied upon.

One of the main geological hazards at the mass scale is faults. Faults can be associated with zones of fractured and weathered material, high permeability and earthquakes although that is not always the case. Faults can be tight, cemented and actually act as seals rather than zones of high permeability. Faults should nevertheless always be looked for and their influence considered. There are many cases of unwary constructers building on or across faults with bad consequences, sometimes leading to the need for reconstruction.

Fig. 4. Caverns for the storage of LPG at Killingholme, Yorkshire

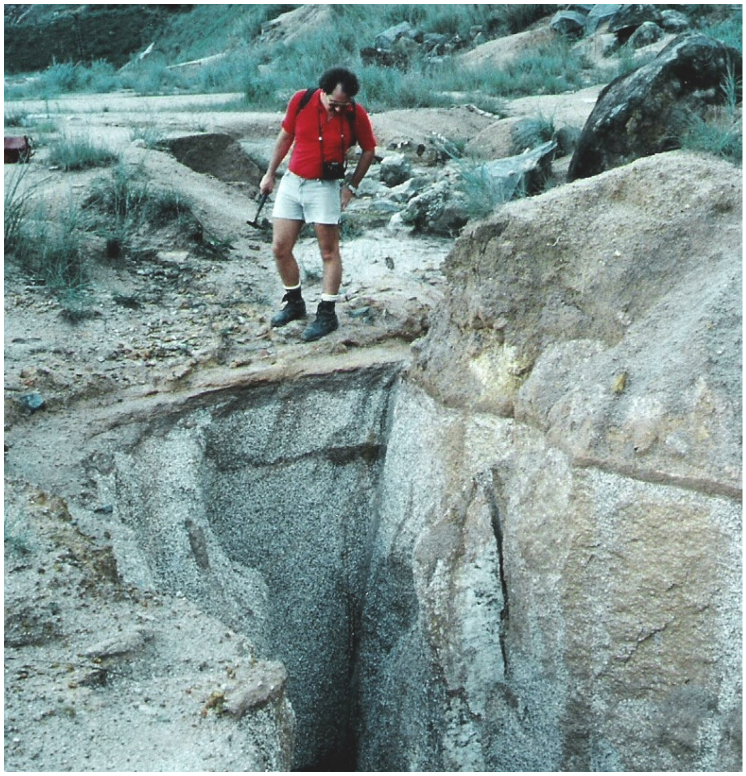

Fig. 5. Gulley in completely decomposed granite, Ngau Chi Wan, Hong Kong

Figure 6 shows foundations under construction at Kornhill, Hong Kong. The presence of a major fault (weathered zone in line with the valley) meant that foundations had to be taken locally 10s of metres deeper than adjacent foundations. Clearly the valley was indicative of the potential for poor ground conditions. That said, all valleys are not associated with faults and all major faults are not associated with valleys. At Kornhill some faults that had been anticipated caused no difficulties whilst other, unpredicted faults were discovered during construction (Muir et al, 1986). Similarly consequence is sometimes difficult to predict. At Sellafield, during cross hole hydrogeological tests, major discontinuities that were predicted to dominate flows did not (Hencher, 1996); flow occurred on other joints. Similarly during tunneling for the Strategic Sewerage Disposal Scheme (SSDS) in Hong Kong, discussed later, many of the water inflows were not associated with major geological features but surprisingly issued from zones with very little apparent jointing or fracturing at the tunnel excavation surface.

Fig. 6. Fault causing problems for foundations, Kornhill, Hong Kong

Fig. 7. Rock slope failure due to adverse rock structure, Dubai

As another example, Figure 7 shows a recent rock fall in Dubai. The failure occurred in a structurally complex zone with structures dipping locally directly out of the cut slope. The local structure was in perhaps difficult to anticipate but the general complexity and necessity for field mapping, reappraisal and decision-making during construction together with specification of appropriate preventive works should perhaps have been known and foreseen.

One last example is the investigation for a potential nuclear waste repository at Sellafield in the UK. The Government specification of acceptable risk was extremely onerous and necessitated an intensive investigation combined with intensive modelling. Part of the modelling involved trying to predict ground water flow and the potential movement of radionucleides. For this, a good ground model was necessary with estimates of permeability for the full rock sequence. For most early models one of the strata, a heterogeneous bed of cemented boulders called the Brockram, was taken to be of very low conductivity (2×10^{-10} to 1×10^{-9} m/s) based largely on borehole tests (Heathcote et al, 1996). Later tests however, showed "significant flows" in the Brockram and the modelling had to be revisited (Hencher, 1996). Michie (1996) reports hydraulic conductivity measurements within the Brockram with a maximum of 1×10^{-5} m/s, i.e. four orders of magnitude higher than adopted for the early models. The changed perception for this important stratum might be deemed just part of what is to be expected in any progressive ground investigation. However the potential for locally high permeabilities associated with extremely widely spaced and persistent joints, at spacing such that they will be rarely sampled in boreholes, could have been anticipated and actually such joints can be observed at exposures in the Lake District. There were also indications in the literature that the Brockram might be permeable at a scale of hundreds of metres. Trotter et al (1937) commented on the possibility of pathways through the Brockram with reference to the distribution of haematite mines within the Carboniferous Limestone underlying the Brockram.

7 ENVIRONMENTAL FACTORS

Environmental factors include in-situ stresses, earthquake shaking and climatic influence and are discussed in some detail in Hencher & Daughton (2000). Such factors, including hydrogeological conditions, will be part of the ground model for a site, but are best considered separately from the basic geology although the two are closely interrelated. The environmental factors to be accounted for depend largely on the nature, sensitivity and design life of structures and the consequence of failure.

One example is shown in Figure 8 which shows tunnels constructed at depth below Hong Kong Harbour in 1995. These are tunnels from the first stage of the SSDS, now HATS, where high water inflows caused the job to be stopped and a large legal dispute between the Hong Kong Government and the Contractors followed. To quote from Buckingham (2003): *"when the SSDS project was conceived, site investigation was undertaken along the planned alignment to levels determined by this alignment. This revealed ground conditions at the planned depth to be worse than expected, the tunnels were lowered by several tens of metres below the depth of these boreholes with the idea that they would be below the poor ground. The tender was based upon this assumption that the tunnels would be in better rock with minimal water ingress."*

The Contractors elected to use open face rock tunnel boring machines (TBM) with very limited ability to grout ahead of the tunnels and a low level of shielding for electrical and mechanical devices on the wrong assumption that water inflow would be low. In the event very high water pressures and inflows were encountered that required extensive grouting in some tunnels. Grouting behind the TBMs was very ineffective.

To the author's knowledge there was little or no attempt to predict water in-flow at the design stage despite the tunnels being beneath the sea and it seems that the design engineers simply assumed that there would be no difficulty if the tunnels were taken deep enough. On the basis of the design specification, the Contractor then selected the TBM machines that proved to be unsuited to the conditions.

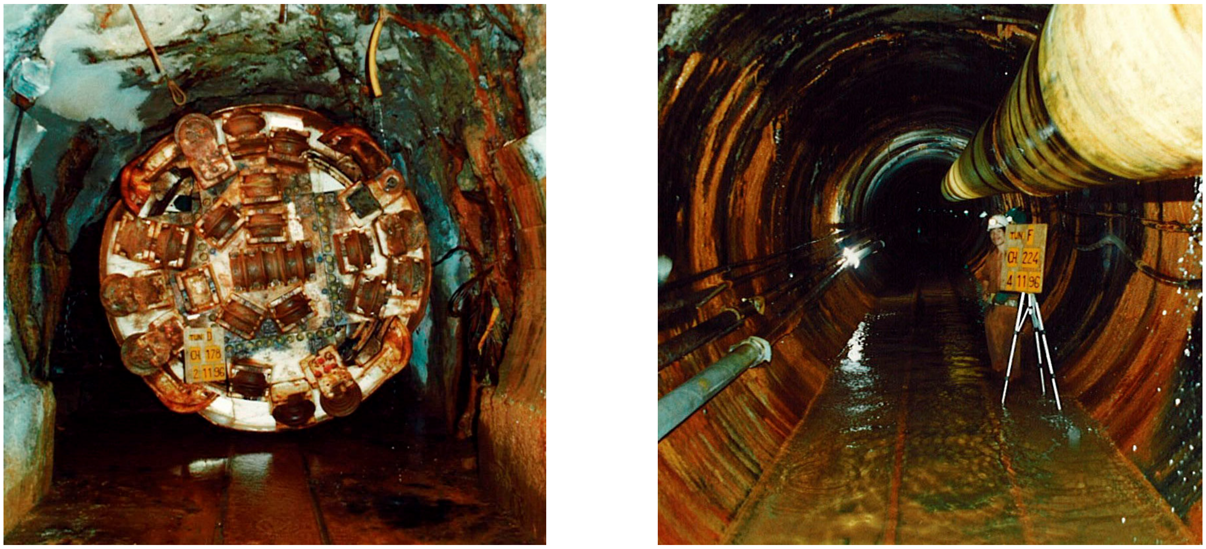

Fig. 8. Open face TBM and water flow from tunnel, SSDS, Hong Kong

The Contractor had accepted all geotechnical risks such that there was no provision for “unexpected conditions” leading to additional payment to deal with the severe inflows that occurred in 2 out of the 5 tunnels. Neither the Engineer nor Contractor had anticipated such poor conditions for whatever reason and it is argued that the poor contractual arrangement contributed to the huge delays and costs that resulted.

8 CONSTRUCTION

The third verbal equation of Knill and Price (Knill, 2002) addresses the interaction between the geological and environmental conditions at a site and the construction and operation constraints (Hencher & Daughton, 2000). The ground model requirements for the same site would be very different for significantly different projects such as foundations, a slope cutting or a nuclear waste storage facility. The systematic review and investigation of site geology and environmental factors, discussed earlier, needs to be conducted with specific reference to the project at hand.

Hencher & Mallard (1989) discuss problems encountered whilst driving piles for the 2nd half of Drax Power Station. Piles terminated at significantly different levels despite apparently consistent geological conditions across the site (Figure 9). In some areas of the site piles were driven to depths far deeper than anticipated in the design whilst encountering low resistance. Subsequent investigations confirmed that this occurred in areas where the founding sand stratum had a high fines fraction, was of relatively low permeability and where excess pore pressures developed during pile driving. In other areas, where the sand was cleaner and of higher permeability, piles terminated at the higher levels anticipated in the design. All the piles met the design carrying capacity but the variability in driven pile lengths caused difficulties for pile manufacture, programming and ultimately cost. This problem had not been anticipated and was related entirely to of the method of construction. If bored piles had been used instead of driven piles for the Drax foundations, which would have been an acceptable solution, then the problem would not have arisen.

A recently reported example is that of a tunnel in Kingston on Hull (Grose & Benton, 2005). The tunnel was constructed with a TBM through a sequence of saturated Quaternary sediments. During construction, water and then soil migrated through one of the already constructed segmental liner joints and the tunnel had to be abandoned temporarily as the situation deteriorated. A subsequent investigation failed to come up with a definitive answer but it was clearly a matter of soil-structure interaction and possibly construction defects. The discussions by Hartwell (2006) and Shirlaw (2006) are instructive and they come up with various ideas for the failure that seem feasible. The bottom line seems to be that the tunnel design and construction methodology was not robust for the ground conditions. Whatever the geological variability that ultimately brought about the failure, it is apparent that some variability was to be anticipated and it is suggested that the design and construction methodology should have coped with this. One of Terzhagi’s principles as reported by Goodman (2002) was to *“assume the worst configuration of properties and boundary conditions consistent with the data from site investigations”*, i.e. within the confines of an appropriate geological model.

The process of systematic appraisal of ground conditions advocated earlier will hopefully allow the key hazards to be identified and cost-effective design but models are always simplifications, and the engineer must adopt a “what if” scepticism when designing, especially where the geology is potentially complex.

Fig. 9. Piles driven to different levels at Drax Power Station. The hole in the foreground is where a pile has been driven below ground level without achieving the required set.

9 DISCUSSION

It is evident that site investigation cannot provide a comprehensive picture of the 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 which prevents boreholes being put down to tunnel level or makes their cost unjustifiable. 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 that are important to the project and not to waste money and time investigating and testing aspects that can be readily estimated to an acceptable level or aspects that are simply irrelevant. This requires a careful review of geotechnical hazards as advocated in this paper. Even then, one must remain wary of the unknowns and consider ways in which residual risks can be investigated further and mitigated, perhaps during construction.

There is a somewhat unhealthy belief that standardization (for example British Standards, Eurocodes, Geoguides and ISRM Standard Methods) will provide protection against ground condition hazards. Whilst most standards certainly encompass and encourage good practice, they often do so in a generic way that may not always be appropriate to the project at hand and they may not provide specific advice for coping with a particular situation. Ground investigations are often designed on the basis of some kind of norm - a *"one size fits all"* approach to ground investigation. It is imagined that a certain number of boreholes and tests will suffice for a particular project essentially irrespective of the actual ground conditions at the site. This ignores the fact that ground investigations of average scope are probably unnecessary for many sites but will fail to identify the actual ground condition hazards at rare but less forgiving sites. Similarly an averaging type approach will mean that many irrelevant and unnecessary samples are taken and tested whilst the most important aspects of a site are perhaps missed or poorly appreciated. This is, unfortunately, commonplace.

10 CONCLUSIONS

Ground conditions must be carefully assessed to establish their potential impact on the economy and safety of projects. Sometimes the complexity of the situation is such that many hazards can be identified that could potentially cause problems and these need to be considered systematically and mitigated. At many other sites, a single, simple aspect of the site, that might be identified and dealt with very cheaply, may control the success or otherwise of the whole project. Other sites have no significant hazards and the risks are minimal.

All rock and soil masses are complex to some degree or other at some scale. Gross geological complexity is readily recognised from mapping but the importance of apparently minor features may be overlooked. It is argued that a careful appraisal of the possible engineering geological conditions based on general knowledge and past performance of the particular features or materials that will interact with engineering structures can go a long way to preventing surprises during construction. This is best done systematically by properly trained and experienced engineering geologists as advocated in this paper. Once identified, the various hazards must be taken seriously and appropriate action taken to investigate them and to mitigate the risks.

11 ACKNOWLEDGEMENT

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