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On the nexus of engineering failures in the ground

Au sujet du nexus entre les défaillances d'ingénierie dans le sol

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ABSTRACT: Ground-related failures continue seemingly unabated despite enormous increases in knowledge in recent times. The authors have examined more than 100 cases ranging from some involving limited cost and delay through to major cases and catastrophic events. The failures are commonly the nexus of several issues that, on their own, would not have caused failure but together create the problem; the combination of hazardous ground conditions with inadequate interpretation and geotechnical management by inexperienced or unwary client teams and advisers. The paper explores and discusses these interactions, illustrated by examples of what can go wrong and learning points of what might have been done at various stages to identify and manage the risks. It examines the role of Geotechnical Adviser in identifying and managing Geotechnical Risks and how successful outcomes can be achieved in even the most challenging ground conditions and projects.

RÉSUMÉ: Les défaillances liées au sol continuent apparemment sans relâche malgré un gain de connaissances considérable dans ce domaine ces derniers temps. Les auteurs ont examiné plus de 100 cas allant de ceux à faibles coûts et délai moindres aux cas majeurs et aux événements catastrophiques. Les défaillances sont souvent liées à plusieurs problèmes qui pris séparément n'auraient pas provoqués de défaillance, mais qui une fois rassemblés sont à la cause de celle-ci; l'ensemble de conditions de terrain dangereuses avec une interprétation inadéquate et une gestion géotechnique par des équipes et des conseillers inexpérimentés ou imprudents. L'article étudie et discute ces interactions, illustrées par des exemples de ce qui peut aller mal et des points d'apprentissage de ce qui aurait pu être fait aux différentes étapes pour lever et gérer les risques. Il examine le rôle du conseiller géotechnique dans l'identification et la gestion des risques géotechniques et la façon dont les résultats peuvent être atteints dans les conditions du sol et les projets les plus difficiles.

Keywords: Geotechnical failure; ground risk; safety; hazards; investigations

1 INTRODUCTION

A recent paper by the authors, entitled 'Grounds for Concern', Tonks *et al*., (2017), reviewed more than 100 cases of ground-related failures and disputes. It concluded, inter alia, that most such cases involved fairly routine projects and known geotechnical issues, but the complexities of the ground engineering behaviour had not been duly recognised. "*We are led to the conclusion that the overwhelming majority of issues arise from human factors rather than the ground itself*."

The paper generated some interest and interesting responses. Ruffell (2017) discussed the concept of a 'nexus' of several issues combining to lead to failures, from his lengthy experience at the helm of a major geotechnical consultancy: *"It's the combination of risky ground; risky client and unwary project team"*. Each of these may have several components. The physical hazards may interact and compound the risks. The team may fail to interact, or suitably identify, communicate or manage the risks.

Nexus can be defined as *'a connection or series of connections linking two or more things'*, a central or focal point, from the Latin, a binding together. For present purposes it is taken as the simultaneous connection of several independent conditions; none of which might have been of particular consequence on their own, but together lead to a signficant event. For example, the co-existence of a weak layer below or within a dam; a storm flood event; inadequate or inappropriate monitoring and the presence of various buildings in the path of the debris torrent released by the dam's failure.

This paper discusses the concept of a nexus, illustrated by examples of how this may occur and learning points as to what might have been done to better identify and manage the risks. The examples are drawn from our experiences in investigating a wide variety of geotechnical cases, suitably anonymised to assist discussion.

It is important to assert from the outset that vastly increased geotechnical knowledge and experience has enabled enormously complex projects to be undertaken in the most challenging geotechnical conditions. The problems tend to relate to failures to appropriately engage the geotechnical knowledge which is available. There are many cases where the original investigations and/or interpretations have been very limited, even unsatisfactory, but the issues could still have been identified and circumvented by design and suitable risk management later.

2 MANAGING GROUND RISKS

Much has been written on Geohazards, and Geotechnical Risk Management (GeoRM). The interested reader is referred to Clayton (2001), van Staveren (2006) and ISSMGE (2013) which lead to numerous links. Key points here are:

- Geotechnical risk should be 'owned' by professionals with appropriate expertise (as should each type of risk identified).
- GeoRM needs to be suitably integrated within Project Risk Management (ProjectRM). Figure 1 illustrates this. This requires good integration and incorporation of experienced geotechnical professionals within the project core team.

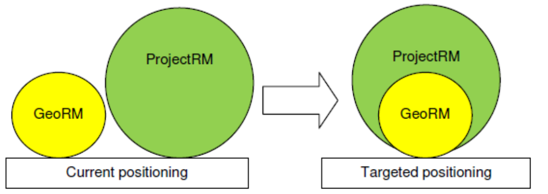

Figure 1 Importance of including GeoRM within overall ProjectRM, after ISSMGE (2013)

Chapman (2012) considers geotechnical risks and their context for the whole project. Amongst many useful comments and advice are:

- ground engineering problems are rarely caused by gaps in knowledge; mostly caused by failure to apply existing processes adequately;
- expect the unexpected, with particular reference to 'known and unknown unknowns' and 'Black Swans', noting geotechnical uncertainties can be 'wildly random'.

It is instructive to consider some examples of the interaction of ground risks and human factors. In some cases, very challenging conditions have been successfully addressed. In others, relatively straightforward ground risks were not identified or provided for at the outset and warnings were later missed resulting in substantial losses.

2.1 Soft Ground

A large proportion of ground-related problems (over 50% in our experience) arise from construction on soft ground, including many types of made ground or fill materials. This topic has been discussed by Tonks and Antonopoulos (2015). Tonks and Ameratunga (2012) discussed the benefits of trial banks for managing risks on soft ground. However, a recent major international Engineer-Procure-Construct (EPC) Scheme involved a trial bank which somehow led designers to predict that consolidation of deep soft clay with surcharging and prefabricated vertical drains would be near complete in only a few weeks. This was quite simply not reasonably credible in the face of all the data – the true figure was more than 3 months.

This was project critical, as the works involved numerous stages and sequential areas, so that a project programme of around one year would truly take many years. Although the geotechnical works were a small proportion of the major scheme, the contract was eventually terminated. The nexus of issues included:

- the client's minimal, arguably misleading, original investigations;
- seeking to place all ground risk with the EPC Contractor;
- very late access, post contract, to the critical areas of soft ground;
- failure to appreciate that the trial bank was not representative;
- unsatisfactory and conflicting trial bank monitoring data;
- misinterpretation of the data, failing to appreciate that these and the ensuing scheme were contrary to published experience for comparable cases, and
- failure to appreciate the risks that the ground element posed to the entire scheme and pursue an alternative.

The true ground conditions were not evident from the tender documentation, but the risks might well have been foreseen by a geotechnical specialist. The relevant areas were then not investigated until far too late. Thereafter the geotechnical issues were still not correctly identified until they became intractable. This may have some resonance with other major rail schemes which are currently 'in the pipeline'.

2.2 Landslides and debris flows

The authors have long been involved in a very wide range of slope projects for road, rail, and various public or private developments. The vast majority on our files, which run into several thousand projects, have either been new works designed and constructed satisfactorily, or existing, often quite old 'assets' identified as at risk, by standard inspection procedures, and suitably managed and or remediated. However, each year we encounter a number of failures, mostly requiring emergency works and some of which involve substantial inquiries, forensic investigations, legal cases or inquests.

Nettleton *et al*. (2010) discuss a number of examples. We would summarise some key points and common features:

- the engineering geology is crucial. Almost all soil and rock types, at least in the UK, have been studied, many in great detail, and there are numerous case studies of the more problematical formations and their issues, which should be identified in desk studies (but too frequently are not);
- high quality fieldwork and attention to detail is very important. Analysis of Digital Terrain Models (DTM) has advanced greatly in recent years and allows far more attention to the three-dimensional geometry and geology;
- there continue to be many incidents due to natural or climatic conditions, notably high antecedent and / or short duration high intensity rainfall. Cases continue to occur when surface and groundwater drainage needed to be better understood and managed both during construction and operation (Photo 1);
- slopes in clay soils and rock, including mudrocks can stand at steep angles in the short term but fail, sometimes dramatically, with time due to changes in pore water pressure. This follows well understood geotechnical principles (effective stress) but remains a mystery to most non-geotechnical specialists; and
- there are various other forms of soil and slope deterioration, including weathering, again increasingly being understood from studies and forensic investigations.

Photo 1. Surface water flooding above metastable slopes (Photo courtesy of Ms. S. Marsh).

A number of major landslides investigated by the authors on various infrastructure, public amenity and private development site across the UK and overseas have highlighted cases where the nexus included:

- ground investigations failed to identify and/or adequately characterise the critical issues/materials;
- failure to identify or allow for the groundwater and/or, in many cases, more significantly surface water from anthropogenic sources (Photo 1);
- failure to appreciate the changes to site materials over time (e.g. mudrock weathering to a clay);
- temporal changes in the purpose / loadings on geotechnical or structural assets (e.g. masonry facings: deterioration of the materials they protect leads to the facing having to perform a support and retention role);
- increasing demands on aging infrastructure (e.g. increase in frequency of use and / or loadings);
- insufficient time / resource to enable the identification of the issue and any significant combinations of issues (multi hazard interaction);
- ‘siloing’ different disciplines / failing to consider interactions (e.g. of drainage relative to the geotechnics); and
- inadequate attention to the investigation and descriptive, spatial and temporal record keeping for reported ‘issues’.

A tragic recent fatal landslide inquest brought together a nexus of multi-hazard issues includeing surface water; metastable slopes, and increasing demands on aging infrastructure (Photo 2).

Photo 2. Fatal landslide of metastable slope.

2.3 Foundations and Excavations

Problems can arise working near structures on variable or mixed ground where the differential movements may need detailed assessment.

A recent case involved an old masonry bridge which ‘broke its back’ when a quite limited trench was dug to about 3m depth some 8m away. Experience did not suggest a problem for such excavations. Only during the re-construction was most of the bridge abutment shown to be founded on rock, but the edge nearest the trench on clay.

The issues included:

- the pipeline subcontractor dug as and where instructed. He had no geotechnical expertise. He reasonably allowed support required for safety of the excavation only;
- he completed similar work only about 4 m from the first abutment without incident;

- following excavation about 8 m from the second abutment this settled and rotated and a large crack opened in the bridge;
- the site investigations showed soft ground near the bridge, but it was taken to be founded on competent rock or very stiff clay, in which case the trenching should not have caused collapse;
- the bridge owner had no records of the original foundations, but had experienced no prior issues, with a good track record of routine inspections;
- the very experienced main designer selected the alignment and saw no need for support to the bridge:
- the Principal Contractor, responsible for the temporary works, employed an experienced consultancy to supervise, for site health and safety and safe-work compliance, who again saw no need for support to the bridge; and
- investigations, even in the light of the failure, did not reveal the foundation anomaly. This was only found during excavations for the new foundations.

In essence the excavation could easily have been located further from the bridge. With more difficulty and cost, some structural support could have been provided. However none of six experienced parties foresaw the need. The more onerous excavation adjacent to the north abutment was successful. It was argued that the failure was thus not reasonably foreseeable – this is what insurance is for. However, the parties eventually settled for most of the cost of the rebuild through mediation, in relation to their varying perceptions of their exposure.

2.4 Quarries and mineworking

An interesting case arose recently with a conveyor system for a major mining operation. Movements between adjacent piers had to be restricted to a few mm. Unfortunately, there was a massive waste tip across part of the route. The conveyor was routed to the crest of the new embankment which was around 40 m high. The tip behind continued to be filled leading to small, but significant ongoing lateral and vertical movements of the crest. The mechanical requirements needed tight tolerances, in contrast to ground movements routinely managed in mining operations. Geotechnics was not a major consideration at the outset of a massive turnkey operation. The nexus of issues included:

- during the works, the owner raised an extensive tip of variable mine wastes;
- these fills were over some soft, very compressible wastes in settlement ponds;
- original construction details and design were not well established;
- initial remedial works included a buttress of variable mine waste but not compacted, to a suitable engineering specification;
- substantial settlements and movements ensued, but were not suitably monitored;
- up to 450 mm of lateral movement ensued over less than 2 months;
- ongoing movements of similar order continued at substantial rates

In the event these issues led to project termination and a very major dispute.

2.5 Waste containment

Waste and landfill projects frequently include significant geotechnical issues which sometimes go inadequately recognised when focus is more on environmental aspects. Some recent cases involve substantial slope stability and settlement issues. There continue to be significant failures of geosynthetic liners, often attributable to poor design and / or construction practices. Gallagher *et al.* (2016) discuss several examples..

Experience and knowledge has developed rapidly since the 1980s and 'geocontainment' is now a mature technology'. Numerous issues in the early, 'innovative' stages of development led to extensive guidance for design and specifications, together with procedures for a high level of construction quality assurance (CQA), now commonplace in highly regulated facilities.

In recent years we have investigated several failures of relatively small facilities for agricultural or other wastes including lagoons for anaerobic digester plants. One such lagoon was formed of geomembrane-lined earthen bunds of about 4.5 m height constructed at slopes of 1V:1H.Several failures occurred during construction (Photo 3), in the earthworks rather than the geomembrane lining system.

Photo 3. Slope failure in oversteep soil bund (exposed after removal of overlying geomembrane).

The nexus of inter-related issues included:

- inadequate ground investigation and soil characterisation;
- oversteep slope angles for the soils used (predominantly sandy silty clays);
- cursory/inadequate geotechnical design;
- lack of suitable earthworks specifications; supervision or construction quality assurance (CQA) of the earthworks;
- lack of adequate compaction;
- slope failures during construction were reconstructed with unsuitable fill;
- higher-than-anticipated groundwater levels and slope seepages were addressed by localised drainage; and
- apparently no recognition of the warning signs during construction leading to a systemic review of the design.

Creating 1:1 slopes of this height would require lime/cement stabilisation of the soils or geosynthetic reinforcement. Opportunities to intervene before and during construction were available and not taken. This was an example where some limited geotechnical input at an early stage could have ensured the right questions were asked to avoid subsequent, ultimately very expensive, problems.

3 DISCUSSION

Many forensics cases that we have encountered show a nexus of multiple causes. Of some 119 construction cases (updated since our 2017 paper), approximately half could be classified as essentially single issue. The others involved several key issues, the relative contributions of which were difficult to assess or agree.

Geotechnical Construction Cases	119	
Single Geotechnical Issue	61	51%
Multiple Geotechnical Issues	40	34%
Geotechnical plus other	13	11%
Geotechnical plus many other	5	4%

Table 1. Assessment of issues in some Geotechnical Construction Forensics Cases.

Study of the data shows the single-issue cases were commonly relatively straightforward. The 'multiple issue' cases were almost always complex, especially where there were several probable and other possible causes. A few cases proved enormously complex, perhaps disproportionately so. A relatively common and difficult class of problem occurs were there are significant issues of both design and construction, and where these may have combined to cause the defect.

Attention is increasingly being given to 'multi-hazards', i.e. situations where several hazards combine. A recent UN report (UNISDR 2017) defines three types of multi-hazard:

a) Trigger. Hazard A triggers Hazard B
b) Amplification. Hazard A amplifies Hazard B
c) Compound. Hazard A and B coincide in time and/or space to give worse outcome.

Whilst this is addressed to a wide range of 'disasters', it may be a useful in assessing geotechnical hazards and risks, which are included. Many of the 'nexus' cases we have identified could be classified as b) or c). It was the combination of several factors that became a significant issue.

Attention is also drawn to the importance of pro-active risk management, including appropriate monitoring and early warnings. There are too many cases where signs of impending problems were there to be seen at the time (and later by forensic investigators) or could have been found by appropriate monitoring or supervision. A lack of experienced geotechnical staff on site during works appears an increasing issue in places. We intend to look at this and some other grounds for concern in future studies.

The issues that continue to arise are mostly well-known to experienced geotechnical practitioners. Few would be classed as not reasonably foreseeable. The cases almost always involved little or no systematic identification or management of the ground-related risks and uncertainties in the light of knowledge that is, or could be, readily available i.e. failures to suitably engage experienced geotechnical specialists.

Geotechnical risks should be assessed at the outset and regularly re-evaluated: throughout the investigation and design; as the ground is opened up; and until works in the ground are complete; and sometimes thereafter.

We advocate a pro-active approach to Risk Management involving integration of the Geotechnical Risk Register (GRR) and Project Risk Register (PRR), with input from an experienced Geotechnical Adviser (GA) at the earliest appropriate stage and provision to review at key stages thereafter. We refer to the Register of Geotechnical Professionals, RoGEP (ICE, 2009), which has been in use in the UK for some years. (In the present context we intend equivalent experience, not necessarily registered.)

Of the 119 cases reviewed in Table 1, over 60% had no GA and it is reasonable to consider the geotechnical issues would have been identified had such a person been suitably involved. We have several cases where an element of the claim was '*failure to employ a suitably experienced Geotechnical Professional*, or suchlike. In the other 40% of cases the role of the GA was generally significant in helping to manage the geotechnical issues.

Consequence Classes (CC0-4) and Geotechnical Complexity Classes (GCC1-3) and the risk-based guidance proposed in the recent draft Eurocodes (PrEN 1990 and 1997, 2017) appear useful, perhaps particularly in promoting discussion on the hazards and consequences, and hence appropriate procedures and personnel for investigation, design, supervision and monitoring. It is important that the geotechnical thread is as continuous as possible, but also woven into the fabric of the project. This should assist the nexus of possible interactions being explored and pro-actively managed through the project.

4. CONCLUDING REMARKS

We conclude that many geotechnical forensics cases involve a nexus of interactions, rather than a single over-riding cause. It is often not so much the ground-related hazard, but more if or how this was suitably identified and managed. There may be a range of parties involved, with differing responsibilities and expertise, combined with a lack of clarity or direction with regard to the geotechnical issues or their interaction with other issues. This can make due resolution exceedingly complex, not least for clients and advisers dragged into extensive technical detail as to the relative contributions of 'possible or probable' causes. Notwithstanding contractual efforts to place ground risks with the Contractor, the asset owner/ultimate client is likely to find himself with a major headache if things go wrong.

Whilst finalising the text of this paper, the authors have noted the recently issued report of the 2017 Oroville Dam Spillway Incident, IFT (2018). This concluded, inter alia, that there was no single root cause of the incident, nor was there a simple chain of events leading ultimately to the necessity of the evacuation order. "*Rather, the* *incident was caused by a complex interaction of relatively common physical, human, organizational, and industry factors, starting with the design of the project and continuing until the incident… Challenging current assumptions on what constitutes best practice in our industry is overdue.”*

There is increasing interest and recognition of the inter-actions and inter-related nature of working with the ground. Many geotechnical assets are parts of complex infrastructure and are aging; yet their resilience is not well-understood or defined. As the depth of knowledge and quantity of data increase, it is ever more crucial to challenge ‘silos’ in our thinking, improve risk management and communication, and ensure a holistic approach, integrating geotechnical knowledge within the overall project.

It is important to re-affirm that the vast majority of construction works do identify and address the risks in the ground with ever-increasing success in economy and safety. Our comments are addressed to the small but significant number of problem cases that arise primarily because appropriate and available geotechnical expertise is not suitably engaged.

5 ACKNOWLEDGEMENTS

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