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Challenges in geotechnical design for infrastructure projects

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ABSTRACT: Modern infrastructure projects present a number of key challenges for the geotechnical engineering professional. Major influences in terms of uncertainty and risk, commercial drivers and sustainability are explored in the context of two case studies in South East Queensland: a large scale linear highway development and the remediation of a small but critical crib wall.

1 INTRODUCTION

As those involved in the industry would be intimately familiar with, geotechnical design presents many challenges. This can range from confirming the “known knowns”, to the expectation of identifying the “unknown unknowns”. Even where the geotechnical risk may be known, producing a safe and sustainable design can prove to be difficult. Conversely, identification of the unknown is obviously problematic, but nonetheless it often falls to the geotechnical professional to produce a solution.

This paper seeks to explore some of the major challenges facing geotechnical design on current infrastructure projects. An initial review of the common problems that projects often encounter is provided; with three key themes then examined in the context of two case studies, located in Southeast Queensland:

- A large scale linear highway infrastructure project
- A small scale retaining (crib) wall remediation

The two case studies show how similar challenges can occur at different scales, with varying risk profiles and presents example solutions as to how these can be addressed.

2 A REVIEW OF MAJOR CHALLENGES FACING CURRENT GEOTECHNICAL DESIGN

Throughout the development of geotechnical engineering over the last half century, the discipline has broadened to become increasingly interdisciplinary, encompassing not only soil mechanics but related disciplines such as geology, hydrogeology, seismology, civil, structural and environmental engineering (Mitchell and Kopman, 2013). The modern geotechnical professional is expected to provide solutions for increasingly complex structures, in an increasingly competitive industry and for increasingly complex criteria. Operating in such an environment, major challenges can be found in terms of creating a cost-effective, but technically rigorous solution. This challenge is reviewed in terms of three key influences: Uncertainty and risk, commercial drivers, sustainability.

2.1 *Uncertainty and risk*

Managing uncertainty and risk is, and always has been, a fundamental issue for geotechnical design. Natural variation in the sub-surface profile is both expected and yet a potential source of (costly) surprise. In Hoek and Palmieri’s address on geotechnical risks for large infrastructure projects (1998), they noted that unforeseen geological conditions and their associated geotechnical problems, are often a major contributor to project cost and schedule overruns. This is supported by studies such as Alhaby and Whyte (1994), which concluded that “90% of risk to projects originates from unforeseen ground conditions”. Re-search from Chapman and Marcetteau (2004) suggested that in the UK, approximately half of all construction delays are due to ground related issues and Paul et al. (2002) found that unforeseen ground conditions often result in increased project costs of 10% or more.

Whilst the issue of geotechnical uncertainty is a reasonably well-established concept, as new construction projects push the boundaries of engineering practice, the number and frequency of engineering failures is expected to continue to rise. This is in trend with the increased failure rates observed in the last few decades (Agaiby and Ahmed, 2016). It is further likely to be impacted by the effects of climate change, with increased unpredictability in terms of the frequency and intensity of weather events.

To mitigate uncertainty and risk in geotechnical engineering, one must ultimately fall back on the principle of investing in proper investigations. With the advancement of new technologies, geotechnical professionals can look to supplement traditional methods of investigation with additional sources of data, although care must be taken in terms of understanding the limitations of these new methods.

2.2 *Commercial drivers*

Commercial drivers have been identified as a key influence on geotechnical design. Whilst costs clearly impact on aspects such as the scale of the site investigation and the chosen design solution or the construction methodology; the contract, which determines the environment in which the project will operate, should also be considered a critical factor.

The trend for contractual arrangements, particularly on large infrastructure projects, is increasingly moving away from the traditional design – bid – build process, towards a design and construct (D&C) or de-sign-build (DB) format. This is particularly noticeable in terms of Public Private Partnership (PPP) engagements within Australia. Although this delivery method may have certain advantages, such as reducing the client or principal's risk and allowing for expedition of the construction process; it often creates challenges for the geotechnical design. Common is-sues include insufficient geotechnical investigation and risk assessment prior to award, followed by increased pressures on the geotechnical designer, post-award, to produce a design as quickly as possible to allow for foundation and earthworks to commence (Mclain et al. 2014). Both these issues can be considered to potentially increase the geotechnical risk pro-file of the project and must be managed accordingly.

2.3 *Sustainability*

With an increasing global focus on sustainability and environmental management, the construction and engineering industry must look at reducing environmental emissions, energy consumption and meeting stricter environmental regulations.

As geotechnical works are one of the most resource intensive elements within the infrastructure process, it provides the opportunity to significantly influence the overall sustainability outcomes of the project; particularly given its early position in the construction process (Misra and Basu, 2011).

In managing environmental concerns, traditional approaches such as material re-use through zoned embankments is still able to create a large impact. The application of new approaches or alternative solutions should, however, also be considered – with recent environmentally driven approaches (geotechnology) resulting in an increasing range of options. Examples include alternate material such as lignosulfonate for expansive soil stability (Dennis et al. 2018) and the transformation of traditionally waste materials into construction materials (Saride et al. 2010, Meegoda, 2011). A recent well publicised case in Australia is the installation of TonerPlas (an asphalt additive from plastic bags) in Melbourne (Tran and McIver. 2018). Advanced geotechnical solutions typically require both interdisciplinary and specialist knowledge (such as of geochemistry, contamination, hydrogeology or groundwater). As a result, it is important that the geotechnical professional achieves general knowledge of these fields to allow for successful technical interaction (Shackelford, 2005) in the implementation of new technologies.

3 CASE STUDY 1: LARGE HIGHWAY

The key influences of uncertainty, risk and sustainability are examined in the context of a large recent highway infrastructure project, including interaction with commercial drivers.

3.1 *Background*

The project, consisting of the construction of a new multilane road highway, is located within South East Queensland, through both green and brown field sites. The terrain and geology of the area can be considered challenging, varying from flat to highly mountainous, with interfacing tertiary and sedimentary units of different ages. This is underlain by a complex groundwater system, featuring high groundwater levels, perched aquifers and spring systems infiltrating through fractured rock. This profile is further punctuated by extensive areas of colluvium from remnant landslides. Given the complexity and frequent changes in geology, the alignment region can be considered to demonstrate a high level of uncertainty.

3.2 *Discussion*

Pre-award, due diligence had been given in terms of the site investigation – with extensive sub-surface investigation (boreholes, test-pits, mapping, exploratory pilot holes) undertaken on the concept route. However, following the tender design period, changes in the final alignment resulted in a component of the existing information becoming non site-specific. Therefore, while there was an understanding based on previous regional geological mapping in the area, that the alignment would be passing through potential landslide areas; there was a significant information gap in terms of the extent, depth, characteristics and behaviour of the colluvial deposits. These landslide zones were considered a major risk to the project, with significant implications in terms of potential construction costs and risks to safety and operations, should they become mobilised.

Additional investigations were undertaken as part of the design phase, however, due to difficulties in ac-cess and programming, the design needed to be progressed concurrently with the site investigation. Further, as the investigation was typically limited to within the project corridor, it was unable to address the full scale of the colluvial deposits, which were identified to extend beyond the project boundary.

To address the limits of the site investigation and the need for a greater understanding of the risk posed by the landslide hazard, the project explored alternative options of data collection in the form of spatial mapping using Light Detection and Ranging (Li-DAR) and Interferometric Synthetic Aperture Radar (InSAR) imagery.

The use of LiDar allowed for a high resolution terrain model to be developed for the risk area. In terms of landslide mapping, LiDar provided advantages over traditional aerial imagery in allowing for morphological features, that would typically be obscured by vegetation, to be identified with clear georeferenced points. LiDar was then coupled with the use of InSar, a satellite based geodetic technique which can map surface deformations (ground movements) to within 1 mm precision. When applied in the context of landslides, InSar can provide a temporal model showing displacement over time, thus providing clues as to landslide activity. For the project, InSar was available for a period of approximately four years, in the form of 23 images spanning from 2007 to 2011. Figure 1 demonstrates how movement points were overlaid on topography to provide a spatial reference of deformation.

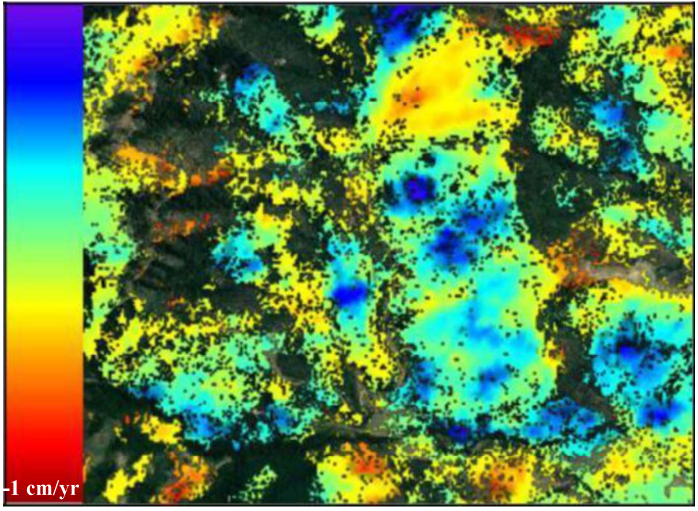

Figure 1. InSar image of project section.

Deriving contours from the recorded rate of motion, the average movement was found to be 0.2 cm/year. According to the AGS (2007) velocity classification, the area could therefore be identified as experiencing extremely slow movement (<15mm/year). It is noted that for this region, the extreme weather event of Cyclone Tasha (December 2010 – January 2011) fell within the data collection period. Unfortunately, due to a four-month gap between images, this event was unable to be included in the analysis. Theoretically, these records could have provided important information as to the behaviour of the colluvial deposits under increased pore water pressure conditions, hence when most at risk of failure.

Whilst both methods proved useful and cost-effective in defining the extent and behaviour of the depos-its, spatial mapping was limited in that it was unable to provide information on the material properties or depth of the colluvium, which was highly variable depending on origin and method of accumulation; the presence of underlying slip planes, which could provide a preferential failure planes; and the rapid changes in geological conditions experienced be-tween the interface of the tertiary and sedimentary units. For these aspects, the design needed to rely on the results of traditional intrusive methods.

Acknowledging the remaining uncertainty within the ground conditions, the project also adopted an observational approach (Peck, 1969); whereby the design was to be reviewed in construction, in conjunction with monitoring and prescribed displacement response levels (trigger limits). Level 1 inspection and testing (in accordance with AS 3798) was undertaken in conjunction with instrumentation and monitoring. Instrumentation included survey monuments, inclinometers and standpipe piezometers. The monitoring results were reviewed in accordance with the project specific action plan and associated trigger limits. The trigger limits were developed based on the monitoring response zone (green, amber and red) and the magnitude of movement, for each response zone, was determined with detailed analysis (utilising site-specific investigation data and spatial mapping results, where applicable).

This monitoring approach benefited the project by increasing excavation rates (increase in staged excavation depths, where applicable), monitoring of known areas of instability during construction and reducing construction risk and confirming key design assumptions.

Whilst not a new concept, recent advances in remote and continuous monitoring allow for improved oversight. The benefit of this approach on the project was two-fold: allowing for further de-risking of the design during the construction phase by requiring on-site confirmation of design assumptions and providing data for back-analysis as required; and allowing for the contractor to achieve a cost-effective solution, in ensuring treatments would not be applied unnecessarily.

3.3 *Sustainable outcomes*

Although the project proved to be fundamentally cost-driven, opportunities for applying sustainable solutions over traditional methods could still nonetheless be identified. A notable example of this was in the case of slope face protection and erosion control, where a steel wire, high tensile mesh, coupled with an erosion control blanket, was applied in preference to shotcrete. Despite the method being typically considered as outside of the client's minimum standards, improvements in material technology meant the design option was able to demonstrate the required technical capacity and design life; and as a result, was accepted as a viable solution.

Advantages noted for this design option included improved visual amenity, reduced up-front costs (expected to be greater than 30-50% cheaper compared to conventional shotcrete protection) and the ability for gentler slopes to be revegetated using hydro-mulch and native seeds, thereby reducing the requirement to import high quality topsoil.

Long-term, this protection measure is expected to reduce maintenance requirements and provide environmentally friendly, sustainable rehabilitation of the surrounding slopes.

Current observations (approximately two years post installation) of the installed green solution are positive and have shown significant vegetation growth and protection against surficial failures.

4 CASE STUDY 2: CRIB WALL

The three key issues of uncertainty and risk, contract and cost and designing for sustainability are examined in the context of a small-scale remediation project for an existing crib wall.

4.1 *Background*

The project consists of an existing crib wall, with a maximum height of approximately 4.5 m and total length of 70 m (for length of wall being assessed). The wall was initially constructed in the mid 1990's and surrounds three large reservoir tanks. The reservoir tanks are a key asset for water supply to a region of South East Queensland.

Following an initial condition assessment of the crib wall, the following key issues were noted:

- Decay of the concrete crib wall units due to carbonation induced reinforcement corrosion and concrete spalling of precast elements.
- Tree root jacking and dislodgement of crib wall units due to well established vegetation along the crest of the retaining wall.
- Piping erosion through the variable backfill, consisting of a mixture of cohesive and non-cohesive material, largely non-compliant with Australian Standards (AS4678) and current design guide-lines.
- Voids up to 900 mm deep in between crib wall units.
- Absence of formalised surface drainage along the crest of the retaining wall.
- State road within close proximity of the wall crest (within 15 m).
- Toe of the retaining wall a maximum 3 m offset from the reservoir tanks.

Figure 2 demonstrates the corrosion induced spalling of the concrete crib wall units. This was a frequent occurrence.

Figure 2. Corrosion induce spalling of concrete crib wall units.

The characteristics observed during the condition assessment can be linked to similar traits as those identified in the collapse of a retaining wall at Harris Park Train Station, Sydney (Transport Sydney Trains, 2013), which was initiated by a rotational slump in a very wet compacted sand backfill. The Harris Park Station wall failed rapidly due to a complex combination of root causes. Similar defective traits between the two crib walls included:

- Non-compliant backfill material – non-compliant with current design standards and consisted of compacted sand rather than the recommended free drainage gravel.
- Poor vegetation control – including vegetation growing directly out of the wall face.

4.2 *Management of uncertainty and risk*

To best identify and mitigate uncertainty and risk for the detailed design phase, a comprehensive options assessment was undertaken. The following crib wall remediation options were evaluated as part of this assessment:

- Shotcrete protection – consisting of a sprayed concrete mix with reinforcement mesh and soil nails to fix the shotcrete facing and provide adequate global stability.
- High tensile steel mesh – combination of UV stabilised erosion control mat to prevent further erosion of the backfill material and apply sufficient confining pressure to the crib wall face, providing structural support. Due to the decaying crib wall units, this mitigation option would require fibrecrete protection prior to the application of the high tensile steel mesh.
- Remove and replace existing crib wall backfill – removal of the crib wall facing units and excavation of the non-compliant backfill material. Short-term temporary stability measures would be re-quired due to the proximity of the State road, within 15 m of the wall crest.
- Formalisation of surface drainage to minimise in-filtration into the backfill material was adopted for all remediation design options.

A framework to evaluate the proposed crib wall remediation options was developed. The evaluation criteria consisted of several themes including specific construction risks, construction safety, complexity, quality, operations and maintenance, environment, programme and cost. For each theme, an objective and associated performance measures was specified. Objectives included volume of demolition / excavation (construction risk), potential damage to the existing crib wall (construction safety), proven technology / methodology (complexity), durability (quality), maintenance effort (operations and maintenance), overall schedule and total timeframe (programme) and construction cost (cost). Further, in consultation with the client, a weighting to each objective was ap-plied to ensure that each item was appropriately considered. For each remediation option, a score to measure the objective and performance measure was equated. This included a theme and objective weighting. The scoring system ranked each item from "Against Objective" through to "Exceeds Objective". If the performance measure failed, or was against the objective, a negative score was given (maximum negative score of -5). Similarly, if the performance measure partially met or exceeded the objective, then a positive score was given (maximum positive score of 3). A total overall score and ranking could then be used to evaluate each remediation option.

Following the engineering review and condition assessment, the shotcrete facing protection and soil nail fixings (also for global stability) was deemed most appropriate, based on the derived evaluation criteria.

4.3 *Contract and cost*

Pre-award of the detailed design phase for the crib wall remediation, geotechnical investigations were undertaken by others. The investigation was limited to eleven (11) hand auger boreholes drilled at the lower section of the retaining wall. The boreholes were drilled horizontally between 1 m to 2 m from the face of the crib wall. Disturbed samples were retrieved from the crib wall backfill for laboratory testing (particle size distribution, Atterberg limits and linear shrinkage). All boreholes were terminated in fill and the backfill comprised of a mixture of free draining fill (sand or sandy gravel) and cohesive fill (low plasticity clay). The presence of cohesive material can potentially be attributed to the absence of a separation layer between the backfill and in situ fill / natural ground, which may have resulted in migration of fines within the backfill layer.

A further investigation consisting of two boreholes, beyond the crib wall backfill, identified the presence fill and residual soils, overlying extremely weathered sandstone.

Post-award, no additional investigation budget was allocated. As such the design was developed with hold points documented in the construction specification to confirm the backfill material type and thick-ness. Minimum bond lengths were documented on the Issue for Construction (IFC) drawings, in conjunction with estimated total soil nail lengths. Design soil nail lengths were based on the anticipated ground conditions. To ensure the minimum bond length was achieved within the in situ soils and weathered sandstone behind the backfill material, full-time construction supervision by a suitably qualified design representative was undertaken. Soil nail lengths were varied on site to match the actual ground conditions. Acceptance testing (1.5 times the working load) of selected soil nails was also undertaken.

This method of investigation and construction supervision allowed confirmation of the as-built soil nail bond length within the in situ material. This proved a successful method for managing the limited site specific information and the design outcomes.

4.4 *Sustainable outcomes*

Providing a sustainable solution was a key driver for the client. The adopted remediation solution for the crib wall, shotcrete surface protection with soil nail fixings, has significant sustainability benefits with regards to minimising negative environmental and societal impacts. In the short-term, this solution limited the impact to road users and limited the removal of spoil and site waste. By leaving the existing crib wall and associated backfill in place, the haulage of waste from site was minimal, reducing the truck movements to an appropriate disposal facility.

In the long-term, the solution provided the client with a remediation measure exceeding the requested 40 year design life (shotcrete solution and encapsulated soil nails are generally accepted for 100 year design life applications), whilst minimising the maintenance requirements.

The development of this solution incorporated specialist knowledge from material scientists, to inspect and provide advice on the decaying nature of the concrete crib wall units, and geotechnical engineers and engineering geologists to analyse and design the retaining wall solution. This successful interaction of technical expertise was a key factor in providing the client with a sustainable remediation solution, both in the short and long-term.

5 CONCLUSION

Providing solutions to problems is intuitively what engineers are trained to do. Consistently providing safe and sustainable solutions, however, continue to provide a challenge to even the most experienced engineer. Two case studies have been presented and related back to three challenges we face as geotechnical engineers in terms of uncertainty and risk, commercial drivers and sustainability.

Experience on the large scale linear highway infra-structure project demonstrated that adopting alternatives to the traditional methods can be beneficial to all parties and allow for technically robust, sustainable and cost-effective solutions. Further, geotechnical uncertainty and cost pressures can be assisted by use of the observational approach, which when applied with care, can provide a safer and more economic out-come, particularly when coupled with modern sensory techniques.

The small scale retaining wall remediation project illustrates that the stature of the project does not dictate the challenges we face as designers. Rather, the challenges broadly remain the same. By adopting an innovative approach to the remediation project, a sustainable solution was developed to meet the client's requirements and cover the technical and commercial challenges of the project.

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