Applications of Ground Improvement to Mitigate Geotechnical Risk

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Abstract

In this paper, a number of infrastructure applications of ground improvement techniques used to address risk associated with construction over poor ground are discussed. In each case, the key design issues and associated risks are described, and the ground improvement methods used described. This paper outlines the projects, discusses geotechnical risks associated with soft ground, presents details of the ground improvement works, and discusses ground improvement selection, design, and construction monitoring. Examples from projects in Asia and Australia of how requirements for cost and programme savings have driven innovations in design and new developments in ground improvement are discussed. Established approaches to managing geotechnical risks on projects are briefly reviewed.

Keywords: Soft ground, ground improvement, monitoring, risk assessment, case history.

1. INTRODUCTION

Ground improvement techniques applied in geotechnical engineering practice to mitigate risk are tools used by the geotechnical engineer for "fixing" the problems of poor ground so that performance risks are acceptable.

By use of imaginative techniques, the engineer forces the ground to adapt to the project's requirements, by altering its natural state, instead of having to alter the design in response to the ground's natural limitations. In this paper, the critical issues, and associated risks affecting the feasibility of the main ground improvement methods are evaluated from both design and construction points of view.

The many types of available ground improvement systems provide the practicing engineer with solutions to today's ever increasingly complex and challenging project requirements. However, the selection of an appropriate and cost- effective ground improvement solution for a specific project requires the engineer to be familiar with the advantages and limitations of each of these systems. The engineer must also understand the applicability of the ground improvement techniques within the constraints of the existing site conditions and time available for construction. Selection of an appropriate and cost-effective design also requires a systematic assessment of the numerous options available.

2. WHAT IS GEOTECHNICAL RISK?

The geotechnical risks that can impact upon projects result from a range of hazards associated with geological conditions, geological processes, and the geo-engineering process. For example, areas of compressible ground beneath a road embankment or facility identified during pre-feasibility or route selection studies will pose one type of hazard. A management decision to limit the extent of a site investigation to save money or time, will pose another type of hazard. A systematic assessment of the nature and the source of the various hazards that can affect projects may be used to differentiate the types of geotechnical risk.

Baynes (2010) also discusses the human factor and finds that total geotechnical risk is a combination of the technical conditions and the competence of the project staff. In fact, "the project staff may actually be the largest source [of risk]." Baynes emphasizes the need to educate and train project staff to "manage and mitigate the geotechnical risks, rather than generate them." He also stresses the need to manage geotechnical risk throughout the project's life cycle, specifically identifying the procurement phase as a point where "inadequate understanding of the importance of ground conditions results in poor acquisition… [that] leads to claims based on contractually unforeseen ground conditions". Risks such as business interruption and financial loss can usually be reversed – at a cost, but a negative impact on reliability, brand reputation, market share or goodwill may be permanent. Thus, risk mitigation for geotechnical professionals involves using trained and experienced staff prepared with the right processes, plans and contingencies to tackle complex risks and unpredictable events.

2.1. International development of risk management

Decades ago, many owners refused to accept risk of any kind and they tried to transfer all the risk to the contractors using abusive contract language, such as disclaimers. They would intentionally not disclose important subsurface data. Claims and lawsuits resulted and our industry, especially in the United States, developed a bad reputation for its ability to build tunnels. The U.S. National Committee on Tunneling Technology (USNC/TT), commissioned a Blue-Ribbon panel in the 1970s, to address these issues. Their report, Better Contracting for Underground Construction (USNC/TT 1974), became a new standard on which to judge construction contracts for underground projects. It still took a long time for owners to accept the fact that they could not pass all risk to the contractor. Slowly the underground construction industry came to recognise the need for risk sharing, and numerous conferences and papers were published on the subject.

The use of Geotechnical Baseline Reports (GBRs) for contractually defining anticipated ground conditions has now become a widely accepted practice in the tunnelling industry in the US and has been adopted on ground improvement projects in Singapore, USA and Australia more recently (Dwyer et al, 2010). The basic premise of a contractual geotechnical baseline has been well developed and communicated to the industry in the Underground Technology Research Council's guideline document titled Geotechnical Baseline Reports for Underground Construction (UTRC, 1997) and in the updated version of this document (UTRC, 2007), as well as being adapted to address risk associated with ground conditions or other ground related projects.

2.2. Risk-based geotechnical design

In the US, The Federal Highway Administration (FHWA), an agency within the U.S. Department of Transportation, introduced risk-based geotechnical design in 1987 when it published the Geotechnical Risk Analysis User's Guide (Baecher, 1987). This document moved geotechnical design on federally-funded highway projects away from a set of "conservative factors of safety" and toward modelling uncertainty on a project-specific basis via a statistically determined reliability index. This shift was necessary because a "fixed factor of safety implies a different likelihood of failure" in each project and creates a situation where "the overall factor of safety in a design is unknown" (Baecher, 1987). Baecher's work assumed that the project would be delivered using design-bid-build (DBB) project delivery and the data used as input for the risk-based design would be based on a thorough program of geotechnical investigation, testing, and analysis.

The Australian mining and geotechnical industry began to adopt a risk management approach to design in the mid-1980s and to support it with a range of research and development initiatives and guidance material. The identification of hazards and the need to then reduce risk associated with these hazards to acceptable levels has been a major driver of innovation.

An Australian study of the implications of inadequate site investigations agreed with Baecher's assertion regarding communicating geotechnical uncertainty and recommended that geotechnical uncertainty be expressed using statistical measures such as confidence limits. Jaksa (2002) argues that doing so permits "any other engineer utilising these values, as well as the client, to appreciate the uncertainty associated with the parameters and, hence, appropriately account for them in the design process." The ability to understand the amount of as-designed geotechnical risk is one key to effectively managing that risk after award.

However, geotechnical risk management is more than the use of sophisticated statistical models to quantify the risk in probabilistic terms. It must be continually evaluated as an integral part of the project development decision- making process (Baecher, 1987; Baynes, 2010). Historically, literature was written in the DBB context where the procurement was based on a completed geotechnical design based on subsurface investigation. The issue of subsurface risk gains focus when the geotechnical investigation moves from being a condition precedent to design- bid-build construction contract award, to more recent practice in Australia, where geotechnical data is often partially procured after award of a design-construct contract.

3. GROUND IMPROVEMENT IN SOFT SOIL

Functions of ground improvement in soft soil include:

- To increase the bearing capacity
- control deformations and accelerate consolidation
- provide lateral stability
- form seepage cut-off and environmental control
- increase resistance to liquefaction.

These functions can be accomplished by modifying the character of the ground, with or without the addition of foreign material. Improving the ground at the surface is usually easily accomplished and relatively inexpensive. At depth, the task becomes more difficult, usually requiring more rigorous analyses and the use of specialised equipment and construction procedures (Hewitt & Munfakh, 2006).

3.1. Design and construction

The common emphasis on accelerated project delivery, driven by project owners, creates an environment where the owner's engineers may be forced to focus on expediting the procurement process rather than fully developing the project's geotechnical requirements. This includes evaluating how much of the geotechnical investigation should be done by the design-builder after contract award. The decision on geotechnical investigation has several ramifications, including the level of liability for the ground conditions that can be transferred along with the geotechnical investigation and design responsibility for the foundation/subsurface design.

3.2. Design process for ground improvement

For ground improvement projects, the design process begins by collecting information about the proposed facility, including the applied loading conditions and performance expectations. Site characterisation studies provide information about site development history, topography, surface drainage, and subsurface information such as stratigraphy, water content, plasticity, organic content, strength, and compressibility of site soils. A phased approach to site characterisation may be appropriate, particularly for large or complex projects.

Flow charts for design and construction of ground improvement involving reinforcement or chemical treatment have been presented by Japan's Coastal Development Institute of Technology (CDIT 2002) and O'Riordan & Seaman (1993) which outline processes to assist in selection of construction methods. Usually a cost comparison between the various methods which are technically feasible will be required by an engineer throughout the design. Project phases normally involve: (1) information collection, (2) analysis and design, (3) contractor procurement, and (4) construction with continuous quality control and quality assurance.

4. SOFT GROUND IMPROVEMENT SELECTION

The selection of a soft ground improvement method to address geotechnical risk is a function usually provided by the design engineer. Owing to the proliferation of available techniques on the market, the many benefits associated with each method and the rapidly developing nature of the ground improvement field, selection of the most appropriate method for a specific project is not an easy task. Selection is best carried out through a thorough evaluation of many factors, and with extensive reliance on intuition and experience, so that the intended outcomes are achieved.

The key factors affecting the selection of a ground improvement method include:

- the ground
- the groundwater
- specification requirements
- construction considerations including: schedule, materials, accessibility, right-of-way, equipment and labour
- environmental and sustainability concerns
- durability, maintenance and operational requirements
- contracting, politics and tradition
- cost/ value for money.

4.1. The ground

The characteristics of the soil have a major impact on the effectiveness of the ground improvement technique adopted. Densification and reinforcement techniques, for instance, rely heavily on the internal friction between the soil particles, or the friction along the soil-reinforcement interface. As such, these methods are suitable for use with frictional soils such as sands and gravels. Some reinforcement methods (stone columns) and consolidation methods (preloading and vacuum consolidation) are suitable for use with fine cohesive soils. Strain compatibility is another factor affecting the design. When the ground is reinforced with extensible elements such as geotextiles, the strain required to mobilise the full strength of the reinforcing elements is much larger than that needed to mobilise the full strength of the soil. Therefore, large internal deformations usually occur, and the soil design parameters are measured at large strains (residual strength). Obviously, these systems are less compatible with soils of relatively low residual strength.

4.2. Groundwater

The level of groundwater and the degree of saturation of the soil affect many techniques. In the densification method, micro-liquefaction is induced in saturated soils below the groundwater table. Groundwater is also needed for ground freezing, or biotechnical stabilisation, to be effective. On the other hand, a high groundwater level may have a damaging effect on certain methods of ground improvement, such as soil nailing and the use of foam for weight reduction.

4.3. Construction considerations

Schedule, materials availability, site accessibility, equipment and labour requirements are important factors affecting the selection of a ground improvement technique. Where preloading and wick drains are used, and to a lesser degree with lime stabilisation, time is of paramount importance. When the site is inaccessible to heavy equipment, such as in rough mountainous terrain or in soft ground, a method that can be implemented with a minimum of equipment, such as geotextile reinforcement, is preferred. On the other hand, labour-intensive systems, such as vacuum consolidation and biotechnical stabilisation, are usually not cost-effective in areas with labour shortages or strong labour union requirements. When low headroom does not allow the use of certain equipment, such as those required for deep soil mixing or stone column installation, methods that can be implemented remotely, such as the various grouting or specialist low-headroom equipment techniques, are preferred. Right-of-way and easement requirements may affect the feasibility of certain methods like mechanical stabilisation and soil nailing. The impact of construction on nearby facilities is an important factor in the selection. The use of the economical method of dynamic compaction, for instance, is often precluded because of its potential impact on existing structures and utilities.

Materials availability is an important factor in the selection of the preferred technique. When fill material is abundant, preloading is a very cost-effective method of ground improvement. If the required amount of surcharge material is not available within a short hauling distance, an alternative preloading scheme, such as vacuum consolidation, can be used. If industrial by-products such as fly ash, kiln dust or slag are available in large quantities, their use for enhancing lime stabilisation, or for weight reduction, may be cost-effective, as may be the use of waste materials such as shredded tyres or wood chips.

4.4. Environmental and sustainability concerns

Sensitivity to potential environmental impacts is a key factor in the selection process. For contaminated sites, methods involving the discharge of large quantities of water, such as vibro-replacement, stone columns, vacuum consolidation and wick drains are avoided. On the other hand, methods that preserve the environment, such as geotextile reinforcement and biotechnical stabilisation, are welcome in environmentally-sensitive areas. Methods that allow construction of embankments with vertical faces (mechanical stabilisation) are preferred in or near wetland areas.

4.5. Durability, maintenance and operational requirements

The durability of materials used in ground improvement is a strong governing factor, particularly where the ground is exposed to heavy weathering elements. The use of metallic reinforcements, for instance, is avoided near stray currents or in highly corrosive soils. When geosynthetics are used, they require protection from the effects of heat, chemicals and exposure to ultraviolet light. Although all geosynthetic materials degrade upon exposure to ultraviolet radiation, their reaction to other durability effects varies. This should be considered in the selection process. For instance, although polyester is susceptible to hydrolysis and loss of strength when in contact with water, polyethylene and polypropylene are not affected. However, the latter materials do tend to break down upon thermal oxidation in the presence of heat and oxygen, contrary to the behaviour of polyester.

The effects of wet-dry and freeze-thaw cycles are particularly important in chemical stabilisation. Extreme weather conditions, such as dry heat or ice, may have damaging consequences on biotechnical stabilisation. Thus, this technique should not be selected in areas with arid or frigid climates, and where there is a shortage of maintenance staff to take care of the foliage.

The selection process is also influenced by the operational requirements of the facility. If there is ample time before the facility is operational, a rolling surcharge can be used. If the available time is relatively short, vertical drains and/or vacuum consolidation may be selected. To further reduce the ground improvement time, stone columns can be used, but at a relative cost penalty.

4.6. Cost and value for money

Value for money has been defined by others as “the most cost effective way to reliably accomplish a function meeting the users’ needs, desires and expectations.”, and “…a function of much more than the initial cost”. This is usually the most important factor in the selection process. If all other factors are satisfied, cost becomes the governing parameter. When analysing the cost, the long-term behaviour of the system and the required maintenance cost should be considered. A scheme with the lowest construction cost may not necessarily be the most economical, if it will require substantial maintenance and repair costs in the future. When different schemes are close to each other in cost, alternative ground improvement methods may be specified.

5. CASE STUDIES

The following case studies describe the use of ground improvement techniques on a single project to mitigate risk. The factors affecting the selection of the multiple schemes are also discussed for the following cases where the ground improvement has been used to achieve design requirements, and where the drive for cost and programme savings has led to innovations in ground improvement:

- the support of road and industrial pavements
- deep excavations
- groundwater control
- the stabilisation of slopes.

5.1. Geotechnical monitoring system for soft ground treatment on Pacific Highway upgrade, NSW Australia

The Woolgoolga to Ballina (W2B) project will upgrade about 155 kilometres of highway. The project starts about six kilometres north of Woolgoolga (north of Coffs Harbour) and ends approximately six kilometres south of Ballina. Roads and Maritime Services (RMS) engaged Pacific Complete, comprising Laing O'Rourke and WSP (formerly Parsons Brinckerhoff), to deliver the project in partnership with RMS. As with many other sections of the Pacific Highway, the design required embankments on soft ground to meet pavement performance criteria, and address risks such as the potential impact of the new works on existing infrastructure (Hewitt et al, 2012).

One of the biggest challenges on the W2B project is constructing more than 25km of infrastructure over soft ground within 1 to 2 years. For monitoring the performance of soft ground treatments on the W2B project, an innovative monitoring system was adopted. During construction, short term slope stability and settlement were monitored by about 1500 instruments recording up to 10 million measurements. This enabled the team to maintain slope stability with early preventative action and ensure that projected long term settlements are within acceptable limits.

Standard approaches, adopted by others on adjacent sections of the highway, would have produced up to 80000 data files requiring manual handling. To process the data efficiently and limit the potential for manual handling errors, Pacific Complete developed an Instrumentation and Monitoring (I&M) system using its project integration platform. The system automatically warehouses data on the project's servers and provides an integrated solution comprising of 'live' instrumentation that transmits data in real time directly to the dashboard, where the data is monitored against agreed project parameters and its GIS extension. Automatic alerts give warnings when potential problems are identified, which are transmitted to Pacific Complete to ensure immediate responses. In addition to providing high information availability, transparency, and reliability, this system is expected to realise savings of $A2.5 million in manual information handling costs alone (Zhang, 2017). The benefits of this I&M system included:

- real-time data processing
- electronic document management
- automatic integration with GIS, and
- specific user interfaces which provided: chainages, instrument type and locations, lateral displacement plots, settlement plots (predicted and measured) in longitudinal sections, ratios of lateral to vertical displacement and fill height plots, pore pressure plots and existing road/structure movement plots.

Additional opportunities realised through use of the system included:

- Removal of stabilising berm requirements
- Removal of high strength geotextile requirements for some sections
- Rationalisation of high strength geotextile requirements in Maclean Interchange
- General reduction of waiting periods for early works surcharged embankments
- Reduction of waiting periods for early works surcharged embankments through verification based on review of monitoring data.

5.2. Wharf Structure, USA

The expansion of the Norfolk International Terminal in Norfolk, Virginia, in the United States, involved the construction of a wharf structure and a storage area on land that had been previously reclaimed using dredged material placed over soft clays (Munfakh & Wyllie, 2000). Figure 1 illustrates a cross-section of the wharf structure and the storage area behind it. The 3 horizontal to 1 vertical slope under the wharf structure was established to minimise the width of the pile-supported platform, and to avoid encroachment on existing facilities behind the wharf, including a sewer outfall pipe that could not be relocated.

As the new facility would place additional loads on the in situ soils, and the soft compressible soils were too deep to be practically or economically removed, ground improvement was needed at the site to: allow dredging of the soil to the required slope, minimise the soil's long-term settlement and down-drag impact on the piles, and reduce the lateral earth pressure on the bulkhead. Selection of an appropriate ground improvement method was a challenge. After evaluating the many selection factors discussed above, and to satisfy economical, operational, environmental and construction-related requirements, a combination of ground improvement techniques was adopted.

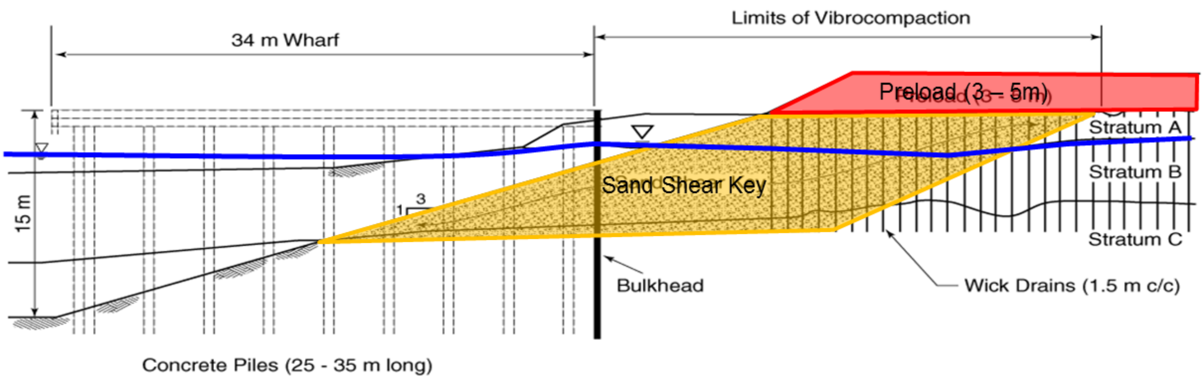

Figure 1. Cross-section of wharf at the Norfolk International Terminal, USA

Preloading of the soft clay was the most economical solution. However, due to operational requirements, the wharf structure was positioned partly on land and partly over water. Since placing fill in the water was prohibited by environmental restrictions, the surcharge load had to be placed on the land side of the bulkhead. However, this preloading configuration was not adequate to achieve the minimum shear strength required for the stability of the dredged slope and the design of the bulkhead behind the structure. To accomplish that, a large enough section of the soft soil at both sides of the bulkhead was removed and replaced with sand forming a sand shear key. Preloading of the soft soil on land was still needed to allow safe excavation of that section for construction of the sand shear key. Furthermore, because the sand shear key material was placed underwater, it had a relative density of only 10 to 40%, which was substantially lower than the 70% relative density used in the design. To achieve the required relative density, the shear key material was densified using vibro-compaction.

Preloading was accomplished by placing 3 to 5 m of surcharge fill. To accelerate consolidation, wick drains were installed to depths of 10 to 17 m, at a spacing of 1.5 m centres, in a triangular array. The preloading program increased the shear strength of the soft clay from 10 kPa to up to 75 kPa, with over 90% of the long-term settlement completed within the 9-month construction period. Vibro-compaction was achieved with an electric vibroprobe, using water jetting and vibration. A probe spacing of 3 m was applied and sand was added during compaction to achieve the required 70% relative density.

The selection of ground improvement techniques to mitigate project risk was controlled by many factors including: the ground conditions, right-of-way limitations, operational requirements, environmental restrictions, construction issues, time constraints, and cost.

5.3. Highway Embankment, Korea

As part of negotiating an agreement for purchase of a new 80 km expressway the author conducted a due diligence review of the asset, which included several sections of embankment located on soft ground. The objectives of the work were to develop an engineering assessment of the asset, and to assess potential engineering liabilities with respect to Korean and international guidelines and our client's own risk position. This included identifying potential areas of concern and areas of omission or deficiency in the adopted design approach. Ground improvement methods included wick drains and sand compaction piles (SCP) (Figure 2).

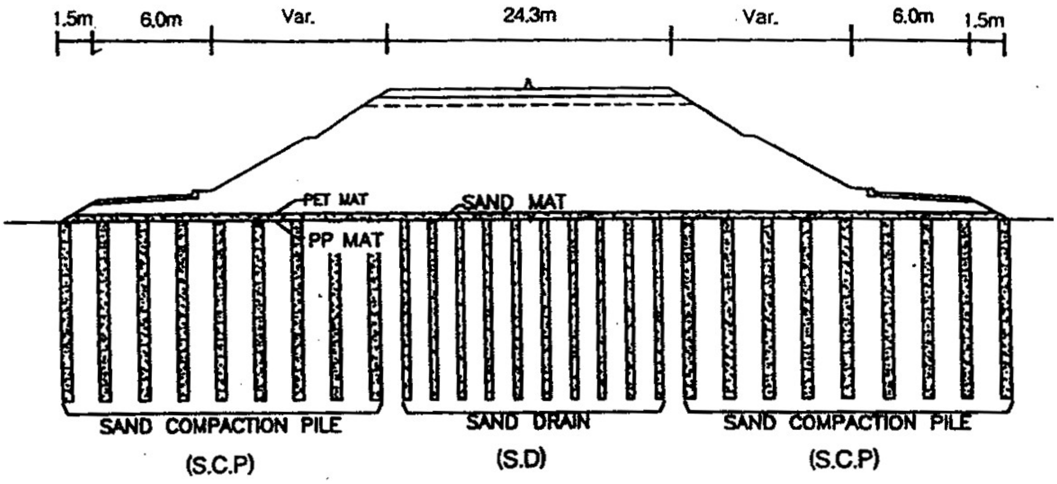

Figure 2. Cross-section of embankment with sand drain and sand compaction pile in soft ground

Figure 3. Bridge abutment settlement

Figure 4. Remedial works at abutment

Evidence of settlement was found at the abutments and approach sections to the bridges, where located on compressible ground (see Figures 3 & 4). The observed maximum settlement was up to 0.2 m and residual settlement of up to 0.1m is expected.

There was no evidence to indicate that experience from previous embankment construction on or near to the site, or trial embankment information, had been included in the design. Review of the design revealed that pre-consolidation of the alluvial soils by surcharge on the road embankment was not achieved over several sections on the route. The transition zones between the settling alluvium/silts and rigidly supported bridge structures will likely require substantial maintenance. It also appears paving has commenced prior to the required settlement occurring, which may result in unacceptable distortion of asphalt concrete pavements, and the need to "top-up" the transition zone.

In this case design allowances to address creep issues were not addressed in design, and it appears stress history or over-consolidation effects were not addressed rigorously. Ongoing maintenance will be required in soft ground areas, especially at bridge approaches and fixed points such as piled bridges and culverts.

5.4. Marina Coastal Expressway, Singapore

Adoption of the Geotechnical Baseline Report (GBR) concept and smart use of ground improvement on Singapore's Marina Coastal Expressway (MCE) has enabled faster, more efficient construction while meeting tough safety and performance requirements. Building the 5-km dual five lane expressway was one of Singapore's most technically challenging projects thus far, in difficult soil conditions in compressible marine clay up to 60 metres deep (Rozek et al, 2008). The city state has become famous for cut and cover tunnels in the soft ground close to its reclaimed shoreline. However, with a width of 60m, this project was considerably bigger and more challenging than anything that's been done previously (Figure 5). Sophisticated and robust engineering methods were required to prevent undesirable ground movement and reduce base heave.

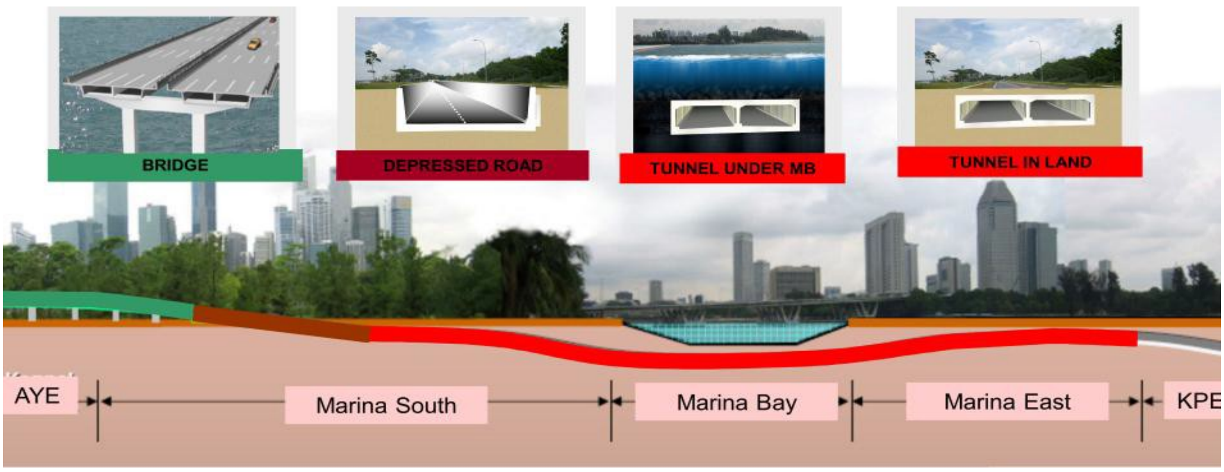

Figure 5. Longitudinal profile of Singapore's Marina Coastal Expressway

The GBR concept allowed contractors to review conventional construction methods and develop more efficient alternatives that have enabled nearly 3km of tunnel to be delivered safely, with cost and time savings. For the tunnel under Marina South/ Marina Bay, examination of the technical performance of deep cement mixing (DCM), instead of jet grout ground improvement provided an opportunity to save cost and add value.
The contractor and their consultants examined the technical performance of both options and found that DCM was more effective. Jet grouting involves drilling into the ground and then injecting cement

grout at high pressure so that it mixes with the surrounding ground. Following a carefully designed pattern, jet grout 'columns' are joined up to form a continuous layer of improved ground. However, on MCE the slender drill strings used for jet grouting would be up to 25m long, making them liable to deviation from their designed path. This presented a risk that grout would not penetrate evenly, resulting in localised weaknesses. DCM uses augers to churn cement slurry into the ground. The larger diameter and resulting stiffness of the auger guaranteed better accuracy - therefore superior quality ground improvement and reduced risk. The DCM base grout was installed to depths of up to 23m below ground level, to form a 9m to 10m deep "strut" below the twin cell box tunnel under Marina Bay which limits lateral deflection of the retaining walls.

Singapore's construction safety culture has been shaped by the sudden and fatal collapse of a cut and cover tunnel in similar ground conditions at Nicoll Highway in 2004. Today, Singapore is managing underground risk by working collaboratively with designers and contractors to characterise the ground as effectively as is practical. By taking a risk-based approach to underground uncertainty in construction, the country is effectively allocating and managing risks. Its well-developed geotechnical interpretive baseline reports and contractor collaboration are improving certainty, responsible design and construction, and safety in project delivery.

5.5. River crossing on Epping to Chatswood Rail Line, Sydney, Australia

One of the significant challenges was a cut and cover crossing of the Lane Cove River in Sydney. The crossing, in a National Park, was used to construct the project's twin tunnels under the Lane Cove River. The 23m deep cut and cover tunnel, was constructed using dewatered cofferdams in two stages enabling the river to flow at all times (Figure 6). During geotechnical and hydrogeological studies, a significant vertical joint swarm and a horizontal transmissive feature at about 5m to 15m below top of rock were identified. These features, associated with typical valley bulging features in the Sydney Basin, could have had a major impact on design and construction of both the river crossing and the adjacent driven tunnel sections, unless ground improvement was adopted.

Ground treatment, using curtain grouting, was used to extend the perimeter coffer dam wall below the sheet piling and to limit inflows to each of the coffer dams to about 20L/s. Ground improvement using cement grout targeted the joint swarm and horizontal transmissive feature where water pressure tests indicated extremely high permeability results of over 100 Lugeon units. Grouting reduced the rock permeability to between 1 and 5 Lugeon units by adopting the correct cementitious materials, pumping to relatively high pressures, and orienting grout holes to intersect the more transmissive bedding horizons and near vertical joints, thus addressing inflow criteria at the river crossing, and permitting safe excavation

Figure 6. High-pressure grouting permitted safe excavation at Lane Cove River crossing

6. CONCLUSIONS

The successful application of ground improvement is influenced by many technical issues related to the characteristics of the ground, the materials added to the ground and their interaction. Other technical issues affecting performance are subject to the equipment and procedures used, the skills of the operator, and external factors, such as weather and proximity to existing structures. Technical, practical, economical, contractual and political factors affect the selection of a ground improvement for a specific site. The factors discussed in this paper reflect the diversity of the ground improvement techniques available on the market, and the complexity facing the design engineer in the attempt to select the most appropriate method, or combination of methods, to be applied to each project to address ground-related risks. The following general conclusions can be drawn:

- the use of ground improvement in soft ground has clear advantages over conventional construction techniques and, sometimes, is necessary to make building of certain projects feasible and/or economical
- the application of ground improvement techniques is almost a routine event on today's underground engineering projects in soft ground
- one trend that will encourage adoption of ground improvement techniques to better suit a project's needs is the use of performance specifications, rather than process or product specifications
- although ground improvement is still considered a novelty by some engineers and its applications are based, to a certain extent, on intuition and experience, the subject is rapidly evolving into a full-fledged area of geotechnical engineering with established analytical procedures, detailed construction specifications, and documented, monitored performance.
- geotechnical risk can be mitigated by working collaboratively with designers and contractors to characterise the ground as effectively as is practical. Risk can be managed by performing extensive site investigation, geotechnical modelling and analysis in the preparation of tender documents, and by taking a risk-based approach to address uncertainty associated with construction in poor ground.

The case histories presented here demonstrate the effectiveness of ground treatment measures for timely project delivery, meeting serviceability requirements and addressing geotechnical risks associated with construction on soft/ compressible ground. The ground treatment methods adopted were varied to match factors such as ground type, embankment heights, thickness of soft or loose deposits, rock mass defects and proximity of adjacent earthworks and structures. With the increasing size, scope and complexity of ground improvement projects, and continuing drive for cost and programme savings, it is important that geotechnical advisors, with appropriate knowledge and experience of ground improvement techniques, are involved at an early stage to assist in specifying the relevant site investigation and performance criteria for the anticipated ground improvement techniques. The steps described in this paper as regards to a ground improvement specific risk management approach will hopefully contribute to achieving successful ground improvement implementation.

7. ACKNOWLEDGEMENTS

This paper is an amended version of a paper previously published by Hewitt & Munfakh (2006). The author acknowledges the contributions made by several of his colleagues and clients, including Steve Summerell, George Munfakh, Dr Jiping Pan, Henry Zhang and Dr Nagen Loganathan.

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