A View on the State of Practice in Transportation Geotechnics

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Australia is undergoing a boom in construction of transportation infrastructure with associated ground improvement. Projects are becoming ever larger and more complex. Geotechnical practitioners make a significant contribution to the delivery of these projects.

Delivering a transportation project requires an understanding of ground behaviour, an understanding of construction, development of options that considers the ground and construction, analysis of the system and well-winnowed experience to manage geotechnical uncertainty. Although these attributes are general they are fundamental to the practice transportation geotechnics. Key elements of a transportation project are earthworks, pavements, rail track and ground improvement as these typically contribute significantly to the cost of transportation projects.

Data on the state of practice was obtained via a survey sent to the members of the Australian Geotechnical Society and people attending the ICGI (2024) conference. I have interpreted this data through the lens of my experience and provide my view on the current state of practice.

Litigation and claims are usually associated with an inadequate understanding of the ground or how the infrastructure interacts with the ground. I argue that understanding ground behaviour has regressed in recent years. Analytical capabilities have increased over the same time but complex analysis is often not required and most of the time empiricism and analytical approaches are adopted in design. Practitioners have a reasonable level of construction experience but more experience is needed. There is uncertainty throughout this process because we can never know everything about the ground and geological, geotechnical and numerical models are simplifications of reality. Consequently, geotechnical practice is characterised by a duality between objective theory and subjective judgements. To some extent geotechnical uncertainty is managed through construction monitoring and the Observational Method.

Geotechnical practice will evolve into the future. Transport infrastructure will get bigger, heavier, faster and longer and the science will need to develop to capture these effects. People will need to have a deep understanding of geotechnical practice or have their roles automated. This includes theoretical, practical and human skills. Artificial intelligence and automation provide great opportunities for increasing productivity. AI is a data driven method and has the potential to help reverse the regression in understanding ground behaviour by requiring high quality data to be collected. Sustainable design and use of materials will become more prevalent along with resilient design. Improvements to construction productivity will occur, possibly including contract risk sharing mechanisms and reliance on information provided by others.

While there are areas of practice that can be improved, geotechnical practice contributes significantly to the well being of our communities and we should all be proud of the work we do.

1.0 Introduction

The International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee TC202 addresses transportation geotechnics. Its goal is to apply broad engineering to bridge the gap between Pavement/Railway/Coastal Engineering and Geotechnical Engineering through the co-operation and exchange of information and knowledge about the geotechnical aspects in design, construction, maintenance, monitoring and upgrading of roads, railways, airfields, waterways, and harbour facilities for sustainable and resilient infrastructure. The state of geotechnical practice in these areas is the scope of this paper.

What is geotechnical practice and how does it differ from the state of the art? The state of the art can be defined as the highest point of technological achievement to date. To paraphrase Peck (1962), the state of the art is created through engineering science by academics who are essentially scientists. In contrast, a practitioner makes liberal use of engineering mechanics and geology as well as a host of other aspects required to deliver their work. Again, paraphrasing Peck (1962), these aspects include:

1. Knowledge of precedents. This can include reading the technical literature but most of all is gaining skill though a variety of hands-on experiences;

2. Familiarity with soil and rock mechanics which provides frameworks that help geo-professionals organise, interpret and evaluate experience. It also provides a basis for extrapolating beyond current practices; and

3. A working knowledge of geology to make the practitioner aware of departures of reality from assumption.

Burland (1987) reinforces this view in Figure 1 in the context of teaching soil mechanics (it also applies to rock mechanics). There are three key areas in geotechnical practice which are: (1) ground modelling (geology, site investigation and behaviour); (2) a framework of applied mechanics and (3) well winnowed experience.

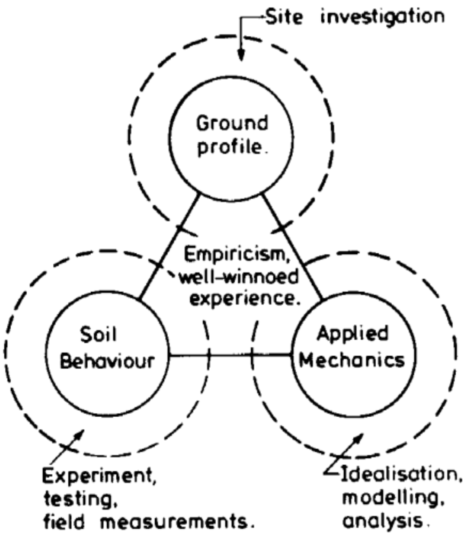


Figure 1 The soil mechanics triangle (Burland, 1987)

Vaughan (1994) makes the case that numerical analysis provides an ability to predict mechanisms of behaviour rather than assume them. Coupled with appropriate assumptions, numerical analysis can result in better predictions. However, he stresses that understanding real behaviour is more important than accurate calculation in engineering problems. He stated that the ability to make exact deterministic theoretical predictions, even by the most advanced methods, is uncertain and that use of experience as a guide to prediction and design may be an effective approach providing it is based on a realistic understanding of mechanisms and materials.

Geotechnical uncertainty and its associated risk has long been recognised. Peck (1969) quotes Terzaghi who wrote "In the past only two methods have been used for coping with the inevitable uncertainties: either adopt an excessive factor of safety, or else to make assumptions according with general, average experience. .....The first method is wasteful; the second method is dangerous. Soil mechanics as we understand it today provides a third method which could be called the experimental method. The procedure is as follows: Base the design on whatever information can be secured. Make a detailed inventory of all the possible differences between reality and assumptions. Then compute, based on the various assumptions various quantities that can be measured in the field….. On the basis of the results of such measurements, gradually close the gaps in knowledge and, if necessary, modify the design during construction." This is a process of risk management encapsulated by Casagrande's (1965) concept of "calculated risk".

These elements of geotechnical practice are general and fall into the scope of ISSMGE Technical Committees TC101, TC102, TC103 and TC304. Engineering geology does not appear to fall into the remit of ISSMGE and is addressed by the International Association of Engineering Geology (IAEG). Similarly, hydro-geology falls under the International Association of Hydro-geologists (IAH). There is no technical committee that focusses on geotechnical aspects of civil construction. Practitioners need to combine all of these elements, and more, into ground and numerical models, analysis and design as well as using their experience to manage uncertainty and risk when delivering transportation infrastructure. Consequently, a large proportion of this paper addresses the state of practice in these elements as it relates to transportation geotechnics despite them falling outside the strict remit of TC202.

More specific to transportation geotechnics, the proportion of construction costs for roads, rail and airports is typically about 25% earthworks, 25% pavements, 25% structures and 25% everything else but these proportions can vary. For example, Drechsler et al (2019) reports that earthworks including the rail formation is about 30% of the cost for Inland Rail, structures is about 30%, track is about 10% and everything else is about 30%. Ports often have significant ground improvement (TC211) costs as part of earthworks. Therefore, earthworks, pavements including rail track and ground improvement will be addressed here given their relative importance to transportation projects. Structures will not be addressed.

I also address some of the host of other factors that contribute to the state of practice in transportation geotechnics including standards and approaches to design, sustainability (TC307), resilience, digital methods (TC309), litigation, claims and geotechnical education (TC306).

Rather than just rely on my interpretation and opinion, a survey was sent to all members of the Australian Geotechnical Society (AGS) and people who submitted an abstract for this conference. The results of the survey are provided in Appendix 1. Responses were received from 189 individuals. Most people were from Australia, most were private practitioners and there was a wide distribution of age ranges from 25 years to greater than 65 years. Given the preponderance of respondents from Australia it best reflects the state of practice in Australia, but it is hoped that the survey is also relevant internationally.

Lastly, I speculate on possible future directions in geotechnical practice as they relate to transportation geotechnics.

2.0 General Elements of Practice

2.1 Ground Modelling

Development of the ground model is an area that is almost entirely reliant on the skill and understanding of geotechnical practitioners. While there are standards relating to description of geo-materials (eg Australian Standard AS1726-2019, Eurocode 7 Part 2-2007, British Standard BS EN ISO 17892), standards for performing laboratory and in-situ tests and guidelines for the development of engineering geological models (Baynes and Parry, 2022), development of the geotechnical model and the site investigation program to support the model as well as the engineering interpretation of the model relies on the skill and experience of geotechnical practitioners.

Development of a ground model is an iterative process that combines objective data collection with inductive reasoning throughout a project's life cycle. DeJong et al (2016) discuss a systematic approach to ground modelling. The approach is iterative, requires development of geological and geotechnical frameworks to allow analysis and design; then adopts a feedback loop through observations and performance monitoring.

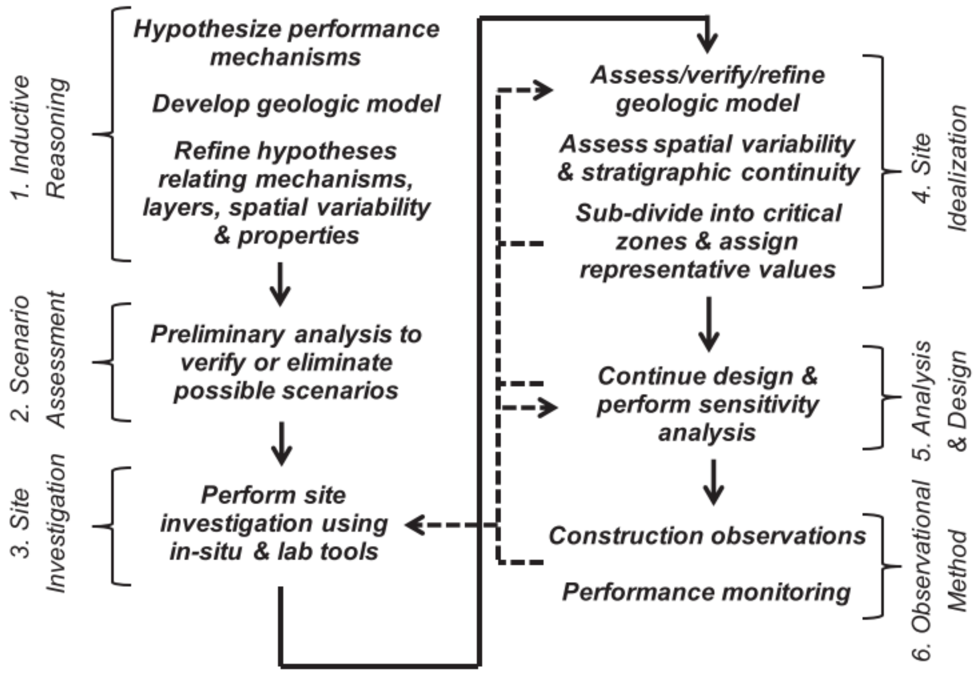


Figure 2 A systematic approach to ground modelling (DeJong et al, 2016)

Development of an appropriate engineering geological model should be fundamental to all projects. The engineering ground model concept includes geological, engineering and digital models. The model for larger high risk projects should be more comprehensive than models for smaller low risk projects. Baynes and Parry (2022) propose an approach to development of the engineering ground model in Figure 3. This approach does not explicitly show hydro-geology but it is implied that groundwater should be included in a geological model. This approach is similar to that expressed by DeJong et al (2016). This process is typically followed in high risk transportation projects that include elements such as tunnelling and underground space particularly within inner city settings, soft soils and reclamations where palaeochannels might exist within the ground profile. The process is not typically followed as rigorously for surface construction or smaller scale regional transport infrastructure projects.

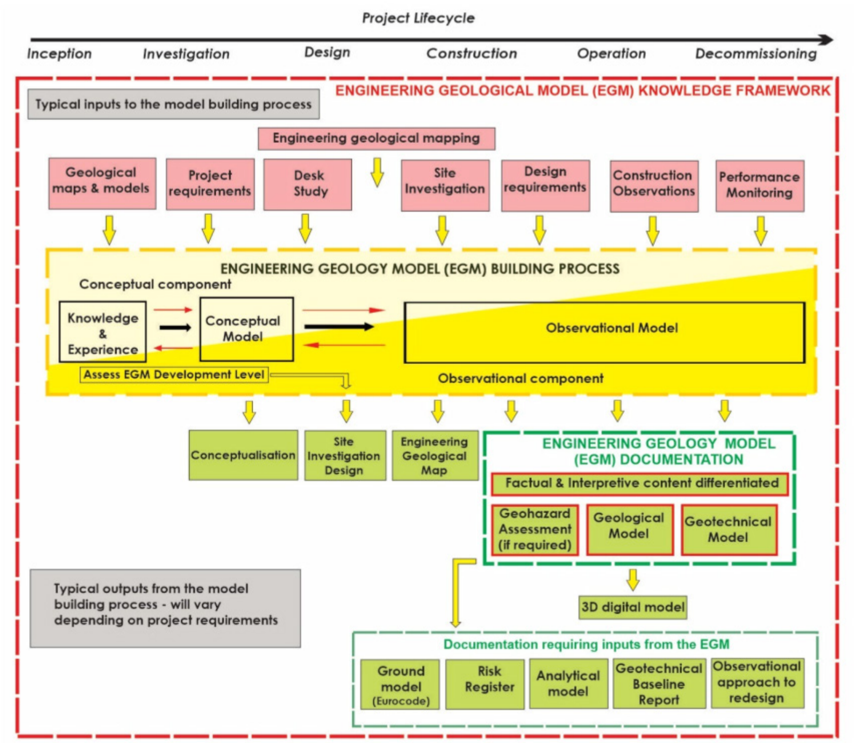


Figure 3 Suggested process for development of an engineering ground model (Baynes and Parry, 2022)

The geological model should identify the geological units, major structural features, regional stress fields, groundwater and provide guidance to the engineer on issues such as whether ground can be modelled as a continuum or a discontinuum, anticipated geohazards even if they have not been intersected during the site investigation, likely material utilisation and durability of materials. The models should be presented in digital and/or paper format in plan and sections.

Rock structural features generally need to be identified by visual inspection, drone survey (Stariha and Baxter-Crawford, 2022) or interpolation between boreholes and excavator pits. The persistence of the feature can be hard to measure as it can be obscured and subjective judgements can be required.

Soil stratigraphy can be important to understand (refer Nichols, 2009). Palaeochannels in soft soils can affect settlement and stability of structures. Variations in soil thickness over rock can affect tunnelling, excavation and underboring. Typically profiles are interpolated between discrete test locations but geophysics can be used to help develop soil stratigraphy profiles. Soils generally do not need to consider structure in the sense of discontinua because they can generally be assumed to behave as a continuum except, for example, in cases where they are fissured.

To assess the current state of practice in geological modelling, practitioners were asked the following questions:

- To what extent are you involved in developing geological models for a project?
- To what extent are you involved in developing groundwater models for a project?
- To what extent do you adopt the process outlined in the Guidelines for the Development and Application of Engineering Geological Models on Projects (Baynes and Parry, 2022) [If you have not heard of the guidelines, please indicate 'Never']
- How frequently do you specify an investigation to strategically assess the key engineering parameters and geological conditions affecting construction of a project?

Results of these questions are summarized in Figure 4 and show that respondents are frequently involved in development of the geological model and strategic specification of investigations but are seldom involved in the groundwater model. Most respondents had not heard of, or used, the IEAG (Baynes and Parry, 2022) guidelines.

Later in this paper I present a view that when unexpected behaviour occurs during or after construction it is usually associated with an inadequate ground model. Hence, there is a contradiction between practitioners being usually involved in development of geological models as part of the design process and my experience. Perhaps the answer lies with most practitioners not being aware of the Baynes and Parry (2022) guidelines and not being involved in developing the groundwater model. Perhaps practitioners know that the geological model is a fundamentally important part of the process but lack the knowledge of geology and groundwater to consistently develop an appropriate model. Maybe there is insufficient budget to develop and engineering ground model until something has gone significantly wrong. Perhaps groundwater measurements are not obtained during wet periods in the site investigation leading to incorrect assumptions. Perhaps the geological and groundwater models are not updated adequately during construction to manage variability in ground conditions possibly because adverse updates could lead to large increases in construction cost. Perhaps practitioners lack skills in inductive reasoning.

Ground models are often viewed as an early step in a design process which is completed before work starts on the engineering. In this case, the model is considered complete and subsequent stages of work progress. This is not the iterative and immersive approach recommended in the Guideline by Baynes and Parry (2022). Designs for permanent works in transport infrastructure often consider only some of the ground beneath the proposed structure to be constructed. For example, the characteristics of soft alluvial soil may be ignored if a large bridge is to be piled to rock, leaving the project engineering geological model incomplete, and the designer of enabling works essentially without a model. These are all reasons why a model may be poor, incomplete or non-existent. Whether or not these issues are true in general, it is my experience that the development of a detailed “living” model is not universally applied or even broadly considered as a project necessity.

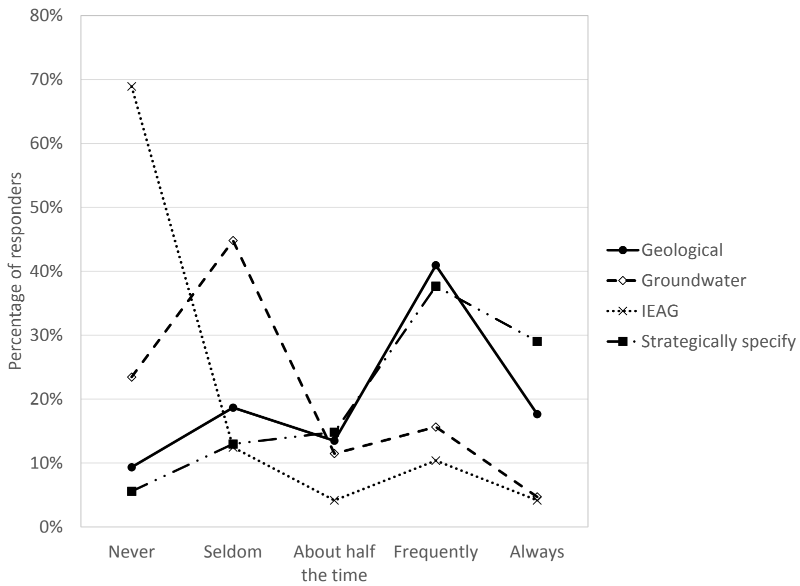


Figure 4 Responses from questions on geological modelling

Once a conceptual geological model has been developed a site investigation program is scoped to obtain geological data, in-situ and laboratory data for development of the engineering parameters. Practitioners were surveyed on site investigation practices. The questions were:

- How often do you specify routine investigations including drilling, sampling and SPT tests?
- How frequently do you specify more advanced investigations including geophysics, CPT and other forms of soil or rock in situ testing?
- How frequently do you request routine laboratory testing such as index, earthworks, strength and compression tests?
- How frequently do you request advanced laboratory testing such as cyclic triaxial testing or unsaturated soils testing?

The results (Figure 5) indicate that people specify routine investigations fairly frequently and more advanced investigations less frequently. Routine laboratory testing is specified relatively frequently but advanced laboratory testing is either specified infrequently or never. To an extent these results reflect that most projects are relatively routine and do not require advanced insitu or laboratory testing. However, in my opinion, a lack of familiarity with the advanced tests and the cost of advanced tests contribute to their lower frequency of use.

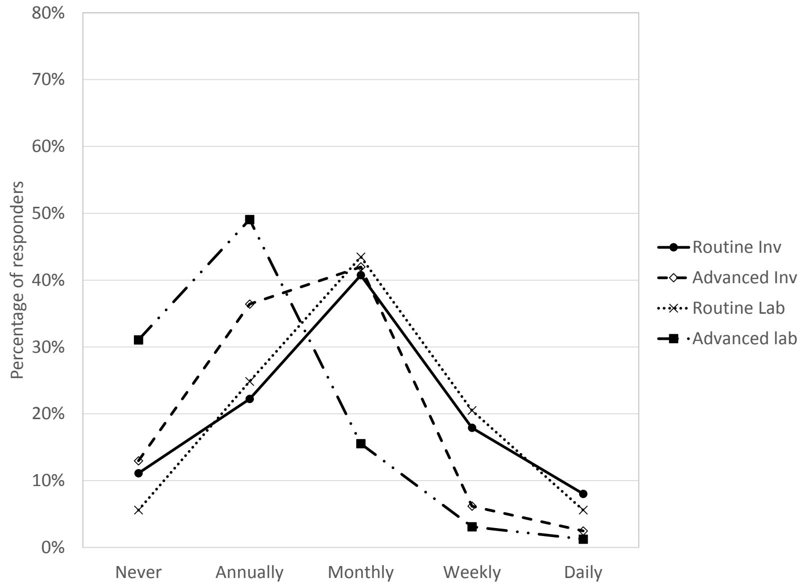


Figure 5 Results from questions on site investigation

The next series of questions aimed to assess interpretation of laboratory and insitu tests. The questions were:

- To what extent do you check the laboratory and insitu test data for errors or consistency with other data sets?
- How frequently do you interpret data to derive generic parameters for soils and rocks according to their density, consistency or other?
- How frequently do you interpret the data to derive optimal parameters for soils and rocks based on advanced in situ and laboratory testing?

The results (Figure 6) indicate that most people always check the data but do not always derive parameters from the data. Generic parameters are derived more frequently than optimal parameters. In my experience, the insitu and laboratory testing programmes do not always allow all of the required parameters to be collected. For example, the radius of the smear zone around prefabricated vertical drains and the permeability within this zone are not easily measured in a site investigation. Where this happens, parameters are adopted from correlations with other parameters or extracted from the technical literature. Often there is a scatter of data with depth and engineers use judgement to select a design set of parameters that are considered moderately conservative. Often parameters are affected by sample disturbance or empirical correlations with say cone tip resistance, the effects of which are not always incorporated into the interpretation. The characteristic value of a parameter for use in design can be assessed in different ways. On larger projects where more data is collected, cumulative distributions can be created to define both the median (or mean) and coefficient of variation of soil properties. This enables systematic parametric calculations in design (or stochastic analysis). In other cases designers may choose say the 34% percentile value, minus ½ standard deviation, and use it in design (Prof DeJong, personal communication).

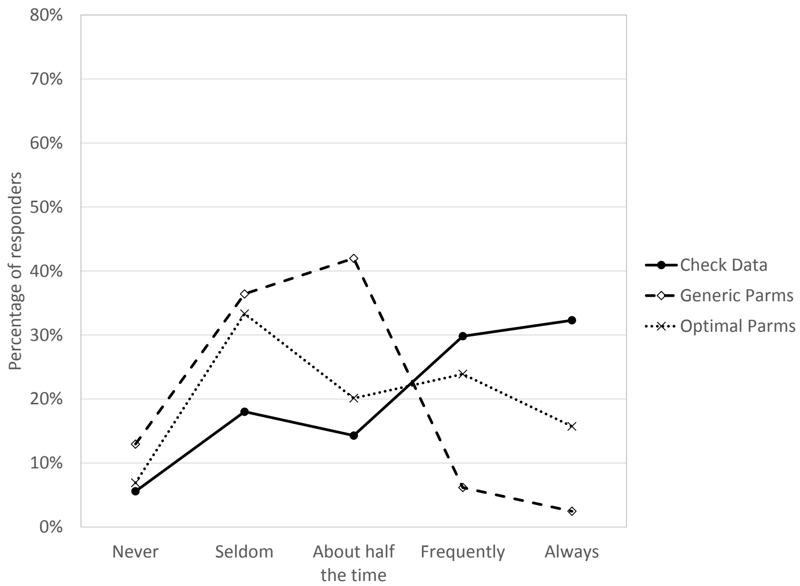


Figure 6 Summary of responses for interpretation of laboratory and insitu tests

The process of interpreting measurements to obtain material parameters can, and perhaps should, consider the constitutive behaviour of soil and rock masses to provide a consistent framework for subjective reasoning. The next series of questions aimed to understand how well practice understood soil and rock behaviour:

- To what extent do you understand critical state soil mechanics?
- To what extent do you understand earthworks material behaviour including effects related to partial saturation and durability of earthworks materials?
- To what extent do you understand the behaviour of rock masses including excavation, changes in properties over time, collapse and deformation?
- To what extent to you understand the cyclic behaviour of materials in rail track and pavements?

Responses are shown in Figure 7 and the majority lay in the range of some understanding to understanding well. Earthworks and the behaviour of rock masses are considered to be understood a little better than critical state soil mechanics. Cyclic behaviour of soils and rock masses are the least well understood.

If practitioners understand theory reasonably well but do not regularly specify advanced laboratory and insitu testing what might that mean? It is possible that most projects are relatively routine and do not require advanced testing. It is possible that perceived cost pressures limit the amount of advanced testing. It is possible that investigations are delivered in one contract but used by people as part of another contract and the designers do not scope the (initial) investigation. I also believe that geotechnical practitioners are not good at connecting performing advanced testing with better design and construction outcomes to justify the cost of the testing. Making the case for advanced testing requires the practitioner to have construction experience and know how the benefit of advanced testing will be realised and to sell the idea to their client.

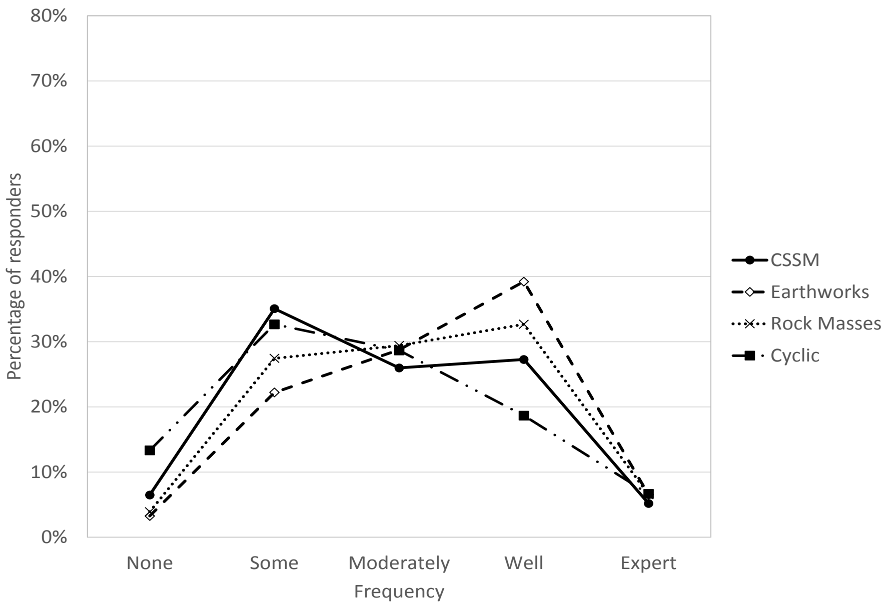


Figure 7 Responses relating to ground behaviour

Rock continuum parameters are derived from empirical rock mass characterisation systems such as RMR (Bienekowski (1989)), Q (Barton et al (1974)) and GSI (Hoek (1994)). Tunnel support systems are derived from RMR and Q in particular. Cut material parameters tend to be characterised using GSI. These systems work well in medium strength and stronger rocks. They are less effective in soft rocks with UCS less than 15MPa. Transitional materials from hard clays having UCS in the order of 400kPa to very low strength rocks having UCS in the order of 600kPa are particularly difficult to characterise and are not suited to rock mass classification systems. Rock mass continuum parameters also need laboratory and insitu tests to obtain parameters like intact UCS and elastic modulus. Interpretation of these tests can be challenging due to different mechanisms of rock failure affecting the results. Downhole and surface geophysics can also be used to infer parameters like density and elastic modulus.

Defects need to be explicitly considered in an analysis when mechanisms of failure are controlled by the defects. Mechanisms of failure can be scale-dependent. For example, an earth dam has a large footprint and long, persistent, faults could trigger failure whereas a jointed rock mass may not cause failure. Similarly, large scale slope instability may be controlled by long persistent defects whereas wedge and block failures may be controlled by smaller scale features. In tunnels, the critical scale of the defects is related to the diameter of the tunnel. Characterising defects involves identifying their orientation, their length (persistence) and the frictional parameters along the defects. Orientation of defects can be assessed from rock core obtained from boreholes drilled at various angles, from excavations and surface observations with reasonable confidence. The length of defects is much harder to measure as boreholes are usually not drilled at close enough spacing to directly measure length. Length needs to be interpreted inferred from surface observations, excavations or inference from the type of defect (ie faults may have long length whereas joints could have short length). The scale and shape of defect asperities may significantly affect defect shear strength. Localised surface roughness and associated strengths can be obtained from borehole core and laboratory shear testing of the defect. Extrapolating this to larger length and scale depends on waviness and shape of the defect which can be difficult to observe and predict, except in outcrop. Consequently, there is often considerable uncertainty when developing the engineering geological model for mechanisms of failure that are defect controlled. Standards such as Australian Standard AS1726 which emphasise the origin of defects (eg a sheared seam is probably associated with a fault) may have the potential to improve practice through better understanding of critical defect characteristics such as persistence.

In-situ stress measurements in rock are obtained by either interpreting the results of hydro-fracture tests or over-coring tests. The magnitude of in-situ stress is a key parameter when modelling underground excavations but is quite difficult to measure and interpret accurately. It is common for 50% of tests to fail or produce inconclusive results (Zooragrabi, 2021).

Soils can generally be treated as a continuum where drained and undrained shear strength, various stiffness parameters and permeability are the key parameters of interest. A few of the parameters are intrinsic material parameters, such as critical state friction angle and reconstituted coefficient of compression, but most parameters depend on their state (Atkinson, 2014). Factors such as over-consolidation ratio, density, load and degree of saturation change strengths, stiffnesses and permeabilities of soils. A combination of test pits, boreholes, insitu tests, geophysics and laboratory tests are used to derive these parameters. Some parameters, such as the extent and permeability of smear zones that form around vertical drains during their installation can not easily be measured. Practitioners need to assume values for these parameters typically from values reported in the technical literature (Kelly, 2014) however there is a wide range of values in the literature leading to potential variances between prediction and performance.

Most insitu tests require empirical correlations to convert measurements into material parameters. The standard penetration test (SPT) is widely used in practice but its measurements can be variable due to variability in the hammer system, interpretation can be complicated by modern use of heavy N rods over than the lighter A rods used decades ago when the correlations were developed and through complete empiricism. The SPT is performed at various depth intervals and does not test a near continuous soil profile. In my practice I typically ignore SPT results when interpreting the shear strength of clays because they are unreliable but do use the data with sands and gravels. Cone penetrometer and dilatometer tests are common as are pressuremeter tests in some parts of the world. Discussions on the state of practice when performing and interpreting these tests can be found in the ISC, CPT and DMT series of conferences under the banner of the ISSMGE technical committee TC102. These more modern forms of testing are based on more theoretical interpretation systems but still require some empiricism and calibration to obtain parameters. Interpretation is not always straightforward. Use of the SPT does have application in ground that is difficult to penetrate by CPT, DMT or other device. However, it is desirable to use the more advanced insitu tests and it is often very economical to do so.

Geophysical methods are often routinely used for geotechnical and hydrogeological investigations for transportation projects either for: -

- route planning,
- general geological mapping for a site investigation,
- hazard prediction ahead of surface, underwater or underground construction affecting the transportation route and design (such as soft or corrosive/ reactive soils, water inflows, voids, services location, shear zones, land slippage, rippability, rockbursts, quick clays, subsidence, liquefaction and seismic risk etc.),
- definition of historical or environmental assets to be protected from construction planning /activity,
- supplementing drilling core and core loss data with borehole imaging and geophysical logging,
- general empirically calibrated characterization and scaling up of soil or rock mass geotechnical or hydrogeological from geophysical properties for input to geotechnical or hydrogeological models,
- investigating geotechnical or groundwater related failures disrupting existing transportation assets,
- monitoring environmental and noise disturbance from construction activities, and
- transportation infrastructure condition assessment (non-destructive testing).

Traditional geophysical methods and associated geophysical modelling approaches used are seismic, resistivity, electromagnetics, magnetics, gravity, ground penetrating radar, radiometrics, remote sensing and geophysical logging and these all have differing technology and physics related limitations, in terms of either resolution, uniqueness and simplification of complexity and heterogeneity inherent to all geoscience and engineering modelling of a complex earth, that geotechnical practitioners as end-users of geophysical methods need to understand.

Notwithstanding these limitations, the state of the art in resolution and uncertainty management is evolving rapidly in each of these traditional methods and in the associated geophysical modelling procedures, with new customised and adapted instrumentation, technologies and data processing / modelling capabilities, being increasingly used or potentially valuable mainly for larger projects projects, notably: -

- seismic for tunnelling conditions prediction (passive and ambient seismic for S-wave modelling, optical fibre monitoring and vertical seismic profiling, ultra-high resolution 3D reflection methods for marine profiling),

- resistivity (3D modelling, remote dipole recording, spectral induced polarisation for clay mapping),
- electromagnetics (rapid transient electromagnetics shallow profiling instrumentation,
- airborne EM (deep cut and tunnel route rapid mapping) and gravity (shallow karst mapping),
- magnetics, gravity, electromagnetic radiometrics and ground penetrating radar – drone mounted sensors,
- ground penetrating radar (3D GPR and cloud computing processing),
- remote sensing (LiDAR becoming routine for structural mapping, SENTINEL mapping of palaeo-channels, ground subsidence monitoring from satellites, and
- geophysical logging (nuclear magnetic resonance for water content, vector temperature fracture groundwater flow, dynamic moduli from sonic and density logging).

Important to understanding and applying geophysics for site mapping, modelling and calibrated transformation of geophysical parameters to geotechnical and hydrogeological parameters are six key factors (Pettifer, 2015): - Empiricism, Scalability, Resolution, Uncertainty, Clay and Experience. Clays in particular often play a critical role in determining soil and rock mass geotechnical, hydrogeological and geophysical properties and this can either be used to advantage in site characterization or create a problem. Scale differences are important when calibrating geophysical data to point / borehole testing measurements.

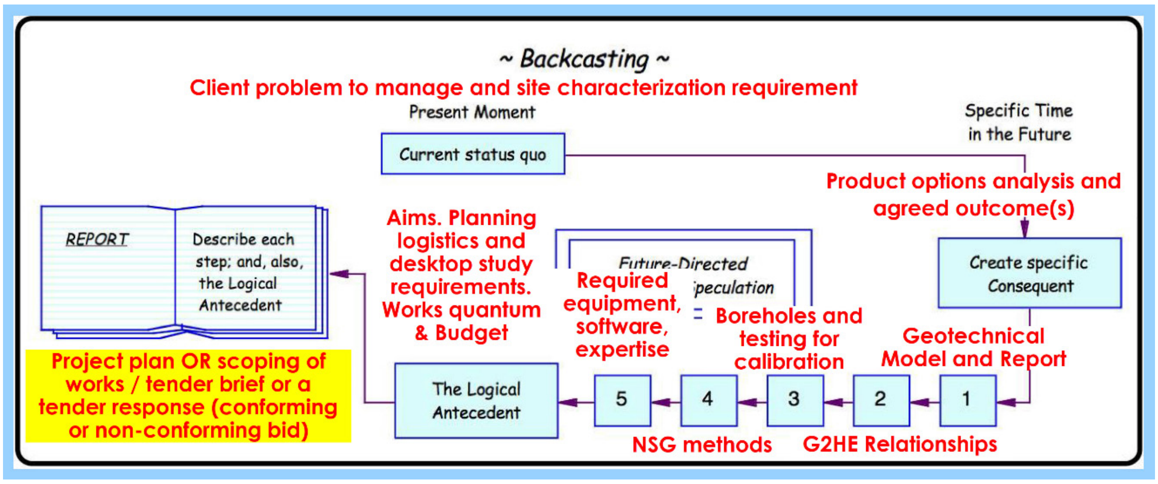


Figure 8 Backcasting – working for a taregeted required outcome to the geophysical methodology and calibration design

Productive use of geophysics for transportation (and in general) site investigations to get a better targeted geophysical survey objective, methodology and outcome and managing expectations of the application outcomes and limitations may be enhanced with judicious use of a process of futurist back-casting methods (Yeates, 2004; Pettifer, 2020; Figure 8). All this understanding comes from experience of applying geophysics across a range of geological conditions and bringing it to transport application projects.

In seismic areas, the seismic CPT (SCPTu) is routinely used as is the seismic DMT (SDMT). Surface geophysics in the form of MASW and SASW is becoming increasingly common. These tests are able to assess the small strain stiffness of the soil and the CPT and DMT can also be used to obtain a stiffness at an indeterminant larger strain.

Ground water models are typically informed by a combination of down hole permeability tests, installation of piezometers and geophysics.

Laboratory strength, stiffness, compression and permeability tests provide direct measurements of these parameters rather than empirical correlation. Index tests and particle size distribution tests including grading also help indicate how soil should behave. A laboratory test programme is usually incorporated into site investigation programmes. Limitations of laboratory testing are sampling can be difficult (De Groot and De Jong, 2020) and disturbance can occur during transport: both of which affect the measured results (eg Kelly et al (2013), Pineda et al (2016), De Groot and Ladd, (2012)): and samples are taken at a limited number of locations.

A well integrated site investigation for a reasonably sized transportation project would include geophysics to obtain a spread of 2D data over a distance but with low resolution; combined with boreholes and insitu tests to provide higher resolution data at 1D lines into the ground but still requiring empirical interpretation; and combined with laboratory tests which provide the most accurate data but limited to discrete locations within the ground. The geotechnical professional interprets all of this information, along with geological information and observations, to develop a stratigraphic model with associated engineering parameters.

2.2 Approaches to analysis

Lacasse (2015) presented a timeline of methods used by practitioners to make decisions which is reproduced in Figure 9. In the early days analytical methods, laboratory and in-situ testing were predominantly used. For example, the standard penetration test was developed in 1927, the CBR test about 1930, compaction testing in the 1930s and the Talbot equation to assess the thickness of granular materials for rail track design in about 1920. The mechanical cone penetration test was developed in the 1930s and the electric cones from the 1960s. The Swedish method of slices was developed for slope stability in the 1930s and elasticity was being used for beams on elastic foundations in the 1940s. The strength and consolidation of soils was further developed in the 1950s along with various types of laboratory testing equipment. The Observational Method was refined in the 1960s and plasticity concepts were used to link strength and compression through the Cam Clay constitutive model. Ground improvement technologies also started in the early part of the 20th century and their development accelerated through the 1960s and 1970s. Geosynthetics were developed from the 1960s. The advent of the personal computer from the 1980s allowed numerical modelling to develop and to some degree supplant analytical solutions and laboratory testing. As computing power has increased so has the range of numerical methods and artificial intelligence is now emerging. Clearly, practice has developed considerably over the past 100 years.

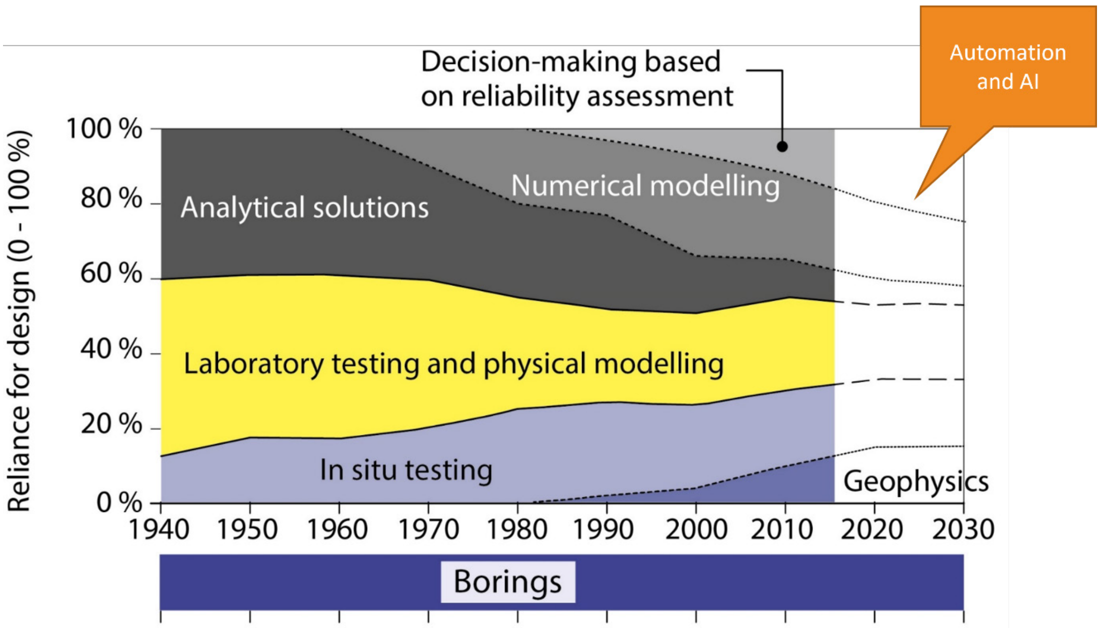


Figure 9 Timeline of methods used to make decisions (Modified from Prof Suzanne Lacasse Rankine Lecture 2015 presentation)

While there have been major advances in theoretical, analytical and numerical analysis in recent decades, it is not always necessary to include these advances in design. For example, the state of the art in rail formation design might be to determine the cyclic and dynamic loading on the ballast and formation, use advanced numerical methods to assess strength, stiffness and porous flow in granular materials and to consider particulate mechanics relating to the breakdown of ballast particles. The state of practice might be to adopt standard thicknesses of ballast, sub-ballast and structural fill having prescribed properties depending on the CBR of the subgrade soils. Our academic colleagues may consider practitioners are Luddites for using such simple approaches but why this occurs is that many decades of experience has proven the approach achieves acceptable performance, that many rail projects are small in scale and do not warrant the time and expense required to optimise earthworks and that quarries are set up to provide standard products and would charge higher rates to supply non-standard materials.

Simple analysis is used when time is short, such as during tenders, when standards and specifications are prescriptive leaving limited opportunity to refine design, to check more complex analysis and when analytical expressions are calibrated to laboratory test data. More complex analysis is required when infrastructure is constructed in congested urban environments and there is concern about damage to adjacent assets, when loads or speeds exceed historical levels and when there is opportunity to realise significant cost or time benefits.

The practitioner survey asked the following questions to assess the current state of practice. Responses are summarised in Figure 10.

- How frequently do you develop design options based on understanding of the asset owners needs, construction methodology and the ground prior to performing detailed analysis?
- How frequently do you use analytical solutions?
- How frequently do you use routine numerical analysis such as limit equilibrium, pile software and retaining wall software?
- How frequently do you use advanced numerical analysis such as finite element and finite difference software?
- Do you understand the scientific and mathematical formulations of the software that you use?

The responses indicate that people perform design options prior to detailed analysis and that people feel they have a good understanding of the scientific formulations of software they use (primary horizontal axis in Figure 12). Analytical solutions and simple numerical procedures are used roughly on a monthly basis and more advanced numerical models are used less frequently (secondary horizontal axis in Figure 12). This data suggests that many projects are relatively routine in nature and do not require more sophisticated analysis. The data might also suggest that while practitioners feel they understand the scientific formulations there may be a lack of confidence when it comes to understanding finite element analysis so it is used less frequently.

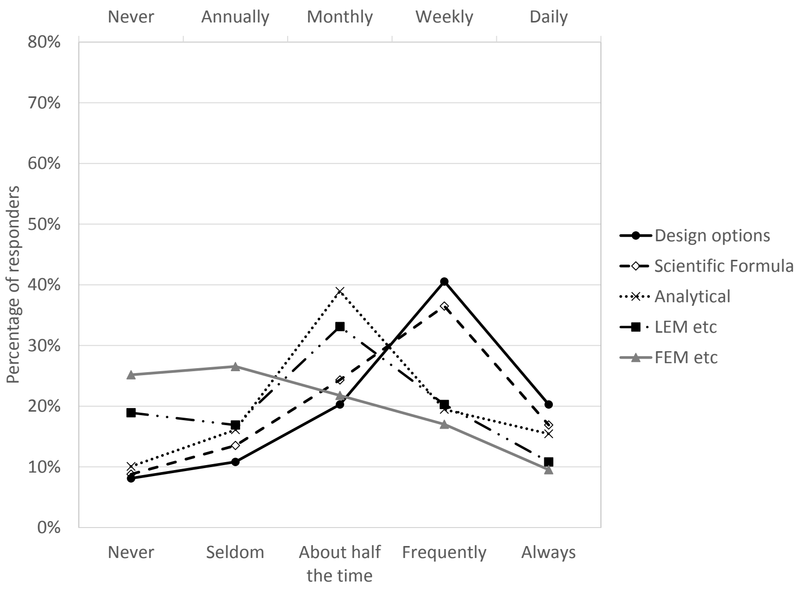


Figure 10 Summary of responses for analysis and design

2.3 Construction testing, instrumentation and monitoring

The process outlined in Figure 2 implies that the design is not complete until construction is complete because observations are required to validate analyses and assumptions. Practitioners were asked the following questions about use of traditional methods and emerging technologies.

- How frequently do you specify or use the Observational Method to validate your designs or control construction risks?

- How frequently do you use / interpret conventional earthworks testing?
- How often do you use alternate methods such as LWFD and intelligent compaction for earthworks testing?
- How often do you specify / interpret inclinometers, settlement plates, VWP etc?
- How often do you use drones / LIDAR and other remote sensing technologies?

The data shows that the Observational Method is frequently used in practice which supports the idea that it forms part of the design during construction. Conventional earthworks testing occurs relatively frequently presumably due to the volume of earthworks required in transportation geotechnics. However, alternative testing methodologies such as the use of light weight falling deflectometers (LWFD) and intelligent compaction (IC) are infrequently used. The reason for this is likely to be that density is usually the specified parameter that must be achieved and there is not a direct correlation between elastic modulus and IC compaction meter values and density (Latimer et al, 2023). Other new sensing technologies also appear to be used relatively infrequently, albeit the rate of their use has probably increased dramatically over the past few years.

Developments are being made in digital monitoring and inclusion into augmented reality (and other) visualisation, for example https://www.youtube.com/watch?v=IkY-B_weRaA.

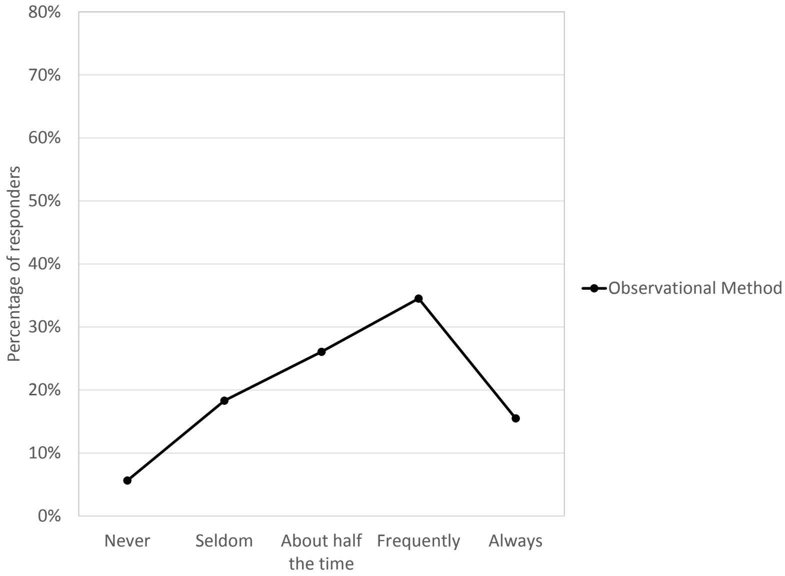


Figure 11 Responses to use of the Observational Method

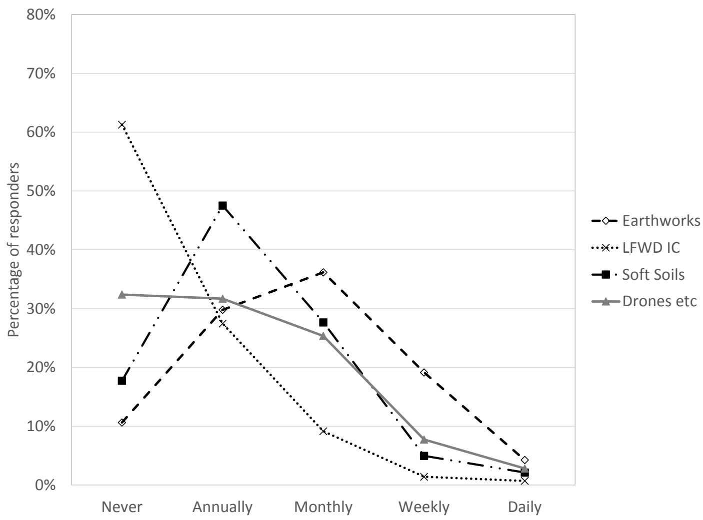


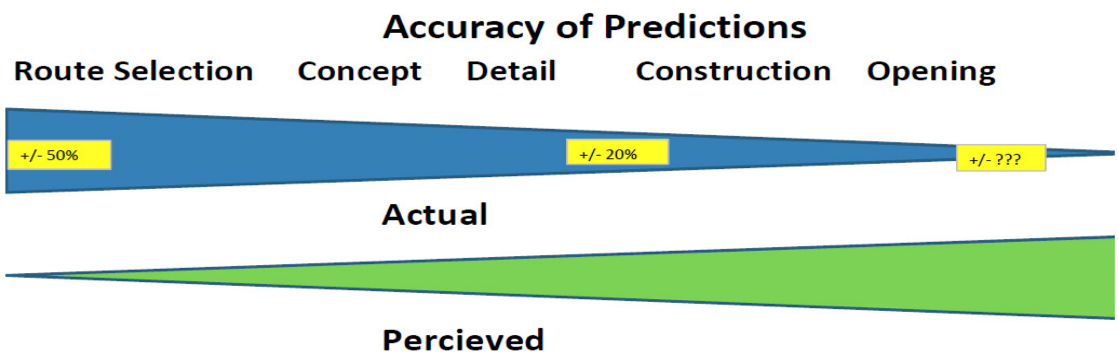
Figure 12 Responses to monitoring questions

2.4 Experience and Judgement

Geological, geotechnical and numerical models are simplifications of reality that allow engineers to design and construct infrastructure. Experience is partly familiarity with the technical literature and past precedent. Experience is partly knowing potential differences between assumptions and reality. Experience is partly knowing how to optimise balances between time, cost, performance requirements, risk, opportunity, environmental requirements, community requirements and any other requirements. Experience is observing how infrastructure is built, how it deformed during construction and also the perspectives of various stakeholders. Design is the application of experience within frameworks of ground behaviour and applied mechanics. An experienced designer will know that actual performance will vary from design prediction and will specify a monitoring regime to compare performance against prediction for the purpose of changing the design during construction if necessary.

Another way to describe well-winnowed experience is the ability to make, or help others make, informed decisions in the face of uncertainty. Geotechnical practitioners will know that the greatest uncertainty exists at the start of a project when the least information is available (Figure 13) and inductive reasoning is required. As the project develops, ground investigations performed and construction observations made the uncertainty reduces. After completion of construction there can still be some variances to expectation but these are expected to be limited in scale. Conversely, client expectations can be the complete opposite. When projects are commenced there is high confidence it will be delivered. As investigations unfold and design develops, original cost estimates can increase making clients perceive there is higher risk. Later during construction and operation when performance does not match prediction perceived uncertainty increases. Those with well-winnowed experience are able to clearly communicate actual risks to clients and help them make informed decisions at all stages of the project.

Figure 13 Actual versus client perceived risk (Courtesy Bob Higgins, Former General Manager Pacific Highway Upgrade, Roads and Maritime



Services of NSW)

Experience comes from spending time on site during and after construction and comparing what was expected to occur with what actually did occur, then reflecting on the experience and investigating why events occurred. Whether or not people get these experiences is partly due to random opportunity and partly the drive and motivation of the geotechnical practitioner. Most people considered industry leaders will have spent a good deal of time on investigation and construction sites.

Do practitioners have construction experience? Practitioners were asked (1) What is your level of construction support experience (Figure 14 primary axis) and (2) noting ground works typically sit on a construction critical path, do you feel geotechnical practitioners have a good understanding of contractor needs/drivers? (Figure 14 secondary axis). A large proportion of the respondents have either performed regular site inspections or have been a resident engineer on a construction site. That should mean that there is a good understanding of construction practices within the geotechnical community. A small majority of the respondents did think they understood contractor needs and drivers but a considerable proportion of the respondents did not think this was the case.

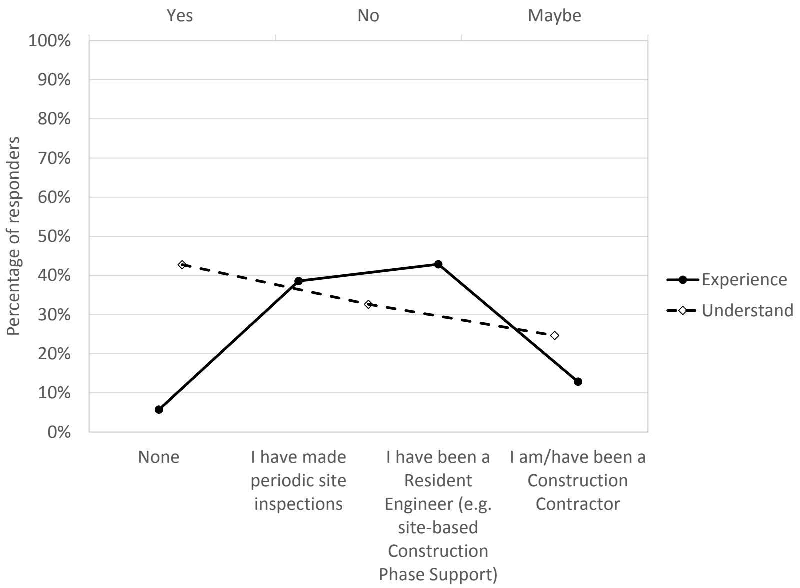


Figure 14 Practitioner responses regarding construction experience

Practitioners were also asked what importance does industry place on specific experience in a geotechnical domain (e.g. specialists or generalists). Twenty-two percent of respondents thought it was low importance, 55% thought it was medium importance and 23% thought it was high importance. The practitioner answers probably depend on which part of industry they lie. Asset owners and multi-disciplinary consultancies are likely to favour generalists who know enough to manage and deliver work. Specialist consultancies and some constructors favour specific experience, particularly on the more challenging technical projects. The lines between specialists and generalists have become increasingly blurred. Bonaparte (2012) reports long term trends where businesses are becoming larger through merger and acquisitions such as the recent acquisition of Golder Associates by WSP. A consequence of this is that people with specialist skills are distributed across industry more widely than if the smaller specialist organisations were not acquired. There will be times when multi-disciplinary teams are required to deliver a project and there will be other times when people with specialist skills will be required. People with those skills are sought after no matter whether they are employed by a large or a small organisation.

3.0 Elements of Transportation Geotechnics

3.1 Earthworks

Earthworks comprises excavation of materials in cuts, tunnels, station boxes and other underground spaces as well as reuse of those materials typically through compaction as fills. Earthworks are considered routine, and perhaps boring, by practitioners in general but the volumes of earth moved are often large and inefficiencies in moving or utilising materials can quickly cause cost over-runs. Practitioners contribute to assessments of unsuitable and suitable materials, stripping and reuse of topsoil, excavatability and compaction of materials. Maximising material use and minimising excavation effort helps deliver a profitable project. Practitioners also assess stability of excavations and deformations caused by excavation.

Excavatability assessments are performed using various methods (eg Pettifer and Fookes (1994), MacGregor et al (1994), Kirsten (1982) the Caterpillar performance handbook (2019)) that usually involve the type of material, the UCS of rock, fracture spacing of rock and seismic refraction geophysics. The methods of assessment are largely empirical and calibrated to observed performance. There has been little update to these methods in the past 30 years other than increasing the size of ripping machinery.

Practitioners contribute to the assessment of tunnel and underbore excavatability through provision of borehole data and laboratory testing for abrasiveness of cutters. These data are typically used by specialist constructors to assess potential rates of progress because progress depends on how the tunnel boring machines or underbore equipment is operated as much as the condition of the ground.

Misleading assessments of excavatability can result in large cost over-runs on projects. For example, a cut on the Ballina Bypass was excavated through a hillside where up to 30% of the material was identified to be comprised of basalt and corestones. This percentage was proven to be about right during excavation, but what was not identified was that basalt blocks up to the size of cars were surrounded by a weathered clay matrix. The blocks were too large to remove by bucket and the clay matrix prevented blasting. Consequently the basalt corestones had to be broken up by hammering. This lead to a multi-million dollar cost over-run for this cut. Seismic refraction, large excavator pits and boreholes were used during the site investigation and the data was interpreted by an experienced engineering geologist. Despite this, the rock structure was not identified during the investigation.

Like all geotechnical engineering, assessment of excavatability can be uncertain due to varying ground conditions. However, these methods can provide a useful guide as long as the initial characterisation of the ground is thorough, i.e. there is a well developed engineering geological model. This also provides the opportunity to employ cross correlation between multiple methods. If the contract for a project assigns the majority of risk to the constructor then the constructor (and their sub-consultant designers) are responsible for assessing excavatability in general. If the risk lies with the asset owner or there is a risk sharing mechanism then claims for unexpected ground conditions relating to harder than expected excavation are more likely.

Generally, acceptable properties of fill materials are defined in asset owner specifications. Occasionally the properties can be modified in consultation with the asset owner. One example of successful modification is the use of granular earth fill on the Coffs Harbour bypass. The parent rock is a lightly metamorphosed phyllite with high silica content. When blasted the material fell between conforming earthfill and rockfill gradings and would have required screening to achieve compliance. However, the blasted material had good mechanical strength due to the silica content and was well graded which aids compaction. Field trials were performed to assess compaction methodology and fill performance and acceptable performance was demonstrated. This meant that the blasted material could be used as fill without needing to process it to achieve a certain grading. This reduced the cost of construction as well as the time for construction.

Unlike most rail earthworks specifications, Inland Rail earthworks materials specification ETC-08-03 allows the designer to vary the properties of the materials if they can demonstrate that the engineering performance requirements will be achieved (Drechsler et al, 2019). The designer must perform testing and do analysis to demonstrate performance and gain acceptance from the asset owner. The purpose for this change was that Inland Rail traverses large distances with limited sources of high quality materials. Consequently, adoption of historic specifications would mean that large volumes of materials would need to be imported from quarries distant from the track alignment which would be very expensive. Designers used these provisions to reduce the quantities of high quality materials and use some materials traditionally not considered appropriate, albeit using lime stabilisation in some cases (Blanchett and Yang, 2021).

Earthworks construction specifications typically mandate minimum ratios of achieved density to standard or modified maximum dry density as well as ranges of moisture content. Most of the time the compacted material performs as expected. However, some recent exceptions have occurred when the fills have been constructed from non-durable materials such as shales and very low strength claystones, siltstones and mudstones (eg Muttuvel et al, 2020). If the excavated material is broadly granular and is not strongly chemically bonded then exposure to oxygen and moisture can cause the granular material to break down into smaller particles and fill voids between larger particles. This leads to settlement of the fill. There are examples of this behaviour in the technical literature (eg Cox (1978), Hopkins and Beckham (1998)) but if the practitioner is unaware of the potential for settlement of fill they are unlikely to consult the technical literature or consider it in their design. Compaction to higher density and at higher moisture contents than usual help break the material down and reduce the potential for settlement.

Slope stability is typically analysed using limit equilibrium (LEM) or rockfall type analyses and sometimes using finite element (FEM) approaches. Traditionally circular and non-circular failure mechanisms were required by asset owners in LEM analyses. Non-circular analyses were interpreted as block-wedge mechanisms of failure. More recently some practitioners have interpreted non-circular analyses using the optimised failure mechanisms found in some software packages. The optimised routines usually result in factors of safety lower than other mechanisms but also can result in unrealistic shapes of failure mechanisms. Some judgement is required to assess whether the results of the analysis is reasonable. Rather than use the optimised routines it would be better to use finite element limit analysis (FELA) (Sloan, 2011) but only one software package is commercially available to the best of my knowledge. LEM is not suitable for slopes where stability is controlled by discontinuities in the rock and rockfall analyses are used in this case. Dip, dip direction and persistence of discontinuities are input and the probability of various failure mechanisms occurring output. Finite element packages that can model discontinuities are also be used.

Deep excavations and tunnels are typically analysed using FEM because geometry can be complex and ground movements can affect adjacent structures. Effects of groundwater drawdown can also be included.

3.2 Pavements

In Australia, national road, airport and port pavements are typically designed to be robust and requiring limited maintenance. This is partly to reduce impact to airport, port and road operations and partly because the federal government helps fund construction and the states build the road and fund maintenance. It is in the state's interest to minimise maintenance. State and local roads are designed to lower technical standards and there are many thousands of kilometres of unsealed road in Australia.

Analysis and design of pavements and track for road, airports, ports and railways follow similar procedures. Elastic analysis is used to assess deformations and strains in the upper pavement layers and track as it is related to fatigue type failures of these elements. The resilient modulus of the materials is used to represent the elastic parameters. Permanent deformations are used to assess structural failure of pavement and rail formations. The major differences between road, airport, port and rail designs are the magnitude of the applied loads, the number of cycles of the applied loads, whether the loads are consistently applied at the same location and the velocity of high speed trains. Performance requirements are usually expressed in terms of a period of time (design life) before the pavement or track does not meet safety or maintenance requirements.

Design of concrete, asphalt and bound pavement layers along with rail, sleepers and slab track is usually of not much interest to geotechnical engineers. Of more interest is the performance of the unbound granular material and of cohesive subgrade material. Of course, soil structure interaction is important to the distribution of loads to geomaterials as well as the influence of geomaterials on the performance of the structural elements of the pavement. Given the interdependency of the pavement, track and geomaterial performance one would think that road, rail and geotechnical practitioners would collaborate closely on their design, but this is often not the case.

Pavements can be designed using simple deemed to comply approaches where various layer thicknesses are specified as a function of subgrade CBR and the number of standard axles of the design life of the pavement (eg Austroads, 2019). This approach is particularly suited to council and state roads where the cost of design is difficult to accommodate and benefits of refinements to deemed to comply design are not large.

Pavements can also be designed using some form of the mechanistic-empirical method (eg AASHTO, 2020). The mechanistic method assesses the pavement performance based on load distributions with depth typically calculated using elastic layer analysis such as the CIRCLY software.

The elastic (resilient) modulus measured in a laboratory or can be derived from empirical correlations with CBR and from correlations with load, density and suction (eg Caicedo, 2019). CBR samples are typically soaked for 4 or 10 days to obtain a lower bound number and a 4.5kg surcharge applied which models the load beneath an approximately 150mm thick layer. Sometimes higher surcharges are used and in some more arid locations soaking is not required (which is an implicit method of incorporating suction into CBR values). The requirements are usually specified by the asset owner. Elastic modulus is a state parameter and not a material parameter and depends on the materials density, pore water conditions (suctions), confining stresses and applied shear stresses. Various empirical relationships between resilient modulus and load, density and suction have been proposed in the literature (Caicedo, 2019).

The process of soaking will reduce or eliminate the suction and probably provide a lower bound estimate to the CBR and possibly the elastic modulus, depending on the validity of the empirical relationship between the two.

The CBR test is neither a strength nor a stiffness test (Hight and Stevens, 1982) so why do we use it for pavement design? I asked a senior roads engineer in one of the Australian transport agencies and the answer was they have decades of experience using CBR and they know how the roads will perform for various CBR (at least for the traffic and weather conditions over those periods of time at those locations). It is hard to argue for a change in approach when performance has been calibrated to such well winnowed experience.

Elastic analysis has a direct relationship with fatigue cracking of the upper pavement layers (Caicedo, 2019) and the parameters are easy to measure or calibrate. Permanent strains are typically assessed using empirical equations that depend on the number of cycles and the applied stresses. These equations are calibrated to some form of laboratory and field testing (Singh and Sahoo, 2021).

Port pavements typically comprise either concrete block paving on a cement bound base or insitu concrete. Both pavement types lie on crushed rock subbase and capping if subgrade CBR is less than 5%. The wheel loads on port pavements are higher than highways and consequently the British Ports Association use FEM to assess the loads within the pavement formation (Knapton, 2009). Fatigue (plastic deformations) is accounted for by defining limiting stresses and reducing those stresses to account for multiple load repetitions. From a geotechnical point of view, the stiffness of the subgrade is empirically assessed as 10 times CBR which is similar to the approach adopted for road pavements. Typical values for granular sub-base and capping materials reported by Knapton (2009) indicate that these could have been selected as 10 times CBR.

3.3 Rail Track

Rail track design in Australia appears to be based on Doyle (1980), updated by Tew et al (1992) and Boyce (2007). Rail track comprises rail, sleepers and ballast (or slab track). The formation underlies the track and comprises various thicknesses of capping (sub-ballast), structural fill and general fill. The formation lies on subgrade which is natural ground. The formation design appears to be mainly based on elastic methods coupled with safe bearing pressures for materials and sometimes the Li-Selig (1996) method for plastic deformation. In many cases, the track and formation designs are controlled by asset owner specifications. In some cases the track and formation can be designed to optimise outcomes. Urban asset owners need to maintain the track in difficult to access congested corridors and aim to design track to reduce maintenance. Heavy haul track typically lies outside of urban centres where maintenance can be performed more readily so track and formation design aims to reduce or minimise capital cost.

Similar to other pavements, elastic displacements are limited to a range to limit fatigue in the rail. For heavy haul rail this range is typically 3.5mm to 6.4mm (Doyle, 1980). Plastic deformations are calculated to assess rutting of the formation. A trigger for formation reconstruction is when the thickness of ballast reaches 500mm, which is associated with ballast spilling over the shoulder of a typical width formation. Depending on the initial ballast thickness, this implies that 200mm to 300mm vertical permanent deformation (rutting) is the limit that triggers track reconstructions. However, permanent deformations at the top of the capping are often limited to 20mm to 30mm (eg Li et al, 2015) in order to reduce the potential for water to pool in ruts and initiate much larger plastic deformations. Formation reconstructions are expensive and best avoided but limiting plastic deformations to small values also increases capital cost because thicker layers of high quality materials are often required. Tamping and ballast cleaning are preferred methods of maintaining track performance.

Mud pumping can be an issue for old track lying on silty ground in areas where water does not drain away. Mud pumping can be controlled through designing the sub-ballast as a filter or use of geosynthetics. (Indraratna & Ngo, 2018).

Many Australian rail asset owners have a specification that mandates the formation design irrespective of the applied axle load and tonnage. The default specifications mandate standard thickness of ballast and capping along with the thickness of structural fill material having to be a minimum of 500mm and 1000mm when lying on subgrades with CBR values of 1 and 3 respectively. In contrast, the Melbourne to Brisbane Inland Rail is a 1,700km heavy haul upgrade that traverses a variety of geological domains where the excavated materials often have poor properties. Inland Rail aimed to reduce capital cost and created specifications and performance requirements that allowed a designer to optimise the track and formation design providing that performance requirements were met. The designs for Inland Rail varied widely. Formation designs for a 30TAL axle load and 40MGT/pa tonnage on subgrade with CBR = 3% ranged from 250mm ballast with 200mm CBR = 50% capping and 250mm CBR = 8% structural fill to 300mm ballast with 600mm capping and 750mm structural fill. Calculated elastic deformations of rail also varied widely.

How is it possible for the design to range so widely? The reasons appear to be that there are various design methods (summarised by Doyle 1980, Esveld 1996, Li et al 2016, Powrie and Fagan 2024) that have various factors to calculate dynamic axle load and impact factors, other factors of safety to limit sleeper to ballast pressure, different methods to assess load distribution into the formation, different approaches to estimating elastic and plastic deformations, different approaches to assigning material parameters and different performance limits adopted. It is not clear why various designers adopted the approaches they did. Perhaps individual designers have preferred methods. Perhaps values adopted for the various factors and performance limits aim to manage risk due to variability in forces, materials and track conditions over time and perhaps how much risk acceptable to a designer is an individual preference.

The process described by Doyle (1980) uses track modulus as a constant input value usually based on values in the literature for various types of track. Track modulus could be calculated as an equivalent spring combining springs in series to represent the formation but this does not appear to be common. Factors for track condition and rail seat load are assumed. One of various methods to calculate dynamic impact factor, rail seat load, ballast contact pressure and stress distribution with depth are adopted. The ballast thickness is input. The stresses in the formation are compared with safe bearing pressures to allow thicknesses of capping and structural fill to be selected to suit a certain subgrade CBR (Figure 15). Figure 15 comes from the design of concrete airport pavement (Packard, 1973) which in turn is based on plate load testing performed by Middlebrooks and Bertram (1942). Despite the various assumptions, empirical relations and comparisons to charts derived from 80 year old data used, formation designs using this approach fell in the middle of the range for Inland Rail. This approach also resulted in thinner layers of structural fill than was mandated in the deemed to comply specifications. Despite the many simplifications and use of very old empirical methods, the approach results in a reasonable design. Arguably this method is adequate when significant cost savings from refinements in the formation design by advanced analysis are not possible.

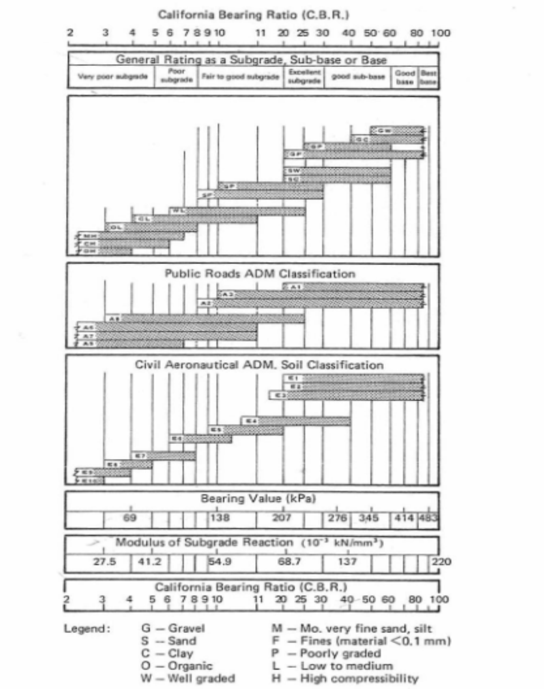


Figure 5.10
Approximate correlation of the Casagrande, PR and CAA classification on the basis of bearing capacity (Department of Scientific and Industrial Research 1961)

Figure 15 Safe bearing capacity chart

Transition design is particularly important for railways as increased frequency of maintenance is associated with these locations. Li et al (2015) state that a transition is a change in track structure at locations such as interfaces between track and bridges, level crossing, turnout, culverts and tunnels. These are associated with rapid changes of track stiffness and creation of large dynamic loads at the interface. Typical problems at transitions are localised changes in track geometry, rapid track degradation, mud pumping, damage to track components on and off a structure. Transition design is typically performed using elastic methods to assess the length of the transition. Permanent deformations triggered by load amplification at the interface of the embankment and structure are often not addressed in design and are manage though tamping.

There are many and varied approaches to create a stiffness transition. Some of these are structural and some of these are geotechnical. Structural solutions include:

- Approach slabs either spanning from a bridge to the embankment or placed on the embankment. If seated on the bridge it acts as a relieving slab to reduce lateral pressures on the bridge as well as providing a stiffness transition. When seated on the embankment it spreads load and increases the track modulus;
- Use of elastomeric elements such as under sleeper mats or pads to tune the stiffness variation from the structure to the embankment;
- Provision of a third rail spanning the structure and the embankment;
- Change sleeper spacing adjacent to the structure to increase the track modulus; and
- Provision of lateral confinement of the ballast to stiffen the response of the ballast.

Geotechnical solutions include:

- Ballast gluing to stiffen the ballast;
- Gradations in stiffness of formation materials from the bridge to the far field including cement and other forms of stabilisation;
- Inclusion of geogrids in granular materials. The geogrids do not change the stiffness of the granular materials but do increase the strength of the material and reduces plastic deformations; and

- Inclusion of geosynthetics to reduce mud pumping.

Finite element analysis is often performed adjacent to bridges partly for transition design and partly for foundation design. Analytical methods are more common for culverts, level crossings and turnouts.

3.4 Drainage

Formations are usually designed based on soaked CBR values but this does not account for the effects of transient pore pressure generation in saturated materials as the wheels pass over an area. These pore pressures can exceed the strength of the overlying materials leading to creation of potholes and hanging sleepers. Well winnowed experience suggests that water gets into places one does not want it to and is a primary reason for increased maintenance and failure of pavements and rail tracks. Consequently, drainage of water is a key consideration in pavement and track design.

Road drainage includes pavement crossfall, provision of subsoil drains below pavement and stormwater drainage. Water can collect at the surface of the pavement when the pavement shape does not allow it to drain and this leads to creation of potholes. Geotechnical designers typically assume that stormwater drains are water proof but this is not the case even for well constructed drains with rubber ring joints. Hydrostatic testing of stormwater pipelines is not required in Australia, but if it is done then the pipe when tested under a minimum head of 1.2m and a maximum head of 6m (12 to 60 kPa) of the pipe, shall not show any leakage in excess of 1.54 litres per hour per linear metre per metre of nominal internal diameter (CPAA, 2017). Stormwater pipes installed in reactive soils will leak and cause the soil to swell which will open the joints and allow greater leakage. This results in heave of the road surface. When stormwater pipes are constructed in fills, the leakage can contribute to hydro-consolidation of the fills, particularly when the fills are constructed from non-durable materials such as mudstones, shales and low strength sandstones. As the fill settles, the joints open up which exacerbates the settlement.

In railways, ballast is highly permeable allowing water to freely flow through it. Ideally the formation is graded to direct water towards the cess drains and culverts. Water tends to collect in sags along the vertical alignment, in ballast pockets that have formed on tangent track or at interfaces with structures. Low height embankments with poor drainage can be associated with mud pumping. Washouts are often associated with blocked or undersized stormwater pipes. Railways are usually constructed in relatively flat terrain and drainage of surface water away from the formation can be difficult to achieve. Designers need to ensure that adequate drainage is provided particularly if refinements to the formation design based on advanced analysis is planned because the refined formation is likely to be more sensitive to moisture than a more conservative design. Maintenance of the system including ballast cleaning and removal of obstructions in the cess drains is important for long term performance. Many railways are old and drainage needs to be retrofitted.

3.5 Ground Improvement

Ground improvement technologies have generally been developed by specialist constructors so that the state of the art is also the state of practice. The state of the art in ground improvement has been reported by Chu et al (2009), Terashi and Juran (2000) and Mitchell (1981). More recently Kitazume and Terashi (2013) describe methods for deep mixing used in Japan for ports and airports in reclaimed land. Recent developments include design guidance for displacement auger piles developed by the ASIRI project (ASIRI, 2013) and mechanisms for geogrid stabilisation of granular materials (Lees and Clausen, 2020). Design and construction methods used in practice are well summarised in these references and are not addressed further here.

Design of ground treatment involves optimisation of cost, time, quality, risk and increasingly sustainability factors. It is not possible to have low cost, high quality, quickly constructed and low risk outcomes. This is shown conceptually in Figure 16.

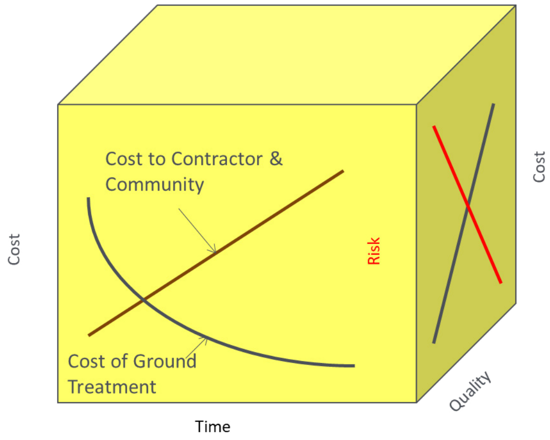


Figure 16 The “Golden Box” for Decision Making Courtesy Bob Higgins, Former General Manager Pacific Highway Upgrade, Roads and Maritime Services of NSW

In Australia, around about 2010, there were examples of most ground improvement technologies being used on projects including prefabricated vertical drains, vacuum consolidation, vibro-compaction, vibro-replacement, dynamic compaction, dynamic replacements, dry and wet soil mixing, jet grouting, other forms of grouting and displacement auger piles. Since that time, use of prefabricated vertical drains and displacement auger piles have dominated the market. The reasons are that prefabricated vertical drains with surcharge is one of the cheapest methods of ground improvement in soft cohesive soils if there is time available and displacement auger piles are the most cost effective way of saving time during construction adjacent to structures, particularly when construction of the structures lies on the critical path. Materials like cement, lime and high quality durable aggregates are expensive in Australia which limits the use of ground improvement technologies that rely on these products, albeit that lime stabilisation of pavements is relatively common on reactive soils. Various technologies are used for specialist requirements such as tunnel grouting, sand densification and remedial works when performance of an original design does not meet expectation. Light weight fills are used for remediation but also to reduce surcharging periods in soft soils. Internationally, the spectrum of ground improvement technologies is used depending on local technical and cost factors.

The practitioner survey asked “to what extent to you understand principles of ground improvement including consolidation, reinforcement (including grids and fabric), chemical stabilisation, densification and reducing permeability” and “to what extent do you understand ground improvement construction?” The results are shown in Figure 17 and indicate that practitioners believe they understand design and construction of ground improvement reasonably well.

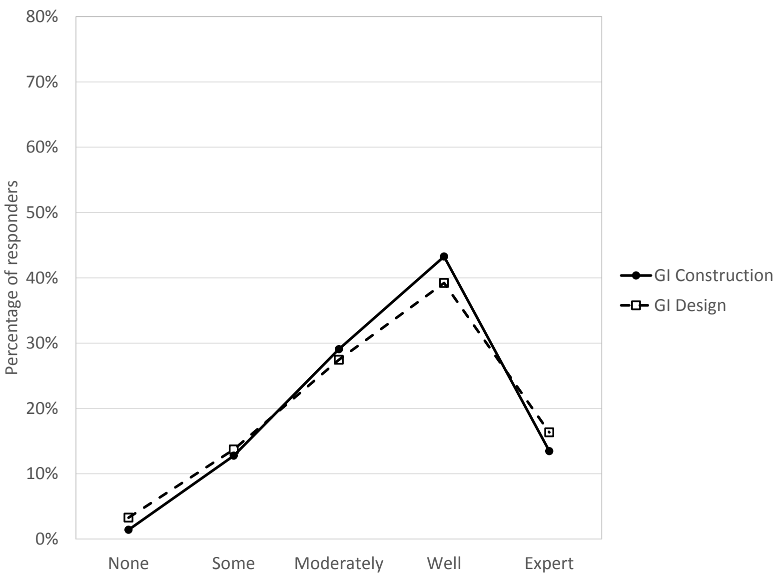


Figure 17 Responses to questions on ground improvement in the practitioner survey

Some feedback provided by colleagues in the ground improvement construction industry on current practices is provided in the following points:

What practice does well:

- Consideration of geotechnics within the overall scheme;
- Integration into the overall scheme (stakeholder management); and
- Consultation with specialists and practitioners (primarily design related).

What practice does not do well:

- Gain an understanding of the construction processes and limits of product application at an early enough stage such that risks are well understood as are the impacts of relatively small changes in soil conditions and site logistics;
- Realistic and practical understanding of the physical characteristics of modified ground; and
- Ground improvement (jet grouting, soil mixing etc) is not a "manufactured" product such as concrete, however it is often specified (designed?) as such. There needs to be an acknowledgement and communication throughout all stages of the works of the design intent and the inherent variability of modified soils.

What practice could do better:

- Site investigation: suitable staged investigations with appropriate testing that are applicable for the product(s) being considered;
- More deeply considered safety in design from the perspective of the construction of the ground improvement;
- Avoid inconsistencies between methodology specifications and performance specifications; and
- Consider using preliminary performance verification works to de-risk the project/take advantage of opportunities (larger projects).

Theories of mechanical stabilisation of granular materials using geogrids have transferred into practice in recent years. Without geogrids, granular particles can translate and rotate under load which reduces the amount of dilation in these materials. Geogrids limit the particle's translation and rotation which increases it's dilation, particularly when the vertical loads are relatively small and cause the peak shear stress to increase as well as the ability of the geogrid reinforced zone to spread loads to underlying layers. A zone of influence of about 300mm on either side of the geogrid has been demonstrated (Lees and Clausen, 2020). Consequently, the bearing capacity of a given thickness of granular material increases meaning that less granular material is required than would be the case without geogrids to support a load.

The effect of the geogrid stabilisation can be incorporated into a design by increasing the effective cohesion of a Mohr-Coulomb failure envelope. The challenge for a designer is to establish what the increase in effective cohesion should be for the adopted granular material and geogrid. This data can be obtained from large scale triaxial or shear box tests but the equipment is rare and the tests relatively expensive. Geogrid suppliers such as NAUE and TENSAR have performed tests for a range of combinations of materials and geogrids and have incorporated the results into their software packages which are available to designers. However, they do not provide the test data and consequently there is some uncertainty about the accuracy of their software for combinations of granular material and geogrid available to a construction project. The uncertainty can be managed using well-winnowed experience relating to how geogrid reinforced materials behave in practice to apply appropriate input parameters to the software and adopt appropriate types of geogrid for the materials available to a project.

4.0 A Host of Other Factors: Sustainability, Resilience, Digital, Standards, Litigation, Claims and Education

4.1 Sustainability

Many government agencies have sustainability policies. These policies translate into requirements of practice for infrastructure procured by government such as the Transport for NSW Sustainable Design Guidelines (TfNSW, 2019). Opportunities for geotechnical practitioners to contribute lie in areas of greenhouse gas emissions, material selection, reductions, reuse and recycling.

Practitioners were asked the following questions on sustainability and are summarised in Figure 18 and Figure 19.

- Do you use digital modelling to do sustainability calculations on your projects?
- Do you currently consider sustainability principles as part of the design process?
- To what extent are sustainability outcomes being specified and required as part of the work packages and designs you are delivering?
- To what extent do you understand the behaviour of recycled materials?

Digital modelling allows volumes to be extracted, and sustainability calculations performed. Based on the data, at the moment it appears that these types of calculations are not performed often by the geotechnical profession. Various organisations might have sustainability consultants who perform this service. Sustainability appears not to be requested by clients very often and consequently is not provided in design very often. This suggests that sustainability outcomes will need to be explicitly required by asset owners or government agencies for them to be realised. Practitioners report they have some to moderate understanding of recycled material behaviour.

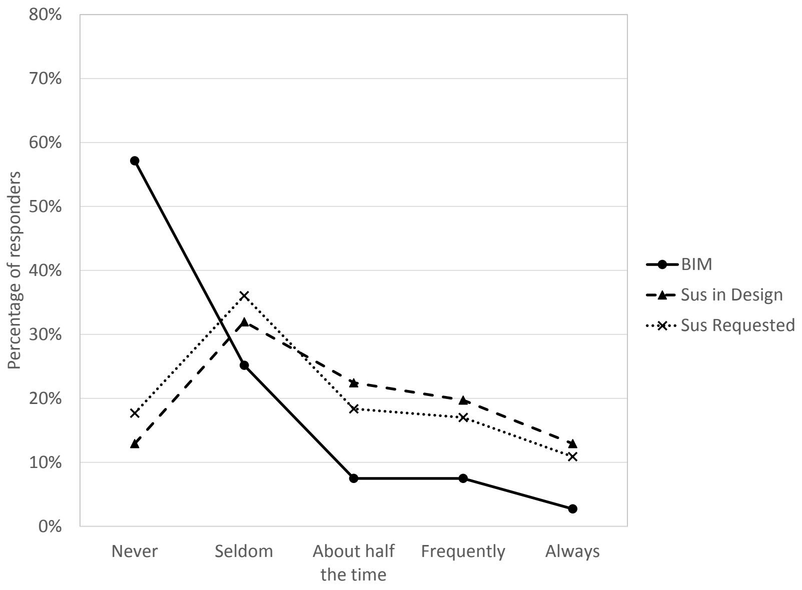


Figure 18 Summary of responses to sustainability questions

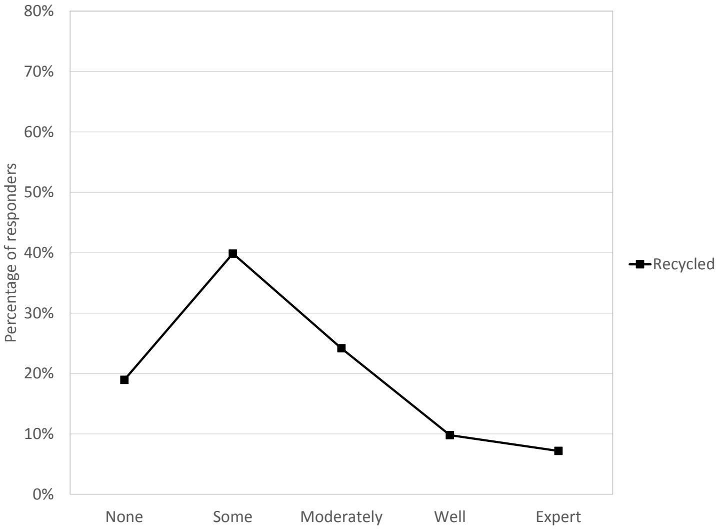


Figure 19 Responses on design of recycled materials

Waste materials have been used as fills instead of quarried products for the Albion Park Rail Bypass in NSW (Figure 20), the New Intercity Fleet Maintenance Facility at Kangy Angy in NSW (Figure 21) and reuse of tunnel spoil on another project (Albion Park Rail Bypass). Recycled asphalt (Reconophalt) has been used in pavements for the Denny Avenue Level Crossing Removal in W, use of crushed glass in asphalt instead of sand (Albion Park Rail Bypass), use of rubber in asphalt, encapsulating contaminated waste in earth fills to reduce spoiling (Albion Park Rail Bypass), and recycling concrete pavements through rubblisation for the Varsity Lakes to Tugun project in QLD (Figure 22). In this case concrete fracturing methods enabled existing materials to remain in situ as select granular materials in lieu of being sent to landfill. Some products from geosynthetic suppliers are also made from recycled materials such as separation fabrics and strip drains.

Figure 20 Granular Coal Wash Rejects at R31 Drainage Layer

Figure 21 Coal ash fill used instead of earth or rockfill at Kangy Angy

Figure 22 Rubblisation of concrete pavement, Varsity to Tugun, QLD

4.2 Resilience

Lifeline routes are transport corridors that needs to remain in service post some form of natural disaster. Critical transport infrastructure are pinch points in systems that would cause a significant loss of services with major consequences (NZ Lifelines Council, 2023). In countries like New Zealand and Australia with low population densities and large distances between towns it is not always possible to duplicate transport corridors and people become isolated with little outside assistance when a natural disaster occurs. Therefore there is an increasing need for certain transport corridors to remain open as lifeline routes and others to remain open to provide services. The corridors do not have to be in pristine condition but need to be accessible and able to be repaired rapidly.

Resilience in earthquake prone areas is well established. The more critical the infrastructure is, the higher the peak ground accelerations are adopted for design to reduce the probability of failure. Post recent rainfall and flooding, New Zealand has extended this concept to slope stability, washouts etc for their transportation networks (NZ Lifelines Council, 2023).

Kelly et al (2022) discuss that flooding can affect road and rail in several ways. A flood can washout ballast, cause scour and saturate the pavement and subgrade leading to loss of strength and degradation in pavement performance as well as batter failure. For new construction, the risks of flooding can be mitigated by raising the vertical alignment of road and rail infrastructure, albeit at increased cost.

The after-effects of flooding on state and rural roads can be managed in practice in several ways:

- Shut road or rail
- Reduced speed to reduce load
- Load limits

Key considerations are

- Adopting a flood return period for design that provide satisfactory immunity at reasonable cost
- Limit damage and safety risks in larger floods
- Re-open the road or rail as soon as practicable with minimal cost.

Guidelines for the protection of flood affected road pavements have been developed by the Queensland Department of Transport and Main Roads (DTMR). These guidelines were developed based on experience of flooding in western Queensland and data from moisture probes installed in unsealed pavements. Their procedure can be summarized as:

1. Assess how many days the pavement was under water
2. Assess the structural capacity of the pavement
    a. Minor inundation: visual
    b. Moderate inundation: inspection or deflection testing
    c. Severe inundation: Deflection testing
3. Compare with historic structural data if available
4. If inspection indicates poor surface seal then adopt a higher inundation condition.
5. Decide whether to open the road or impose load restrictions
6. Depending on structural assessment main load restriction for a period of 3 to 4 weeks.

The period of load restriction is based on a 3 month pavement dry back model where the subgrade modulus increases linearly with time. Based on this model and an 80% load restriction, loss of pavement life is reduced to 33% after 1 week, 58% after 2 weeks, 74% after 3 weeks and 84% after 4 weeks. The 3 month dry back model was validated by unpublished field moisture probe data.

The Binna Burra remediation project is an example of providing resilient design following damage to the area from a severe bush fire. The fire destroyed the historic Binna Burra Lodge (BBL), destabilised many slopes and closed roads. The design utilised rock netting and catch fences as relatively low cost methods to prevent trees and rocks from falling onto the road during a fire to keep the road open during the emergency. Post fire, debris can be removed rapidly from the fence and the fence repaired quickly if needed.

Figure 23 Rock fall netting installed at Binna Burra

4.3 Digital methods

Probabilistic methods are used to generate distributions of material parameters to assess characteristic values (eg Look, 2022) and they have been used in tunnelling to estimate the proportion of different ground behaviours that might be encountered.

Machine learning has been used by the Australian Rail Track Corporation (ARTC) for predictive maintenance in the Hunter region in NSW. Instrumentation mounted on trains is correlated with various types of maintenance performed and the behaviour of the instrumentation in a period of time leading up to the failures incorporated into the models. This allows ARTC to predict when and where a failure might occur and take preventative action. The key challenge for predictive maintenance was organising the rail maintenance records to enable the data to be used by the machine learning algorithms (Prof Jinsong Huang, University of Newcastle, personal communication). Data management was approximately 80% of the effort required to build a predictive maintenance capability.

Emerging areas using stochastic (probabilistic) and artificial intelligence methods were surveyed with the following questions:

- How often do you perform stochastic / probabilistic analyses to inform risk based decision making?
- How often do you use Machine Learning / AI techniques?

Unsurprisingly, the results in Figure 24 show these techniques are currently seldom used in practice. However, this is likely to change rapidly into the future. Anecdotally some contractors in the USA are investigating the use of AI to analyse the field performance data and then better optimize their field operations and efficiency (Prof DeJong, personal communication). It has also been used in finite element simulations for dams, where AI is being used to sort and categorize different simulation runs based on the failure modes. My organisation has used AI methods to assess the risk of slope stability in a given area based on histories of failure, geology, rainfall and topography.

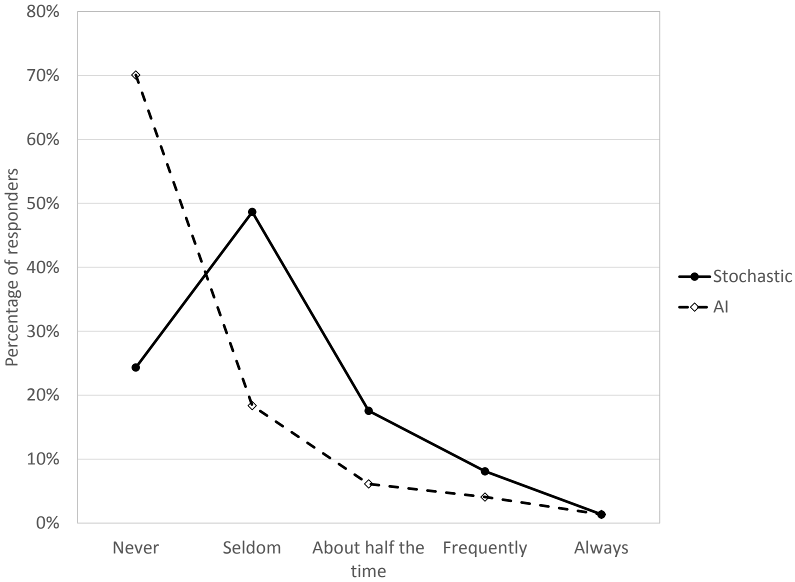


Figure 24 Summary of use of Stochastic and AI methods

4.4 Legislation, standards, specifications and contracts

The state of practice is supported by legislation aimed at ensuring that industry competency is a level acceptable to the community. There are various legislative requirements for professional engineers such as the Queensland Professional Engineers Act (2002). Such acts aim to regulate the engineering profession and protect the public. Compliance with the legislation can be demonstrated through competencies and compliance with standards. Non-compliance can lead to prosecution of individual engineers.

Standards aim to create a level of consistency across industry. On their own, standards are voluntary. There is no requirement for people to comply with standards. However, State and Commonwealth governments often refer to Australian Standards® (AS) or joint Australian/New Zealand Standards (AS/NZS) in their legislation. When this happens, these standards can become mandatory (https://www.standards.org.au/standards-development/what-is-standard). Standards are developed by a group of stakeholders based on the technical knowledge at the time. As knowledge changes over time, standards are also reviewed and changed over time. The USA has a similar approach to standards via ASTM and ASHTO and is likely true in many other countries as well.

Many asset owning agencies also develop a range of specifications. These specifications become contract requirements on their projects. The specifications are developed based on events that happen on past projects over a long period of time. Consequently, not all clauses in specifications are relevant to a particular project. As time goes on and people move or retire the corporate knowledge is lost and often no one knows why certain clauses are in the specifications and in what cases those clauses should be applied. Many specifications have provisions for project specific amendments but often it is difficult to agree these with asset owners during a tender process and even more difficult to amend post contract award. Standards and specifications sometimes have provisions to design outside of their requirements if the engineer can demonstrate through testing or other means that the alternative approach achieves performance requirements. However, conforming with these requirements can take time and expense so often are not pursued.

Legislation, standards and specifications exist to protect the public and help asset owners achieve the performance they are paying for. These are valuable outcomes. However, the processes can stifle innovation and change in many cases.

In addition to the technical requirements, there usually are also contractual requirements that practitioners need to comply with such as standards of care and best industry practices. Unlike objective legislation, standards and specifications these requirements are somewhat subjective.

Yabusaki et al (2020) reviewed legal claims in geotechnical engineering in the USA and stated that A claim ultimately arises out of an assertion that the engineer has failed to meet the Standard of Care (SOC). The Standard of Care is an all-encompassing, ill-defined standard that professionals, such as geotechnical engineers, are legally required to meet. The Geoprofessional Business Association (GBA, formerly the Association of Soil and Foundation Engineers (ASFE)) defines the Standard of Care as "…that level of skill and competence ordinarily and contemporaneously demonstrated by professionals of the same discipline practicing in the same locale and faced with the same or similar facts and circumstances." In some cases it is clear whether or not the contract technical requirements have been met. However, even when all contract technical requirements are met it is still possible to generate a claim using general clauses such as "the works shall be designed and constructed using best industry practices" which mean that the parties are obliged to meet a standard of care. I encountered an example recently where a slope failed as a result of heavy rain. The rainfall exceeded thresholds specified in project technical documents. An expert acting for the insurer provided an opinion that the rainfall could reasonably have been anticipated during the life of the project based on the available historic rainfall records. This implied that the designers breached their standard of care in not considering such heavy rainfall. The competence …contemporaneously demonstrated by professionals… further complicates the state of practice. A defence against a claim could be that despite some performance requirements not being met, common industry practices in year X were provided and therefore the designers met the standard of care. In other words, if everyone does things the same way and that way leads to unexpected outcomes then the standard of care is discharged.

4.5 Litigation and claims

Over time, projects have been increasing in size and complexity and also being constructed in increasingly congested areas. One consequence is that geotechnical risk and unpredictable ground conditions have contributed to increased cost over-runs and delays (Infrastructure Australia, 2021). Further, claims and litigation on major projects is becoming common. Yabusaki et al (2020) found that the major category of claim was technical error and within this category design error and inadequate site investigation were the most significant contributors to technical error along with a category for inadequate testing. Design error is a broad term that captures many factors. In my experience, errors in calculation, lack of review or negligence are rare. The most common source of error is an oversight or incorrect assumption often caused by a misunderstanding of ground behaviour or system behaviour including ground, groundwater and other assets. Peck (1980) also reports that failure can be due to not understanding the ground. Some examples I have encountered are:

- Slope failures in cuts constructed on weak rocks that degrade to clays over time where the time dependent behaviour was not identified or appreciated;
- Slope failures in materials derived from basalt with little or no site investigation and a lack of appreciations that these materials are sensitive to failure. These conditions are common across the eastern states of Australia;
- Failure where a pre-existing shear plane below deep colluvium was not identified;

- Failure of railway capping and deformation of a piled noise wall as a result of blocking drainage from the formation;
- Settlement of fills constructed from non-durable low strength rocks where the time dependent behaviour of the fill was not appreciated (eg Muttuvel et al, 2020); and
- Settlement of fills constructed on soft soils where the effects of sample disturbance on the material properties was not appreciated, and then the back analysed parameters relying on settlement data and ignoring the pore pressure measurements (Kelly and Wong, 2009).

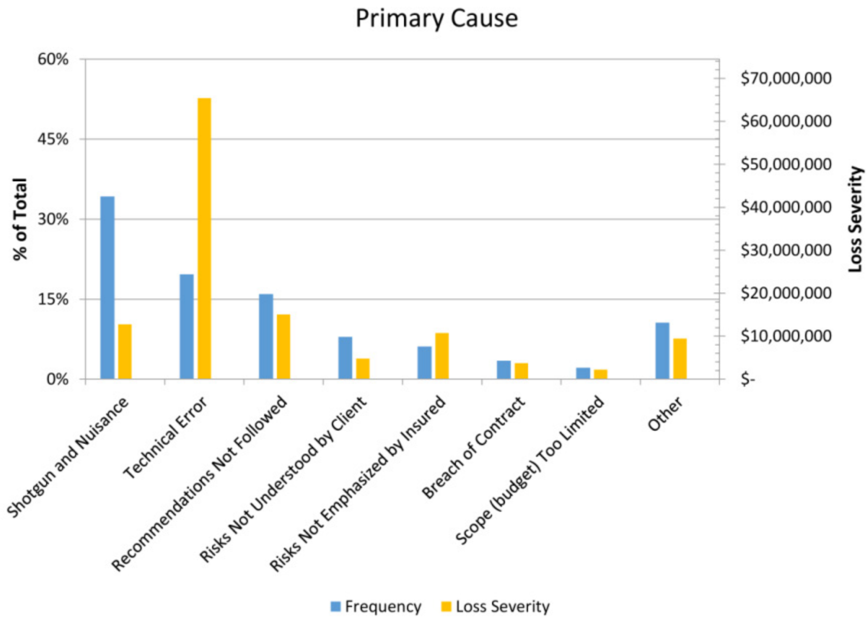


Figure 25 Primary cause of claims (Yabusaki et al, 2020)

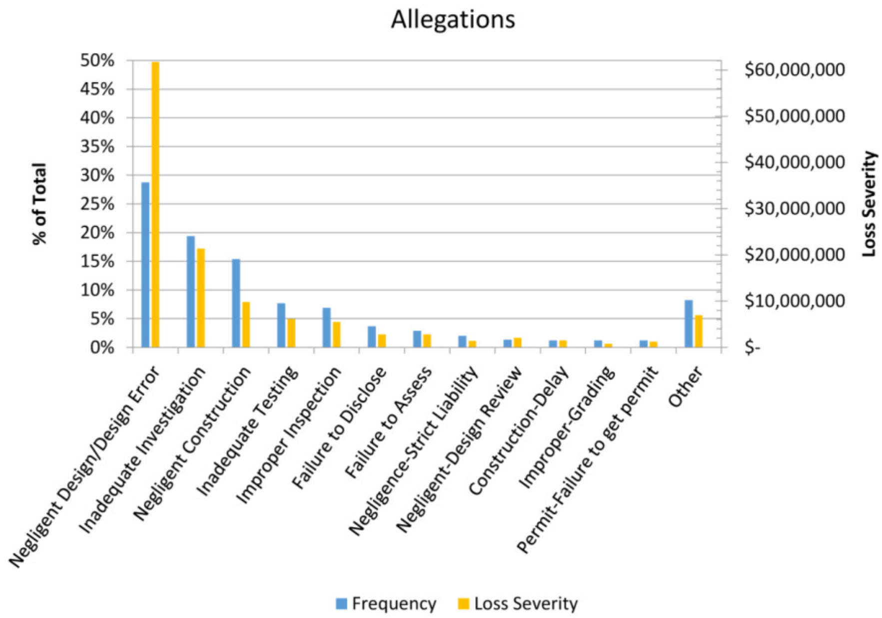


Figure 26 Allegations in claims (Yabusaki et al, 2020)

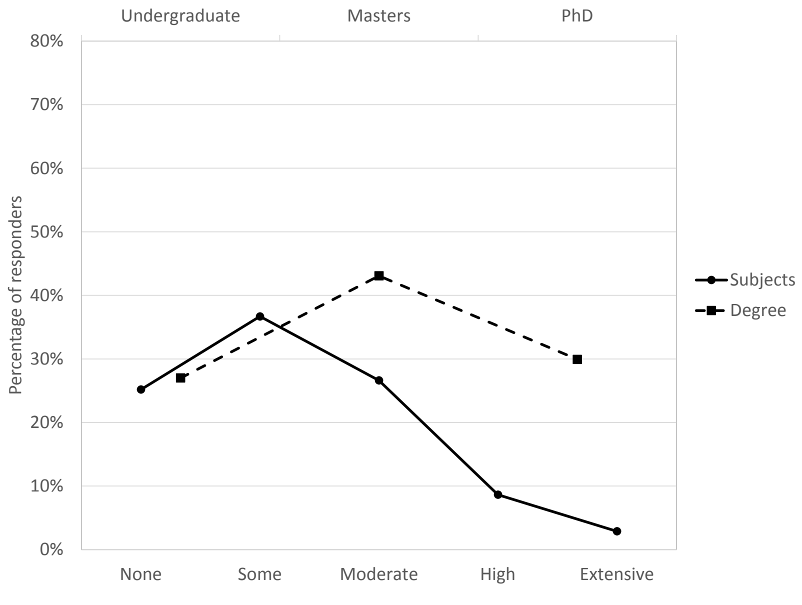
4.5 Education and Training

Part of developing experience is collecting knowledge and skill. While much of this occurs on the job, formal training is also required. Further, collaboration and connection with academia can help a practitioner address a difficult problem while also providing the practitioner with new knowledge and opportunities for professional development. The last series of survey questions was on interaction with academia. The questions asked were:

- What is your highest degree? (secondary axis)
- To what extent were you taught Transportation Engineering or ground improvement in your undergraduate degree? (primary axis)
- Does the organization you work for actively train you in transportation engineering or ground improvement via external or internal courses or coaching / mentoring on projects? ()
- Do you think that engagement with academia on industry-based research leads to improvements in your practice? ()
- Do you have a network of academic contacts who can provide advice on difficult technical issues ()

The responses show that there is a limited amount of subjects taught on transportation geotechnics. Subjects such as deep and shallow foundations, retaining structures, slope stability and laboratory testing are relevant and are taught in undergraduate degrees. Pavement engineering, railways and ground improvement tend to be post graduate masters and PhD subjects. Subjects like site characterisation, ground behaviour, earthworks materials, soil stabilisation, ground improvement and use of geosynthetics tend to be learnt on the job or in industry training sessions, seminars and conferences. Consequently, the majority of respondents report that their organisations provide training for them. The majority of respondents had a master's degree or PhD which suggests that an undergraduate degree does not provide sufficient technical development and post-graduate study is required. Consequently, practitioners reported that engagement with academia leads to improvements in practice and that they have contacts in academia that can help solve difficult problems. This feedback demonstrates that academia has industry impact that goes beyond teaching and research, at least in Australia.

Figure 27 Questions on subjects taught and highest degree



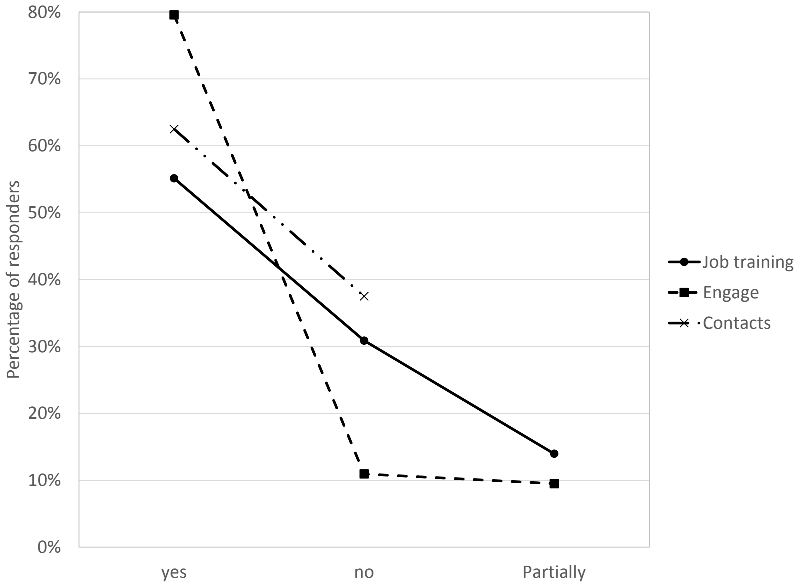


Figure 28 Interaction with academia

5.0 Reflections on the current state of practice in Transportation Geotechnics

Of all the many elements that are required to deliver transportation infrastructure, understanding ground behaviour is by far the most important in my opinion. The reasons are that analysis, design and construction all rely on the ground model and that poor understanding of the ground is the most significant factor in litigation and claims.

It is probably not surprising that many claims can be linked to not fully appreciating ground behaviour because ground is variable, rock masses and soft sensitive soils are hard to sample and test, groundwater flows through discrete features rather than the assumed continuum flow paths and material parameters are often not constants and change with state and time. The materials and systems geotechnical professionals try to understand and model are highly complex. However, it is also possible that ground behaviour should be better understood than insurance claims suggest.

De Groot and De Jong (2020) argue that the practice of site investigation has regressed from decades past as a consequence of commercial pressures, technical knowledge and non-implementation of a systematic approach to ground modelling. Some examples of poor practice identified by De Groot and De Jong are insufficient consideration of site geology, deviation from well-established tooling and procedural guidelines for conducting in-situ and laboratory tests, lack of borehole stabilization with drilling mud, lack of fixed piston for undisturbed tube sampling in softer soils and over-reliance on low-quality strength index testing conducted on poor-quality samples.

In general, I agree with De Groot and De Jong (2020) that ground modelling has regressed from decades past. There are long term trends in (Australian) practice that, in my opinion, have degraded our ability to model and understand ground. Some of these trends are:

- Engineering geology is not taught in undergraduate courses, and until this year was not being taught in any postgraduate courses. In other countries such as New Zealand and the UK the number of universities teaching engineering geology has reduced. Similarly hydro-geology and geophysics are not taught in undergraduate courses and only a limited number of postgraduate courses. Geotechnical engineers, if they are lucky, are taught a 6 month course in geology and increasingly are not being taught any geology at all. Stapledon (1996) identified similar trends in Australian education and arguably the geological teaching content has reduced further over the past 25 years.
- In Australia, engineering geologists are excluded due to having a science rather than engineering degree from Registered Professional Engineering qualifications that are becoming increasingly required to sign off work. The importance of their contribution to the engineering design and project outcomes is not appreciated. One could argue that if a geotechnical engineer is not well skilled in geology and ground modelling they are outside the limits of their expertise if they sign for this work. A Registered Professional is allowed to rely on the work of other Registered Professionals and arguably there should be a mechanism for engineering geologists to be recognised in this way. By not recognising the value of engineering geologists at universities and within the industry we create a perception that this profession is not as valued as engineering. This has lead to fewer people becoming engineering geologists to meet industry demands which is leading to poorer project and professional outcomes for critical infrastructure projects involving dams, tunnels and large earthworks.
- Laboratory testing is being taught less and less in universities.
- Laboratory testing has become a commodity product with low margins. Consequently most consultancies have closed their in-house laboratories and only a limited number of commercial laboratories exist. This results in a limited number of well trained laboratory technicians to perform the work and almost no on the job training for engineers and geologists.
- Design is considered to be application of some form of calculation coupled with generation of drawings or digital models. The ground modelling part of the design process is often considered an input rather than a fundamental basis for design.
- Engineering frameworks such as critical state soil mechanics for soils are not taught at all universities. Key elements of critical state soil mechanics are the behavioural links between strength and compression and the links between strength, stiffness and state (density and load). Consequently, practitioners do not have models of engineering behaviour they can have in their minds as they plan investigations, collect data and interpret that data. Key features can be missed that affect later construction. Note that the mathematics of any particular model is not necessary to know well.

There have been some improvements in site characterisation, particularly developments in electronics increasing the resolution and sensitivity of insitu test equipment such as cone penetration tests, dilatometers and geophysics. This has lead to higher quality data being obtained at lower cost than traditional borehole drilling and testing. Software for creation of digital models has also developed significantly over time. However, it is still difficult to integrate these softwares with civil engineering BIM softwares but I expect that better integration is a matter of time.

Advanced FEM, and similar methods, are typically used for soil structure interaction problems, deep excavations, tunnels, sometimes cuts and ground improvement. Capability in this area has significantly increased over time largely as a result of increasing computing power. Some software packages are very easy to use which allows people with a wide range of expertise to perform advanced numerical calculations. I find that many of my younger colleagues do not understand how these softwares work which results in analyses that require revision. Education and training at undergraduate level, postgraduate level and on the job is important now and will be increasingly important into the future as advanced numerical analysis becomes more common.

Earthworks require little analysis: it is more about understanding material behaviour. Design of earthworks can be crucial due to the large costs involved. This skill is becoming atrophied as a consequence of the same trends affecting understanding of ground behaviour.

Pavements / track use empirical methods and fairly rudimentary analytical methods sometimes many decades old. Part of the reason is asset owners mandate pavements to a large degree which means there is little opportunity to refine designs. Part of the reason is cyclic material behaviour is not well understood and cyclic numerical analysis is complex and seldom performed in practice. One exception is very high speed trains where dynamic loads become important.

Day and Briaud (2022) reported on an ISSMGE survey investigating whether the profession was over-designing. They found that in almost all cases, the average of the responses gave a reasonable answer to the problem. However, the range of responses was unacceptably large and contained many highly improbable outcomes. Only two of the ten problems considered indicated a tendency towards overdesign. The remainder of the problems included evidence of both over and under design. The range of rail formation designs on Inland Rail suggests that the result of the ISSMGE survey is representative of practice. On average over a large number of projects designers probably produce reasonable outcomes based on most projects appear to perform adequately. When negative outcomes occur leading to claims it could be termed under-design. Over design leads to higher capital costs and, in principle, lower maintenance costs. One could argue that highway pavements in Australia are deliberately over-designed to keep maintenance costs low. One could also argue that when maintenance access is difficult or disruptive to operations then rail, roads, airports and ports should be over-designed.

Casagrande (1965) discussed calculated risk in earthworks and foundation engineering. He defined calculated risk as "the taking of a carefully considered risk which is based largely on an analysis of factors that require experience and judgement for their evaluation". This definition was associated with the following two steps:

- The use of imperfect knowledge, guided by judgement and experience, to estimate the probable ranges for all pertinent quantities that enter into the solution of a problem; and
- The decision on an appropriate margin of safety, or degree of risk, taking into consideration economic factors and the magnitude of losses that result from failure.

Practice still grapples with the consequences of imperfect knowledge today and this is the core reason why well-winnowed experience is still important in practice and will probably remain so into the future.

Asset owners manage their risks via contract. Asset owners accept geotechnical risk in design only / construct only contracts. Asset owners transfer most risks to industry when design and construct contracts are used. Asset owners can choose to share risks in alliance and other forms of contracts. There are pros and cons for all types of contracts and there appears to be no conclusions about what type of contract produces optimal project outcomes. The challenge for geotechnical practitioners is that tendering for a project occurs at a time when there is a certain amount of information provided for tender which is insufficient for detailed design and construction. Knowledge is imperfect and calculated risks need to be taken. Various controls including the observational method and incorporating risk into the tender price can be implemented but the lowest price typically wins a tender and judgement is required to price risk in a winning bid. When a tender is won, further geotechnical investigations occur and observations are made during construction. However, the project still needs to be delivered on time and on budget and calculated risks still need to be taken. It is difficult to know what the consequences of this are, however anecdotally, short and long term performance of some projects awarded as low bid have not entirely met asset owner requirements.

The tunnelling industry recognise the consequences of imperfect knowledge and has developed the concept of Geotechnical Baseline Reports (GBR) which describe conditions that are expected and conditions that are not expected and are tied to schedules of commercial rates that apply when expected and unexpected conditions occur (Gomes, 2020). GBRs can and have been used for non-tunnelling applications. Practitioners were asked the following questions and results are summarised in Figure 29.

- Do you see benefit in a move towards risk based contractual mechanisms such as Geotechnical Baseline Reports;
- To eliminate duplication of work and streamline construction would you support reliance mechanisms between various stages of works (i.e. later stages can contractually rely on previous stages rather than duplicate work?); and
- Would you value a national open-access geotechnical database?

There was strong support for moving to risk based contract models, allowing reliance on previous stages of work to reduce duplication of effort and creation of a national open-access geotechnical database. There are concerns allowing reliance regarding who is liable for errors and omissions and hence whether subsequent design development phases are obliged to check previous stages of work in various ways to discharge their duty of care requirements. There are also concerns about open access databases. These are partly about uncertainties in the quality of the data and consequent liability issues and partly that businesses with existing databases view them as commercial advantage and will not share (in Australia).

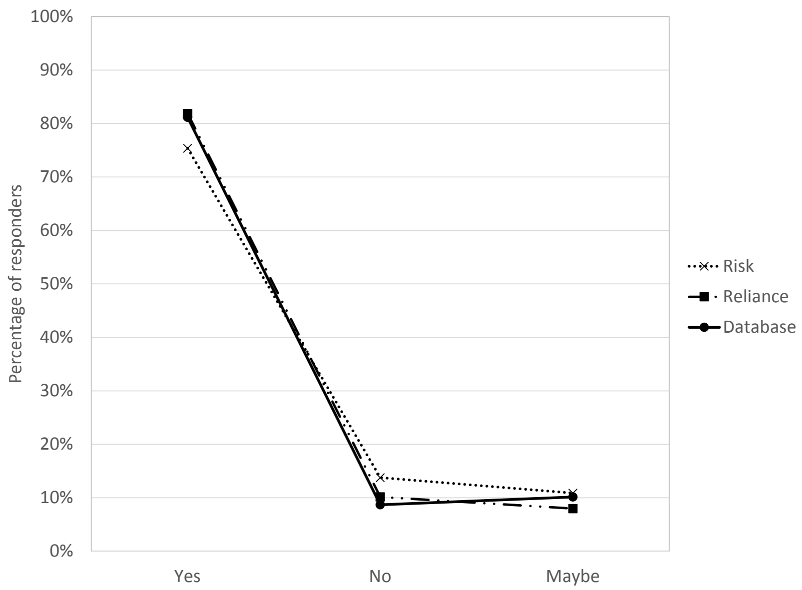


Figure 29 Results of risk and reliance questions

Geotechnical practice is characterised by the duality between objective theory and subjective judgement (Vick, 2002) and this will remain the case forever because it is not possible to know everything about the ground. Effective decision making requires practitioners to collect data, interpret limitations in the data collection, have strong theoretical understanding to allow interpretation of the data in an engineering context and strong analytical skills while at the same time obtaining experience of actual performance compared to predicted performance. The theoretical and analytical components are general in nature but obtaining experience requires involvement in the construction of roads, railways, ports and airports.

Our actual knowledge and understanding of ground behaviour continues to grow, as evidenced in part by the more and more advanced constitutive and numerical models being developed. However, the gap between state of art and state of practice is widening when it comes to a realistic understanding of materials and ground behaviour (Prof DeJong personal communication) and this is due to industry practice relying more and more on past experience, numerical analysis and empirical methods than on ground behaviour. Mostly industry practice is adequate for routine work or work with a long precedent in a particular geological terrain. However, in the future when we build infrastructure for larger, faster, heavier and more frequent transportation in less known ground conditions, we are more and more likely to have a failure and more likely to face insurance claims. When we push the limits of design precedent we must engage more deeply in understanding ground behaviour and make it the basis of our designs.

6.0 Future developments

Mitchell and Kopman (2013) identified ten certain trends that would affect our profession (Figure 30). In the Australian context, all of these predictions have come true and in addition there has been large population growth since that time. A historic level of transport infrastructure is being delivered with a major step change in volume between 2016 and 2018. COVID struck in 2020 which had the effect of stretching supply lines, increasing material costs, encouraging older engineers to retire and restricting migration of international engineers which has lead to a significant blow out in project costs. This is having the consequence of new projects being delayed, reduced in scope and cancelled. At the same time, our communities want to transition from fossil fuels to renewable energy over a relatively short time period. Enormous investment will be required for energy transition and this money needs to come from somewhere. It is likely that some of it will come from a reduced spend on transport infrastructure which will further limit the quantum of work in this area unless our industry can reduce project costs. In parallel, computing power has increased significantly which is enabling new technologies such as artificial intelligence and creating an ability to automate many processes.

TEN CERTAIN TRENDS TO CONSIDER NOW

(from ASFE, 2012)

ASFE's Emerging Issues and Trends Committee addressed the emerging trends most likely to affect the geoprofessional industry during what was termed the "Crystal Ball Workshop" in July 2011. The following list of "Ten 'Certain' Trends to Consider Now" is excerpted from ASFE Practice Alert Number 53 (ASFE, 2012) that reports the results of this workshop.

1. **Technology** will continue to change the way we work - ~~a~~ "bring your own device" and migrate to the "cloud" are examples of strategies that could be adopted to accelerate speed of communication and service delivery.
2. **Technology** is "leveling the playing field" - firms must differentiate themselves to avoid commoditization as a result of looking like everybody else.
3. **The demographic shift** as 80 million "Baby Boomers" begin to retire and 80 million tech-savvy "Millennials" enter the workforce will cause social media to become fundamental business communication media.
4. **Water scarcity and related food shortages** could provide significant opportunities for firms with water-resources expertise.
5. **Climate change** may cause sea level rise, increases in the frequency and intensity of weather-related natural disasters, and adverse impacts on infrastructure, commerce and welfare.
6. **World energy demand** will be 50 percent greater than in 2011. The demand for alternative and renewable energy resources will increase as will that for enhanced recovery techniques for fossil fuels.
7. **Consolidation in the geoprofessional industry** will continue. Smaller firms will need to develop effective profitability, capitalization and ownership transition strategies.
8. **Firm sustainability** will become a growing challenge. Recession-caused downward fee pressure and profit squeeze are making it difficult for many firms to build the balance sheet needed for shareholder retirement.
9. **A "war for talent"** is brewing. Understanding the factors that motivate job satisfaction and employee engagement is critical.
10. **Purpose-driven organizations and corporate responsibility** will be effective in attracting and retaining talent. Younger employees of today are looking more for the "why" than for the "what".

Figure 30 (Mitchell and Kopman, 2013)

In addition to these ten trends, I offer the following five predictions for the future.

- The future of transportation is bigger, heavier, faster and longer ships, planes, vehicles and trains (Kelly et al, 2022) that will require further developments in material science, theory, analysis and construction to ensure new infrastructure can be built effectively and efficiently;
- People with a deep understanding of their subjects will survive and thrive: everything else will be automated
- Education and lifelong learning will be important. Practitioners will need to make themselves aware of the emerging theoretical developments so they can be implemented. Post-graduate study and connections with academia will be required;
- Understanding ground behaviour will remain the core skill of geotechnical engineers and the basis of the value we provide our communities. Fundamentals such as geology, groundwater, soil and rock mechanics, inductive

- reasoning, development of geological and geotechnical models and construction experience will be enduring necessary skills;
- The digital revolution will require skills in mathematical optimisation to understand how AI works as well as computer programming skills; and
- Experience will be just as important to successful delivery of projects as it was thousands of years ago;
- Understanding the duality between objective and subjective elements of our profession, consequent risk and the ability to help people make balanced decisions that optimise cost, quality, time and community requirements; and
- An ability to understand all stakeholders perspectives and communicate effectively to stakeholders and the community.
- Artificial intelligence capability will continue to be developed. AI methods are data driven where mathematical optimisation is used to extract information and the spread of information. For AI to fully realise its potential curation of data and collection of high quality data will be essential. For example, high quality site investigation and instrumentation data helps Bayesian AI methods converge to solutions more rapidly than if poor quality data is used. This has the potential to reverse the decades long regression in site investigation practices because it will be clear that tangible benefits accrue when high quality geotechnical data is collected;
- Sustainability in its widest definition will become increasingly mandated by governments. Geotechnical professionals will need to become familiar with the behaviour of recycled materials, reuse of existing assets and methods to reduce the use of natural materials. There will be a range of other requirements that need to be considered when delivering transportation infrastructure; and
- Construction productivity will increase. Productivity in Australia today is lower than it was in 1990 (https://www.constructors.com.au/wp-content/uploads/2022/11/Disrupt-or-die_November-2022.pdf). Cost pressures and a lack of people will require improvements in productivity in the transport sector. Risk sharing contracts where parties focus on best for project outcomes rather than managing their risk exposure will continue to be explored. From a geotechnical perspective, automation and digital tools will be developed to help people deliver more work in the same amount of time. Duplication of effort will be reduced through reliance on information collected by other parties and use of geotechnical databases providing that liability issues can be managed.

7.0 Closing remarks

In closing, our communities require all forms of infrastructure, including transport infrastructure, in order to exist in their current forms. Gravity dictates that everything on land is connected to the ground and consequently the geotechnical profession has a profound influence on the well-being of our communities. The current state of practice delivers transport infrastructure on a large scale efficiently and effectively most of the time. While there are many areas of practice that can be improved we should all be rightly proud of the contributions we make to the communities we live in.

Acknowledgements

The author thanks the following people for their contributions to this paper. Mr Timothy Thompson (ARUP) for execution of the practitioner survey. Prof Jason DeJong (UC Davis) for review of the manuscript, Mr Brendon Gill (SMEC) for comments on rail track and transition design. Mr Geoff Pettifer (SMEC) for contributions to geophysics. Mr Mark Drechsler (SMEC) for contributions to earthworks, Mr Ian Shipway (EDG) for discussions on ground modelling, Mr Greg Hackney (EDG) for general review, Mr Pablo Balmaceda (SMEC) for discussions on road, port and airport pavements. Prof William Powrie (University of Southhampton) for discussion on railway design. Mr Jonathon Hale (Menard), Mr David Chadwick (Keller) and Mr Oliver Batchelor (Keller) for commentary on ground improvement.

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Appendix 1 Survey data

	To what extent are you involved in developing geological models for a project?				
	Never	Seldom	About half the time	Frequently	Always
Number	18	36	26	79	34
Percentage	9%	19%	13%	41%	18%

	To what extent are you involved in developing groundwater models for a project?				
	Never	Seldom	About half the time	Frequently	Always
Number	45	86	22	30	9
Percentage	23%	45%	11%	16%	5%

	To what extent do you adopt the process outlined in the Guidelines for the Development and Application of Engineering Geological Models on Projects (IAEG, 2022) [If you have not heard of the guidelines, please indicate 'Never']				
	Never	Seldom	About half the time	Frequently	Always
Number	133	24	8	20	8
Percentage	69%	13%	4%	10%	4%

	How frequently do you specify an investigation to strategically assess the key engineering parameters and geological conditions affecting construction of a project?				
	Never	Seldom	About half the time	Frequently	Always
Number	9	21	24	61	47
Percentage	6%	13%	15%	38%	29%

	How often do you specify routine investigations including drilling, sampling and SPT tests?				
	Never	Annually	Monthly	Weekly	Daily
Number	18	36	66	29	13
Percentage	11%	22%	41%	18%	8%

	How frequently do you specify more advanced investigations including geophysics, CPT and other forms of soil or rock in situ testing?				
	Never	**Annually**	**Monthly**	**Weekly**	**Daily**
Number	21	59	68	10	4
Percentage	13%	36%	42%	6%	2%

	How frequently do you request routine laboratory testing such as index, earthworks, strength and compression tests?				
	Never	**Annually**	**Monthly**	**Weekly**	**Daily**
Number	9	40	70	33	9
Percentage	6%	25%	43%	20%	6%

	How frequently do you request advanced laboratory testing such as cyclic triaxial testing or unsaturated soils testing?				
	Never	**Annually**	**Monthly**	**Weekly**	**Daily**
Number	50	79	25	5	2
Percentage	31%	49%	16%	3%	1%

	To what extent do you check the laboratory and insitu test data for errors or consistency with other data sets?				
	Never	**Seldom**	**About half the time**	**Frequently**	**Always**
Number	9	29	23	48	52
Percentage	6%	18%	14%	30%	32%

	How frequently do you interpret data to derive generic parameters for soils and rocks according to their density, consistency or other?				
	Never	**Seldom**	**About half the time**	**Frequently**	**Always**
Number	7	19	33	64	36
Percentage	4%	12%	21%	40%	23%

	How frequently do you interpret the data to derive optimal parameters for soils and rocks based on advanced in situ and laboratory testing?				
	Never	**Seldom**	**About half the time**	**Frequently**	**Always**
Number	11	53	32	38	25
Percentage	7%	33%	20%	24%	16%

	To what extent do you understand critical state soil mechanics?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	10	54	40	42	8
Percentage	7%	35%	26%	27%	5%

	To what extent do you understand earthworks material behaviour including effects related to partial saturation and durability of earthworks materials?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	5	34	44	60	10
Percentage	3%	22%	29%	39%	7%

	To what extent do you understand the behaviour of rock masses including excavation, changes in properties over time, collapse and deformation?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	6	42	45	50	10
Percentage	4%	27%	29%	33%	7%

	To what extent to you understand the cyclic behaviour of materials in rail track and pavements?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	20	49	43	28	10
Percentage	13%	33%	29%	19%	7%

	To what extent to you understand pile behaviour including installation?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	9	37	40	49	18
Percentage	6%	24%	26%	32%	12%

	To what extent do you understand soil structure interaction of retaining walls and around box culverts and bridge abutments?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	10	37	40	50	15
Percentage	7%	24%	26%	33%	10%

	To what extent to you understand principles of ground improvement including consolidation, reinforcement (including grids and fabric), chemical stabilisation, densification and reducing permeability?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	5	21	42	60	25
Percentage	3%	14%	27%	39%	16%

	To what extent to you understand the engineering behaviour of recycled materials?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	29	61	37	15	11
Percentage	19%	40%	24%	10%	7%

	How frequently do you develop design options based on understanding of the asset owners needs, construction methodology and the ground prior to performing detailed analysis?				
	Never	**Seldom**	**About Half the Time**	**Frequently**	**Always**
Number	12	16	30	60	30
Percentage	8%	11%	20%	41%	20%

	How frequently do you use analytical solutions?				
	Never	**Annually**	**Monthly**	**Weekly**	**Daily**
Number	15	24	58	29	23
Percentage	10%	16%	39%	20%	15%

	How frequently do you use routine numerical analysis such as limit equilibrium, pile software and retaining wall software?				
	Never	**Annually**	**Monthly**	**Weekly**	**Daily**
Number	28	25	49	30	16
Percentage	19%	17%	33%	20%	11%

	How frequently do you use advanced numerical analysis such as finite element and finite difference software?				
	Never	**Annually**	**Monthly**	**Weekly**	**Daily**
Number	37	39	32	25	14
Percentage	25%	26%	22%	17%	10%

	Do you understand the scientific and mathematical formulations of the software that you use?				
	Never	**Seldom**	**About Half the Time**	**Frequently**	**Always**
Number	13	20	36	54	25
Percentage	9%	14%	24%	36%	17%

	How often do you perform stochastic / probabilistic analyses to inform risk based decision making?				
	Never	**Seldom**	**About Half the Time**	**Frequently**	**Always**
Number	36	72	26	12	2
Percentage	24%	49%	18%	8%	1%

	How often do you use Machine Learning / AI techniques?				
	Never	**Seldom**	**About Half the Time**	**Frequently**	**Always**
Number	103	27	9	6	2
Percentage	70%	18%	6%	4%	1%

	Do you use digital modelling to do sustainability calculations on your projects?				
	Never	**Seldom**	**About Half the Time**	**Frequently**	**Always**
Number	84	37	11	11	4
Percentage	57%	25%	7%	7%	3%

	Do you currently consider sustainability principles as part of the design process?				
	Never	**Seldom**	**About Half the Time**	**Frequently**	**Always**
Number	19	47	33	29	19
Percentage	13%	32%	22%	20%	13%

	To what extent are sustainability outcomes being specified and required as part of the work packages and designs you are delivering?				
	Never	**Seldom**	**About Half the Time**	**Frequently**	**Always**
Number	26	53	27	25	16
Percentage	18%	36%	18%	17%	11%

	How frequently do you specify or use the Observational Method to validate your designs or control construction risks?				
	Never	Seldom	About Half the Time	Frequently	Always
Number	8	26	37	49	22
Percentage	6%	18%	26%	35%	15%

	How frequently do you use / interpret conventional earthworks testing?				
	Never	Annually	Monthly	Weekly	Daily
Number	15	42	51	27	6
Percentage	11%	30%	36%	19%	4%

	How often do you use alternate methods such as LWFD and intelligent compaction for earthworks testing?				
	Never	Annually	Monthly	Weekly	Daily
Number	87	39	13	2	1
Percentage	61%	28%	9%	1%	1%

	How often do you specify / interpret inclinometers, settlement plates, VWP etc?				
	Never	Annually	Monthly	Weekly	Daily
Number	25	67	39	7	3
Percentage	18%	47%	28%	5%	2%

	How often do you use drones / LIDAR and other remote sensing technologies?				
	Never	Annually	Monthly	Weekly	Daily
Number	46	45	36	11	4
Percentage	32%	32%	25%	8%	3%

	What is your level construction support experience?				
	None	I have made periodic site inspections	I have been a Resident Engineer (e.g. site-based Construction Phase Support)	I am/have been a Construction Contractor	
Number	8	54	60	18	
Percentage	6%	39%	43%	13%	

	Noting ground works typically sit on a construction critical path, do you feel geotechnical practitioners have a good understanding of contractor needs/drivers?		
	Yes	**No**	**Maybe, please explain:**
Number	59	45	34
Percentage	43%	32%	25%
			• Very much depends on the engineer. • Only those who frequently visits sites and work with contractors. Office based roles are restricted. • Insufficient geotechnical data • Depends the practitioners experience • Variable, depending on practitioner and project • Some do. Some don't • Depends on your client, if the client is a contractor yes, otherwise no • Sometimes. Main issues are around temp works integration into perm works • Those geotechnical practitioners that have had exposure to construction quickly develop an understanding of of contractors needs/drivers. Unfortunately I would say between 5-10% of geotechnical practitioners have had this exposure. • Varies • Very important but often you see geotechnical engineers without adequate knowledge to appropriately make decisions that will add value to Contractors work. Training and site based experience required for all practitioners. • It depends on complexity if the project and role of geotech in it. • Technical support from geotechnical design teams during construction operations it is a need, to support flexible and adequate solutions. In geotechnics, there is no place for a gap between design and construction. • There are many who has. • Some do and some don't • Lack the linkage between theoretical and practical applications • Some engineers are better than others! • Often financial race to the bottom, contractors not always seeing value • Contractor attitudes can affect how geotech advice is received and understood / put in context. Geotech practitioners too often fail to present feasible options in a risk context that allows the Contractor to make informed decisions. • Contractors needs tend to revolve around profit margins

	To what extent do you understand ground improvement construction?				
	None	**Some**	**Moderately**	**Well**	**Expert**
Number	2	18	41	61	19
Percentage	1%	13%	29%	43%	14%

	Do you see benefit in a move towards risk based contractual mechanisms such as Geotechnical Baseline Reports?		
	Yes	**No**	**Maybe, please explain:**
Number	104	19	15
Percentage	75%	14%	11%
			• Risk approaches are not a linear process • They may be useful if related to the proposed project. Generalised baseline reports may be less useful if they have to cover all situations with little reference to the proposed project • I HAVE NO IDEA • Don't know. • More work required with contractors, clients and designers required on risk sharing approaches • Only for high risk engineering like dams or tunnels • Not 100% sure what a Geotechnical baseline report is • Its value would be all in the implementation. Risk is often handed off to "someone else" and that someone would still exist in a different contract mechanism. • 1. A GBR may not be appropriate for all contracts. 2. What is included in the GBR needs to be measurable. This simple statement is agreed by most but in practice, measurable often proves contentious. Thus removing the benefit of the GBR. • On case by case basis • Baseline reports only provide a basis against which to judge actual outcomes. Their practicality and advantage depends on the level of conservatism adopted and the impacts of conditions being inconsistent with the baseline. Understanding the ground better would be more beneficial than believing a baseline report reflects the actual conditions. • Most geotechnical designers from what I see don't understand risk at all in particular for Transport projects, geological and geotechnical modelling is often poor and both remedial and new projects are designed on FOS way above what is actually required • If it improves communication and drives a need for a more robust model. • Depends on project specifics and geology.

	Would you value a national open-access geotechnical database?		
	Yes	**No**	**Maybe, please explain:**
Number	112	12	14
Percentage	81%	9%	10%
			• If quality could be maintained • Existing databases are a commercial advantage to specific companies with well developed databases. • Depends on what data base. A proper relational data base? georeferenced? Considering the cost of lab an in situ test results, it is not acceptable that in the end of any project, all data is wasted rubbish, not properly stored and so, not accessible or in conditions to be used in the future to other projects or to support machine learning. When GIS became affordable and accessible technology, would be a priority to organize such information to use in the future. There is a huge effort still to be made on this. Relational data base came from the 70's, GIS were ready in the 80's, but many times we don't take advantages or use those technologies adequately. • Yes and no • Only if all geotechnical entities contribute. The IP issues would be difficult to overcome without legislation. Otherwise coverage would be patchy and would be of limited value for quantitative risk assessments, e.g., landslide risk assessments. • It would be good at times but it's also a commercial advantage for a business with lots of data to keep that in house • It's never going to happen - please stop talking about it • Contributors would need to be vetted as the database would only be as good as the data provided • Removes competitive advantage of established geotechnical companies who have extensive archives of project specific knowledge • So long as everyone contributed it would work. • Its a commercial advantage for established geotechnical practices. • Yes, but this will never happen, I have heard so much talk about this especially from the highest most experienced geotechnical practitioners in Australia, but it's all just talk, there is way too much vested interest in making money especially by the large geotechnical companies • I know that such data bases are implemented elsewhere in the world. Would the implementation of such a database lead to available information being misused by ill-informed contractors and consultants?

			• Consultants, individuals and business as a whole, do not understand the time and cost pressures Contractors are under and provide slow, dis-connected or conservative advice. • Many contractors hide their techniques so practitioners will have missunderestand the needs/ drivers • We are usually engaged to fix a problem or tick a box, its rarely about value adding which comes from early engagement in the project • Contractors are typically cost and schedule driven and often do not make adequate allowances for poor ground condtions, even when identified ahead of time. • Depends on how honest the contractor is. • Some do • Some do, some don't • Maybe 50% of the practitioners do • Some do, a lot dont • Dependant on persons experience level • I'm unsure: I"m not a geotechnical engineer, but an engineering and groundwater geologist • It varies across the industry • I was prevented from pile testing on a bridge because the piling was on the critical path

	To eliminate duplication of work and streamline construction would you support reliance mechanisms between various stages of works (i.e. later stages can contractually rely on previous stages rather than duplicate work)?		
	Yes	**No**	**Maybe, please explain:**
Number	113	14	11
Percentage	82%	10%	8%
			• Depending on many factors • Depends on the design criteria and clients need at the time of engagement. The word "duplicate" is not correct, designer should execute due diligence of works performed by others, if those works directly or indirectly impacting the designer current engagement • Would be nice, but contractually this is very difficult given the possibility of future wrong interp of existing results. • Don't always trust previous works • i confess i don't understand the hypothesis here in consideration • There is value in fresh eyes reassessing data sets and evaluating the validity/value/reliability of information. • Subject to QA/QC and qualified technical reviewers • I don't fully understand the question • The issue is responsibility. And it starts with the client wanting no responsibility for site investigations and/or reference designs they may have done. • It depends on the liability framework that applies. Conservatism or aggressiveness at earlier stages knowing that it becomes someone else's problem wont resolve the issues.

	What importance does industry place on specific experience in a geotechnical domain (e.g.: specific ground improvement methods as compared to general geotechnical capability)		
	Low	**Medium**	**High**
Number	31	76	31
Percentage	22.5%	55%	22.5%

	Do you feel that codes in place align with best industry practice?				
	Yes	**Usually**	**Sometimes**	**Rarely**	**No**
Number	4	49	61	14	10
Percentage	3%	36%	44%	10%	7%

	What is your highest degree?		
	Undergraduate	**Masters**	**PhD**
Number	37	59	41

	What is your highest degree?		
	Undergraduate	**Masters**	**PhD**
Percentage	27%	43%	30%

	To what extent were you taught Transportation Engineering or Ground Improvement in your undergraduate degree?				
	None	**Some**	**Moderate**	**High**	**Extensive**
Number	35	51	37	12	4
Percentage	25%	37%	27%	8%	3%

	Does the organization you work for actively train you in transportation engineering or ground improvement via external or internal courses or coaching / mentoring on projects?		
	Yes	**No**	**Partially, please explain:**
Number	75	42	19
Percentage	55%	31%	14%
			• Lots of skills sharing across disciplines. Transportation engineering outside of geotech as well as geotech specific skills • Small organization with over 60 years experience in field and laboratory testing and construction • Our parent company runs courses in different disciplines. • On the job training based on specific projects which come and go • National and international symposia • Project specific training only • Based on the assignment/task • External courses by suppliers /experts • On the job training (project related); ground improvement selection kept close to senior staff • Courses can be attended, if requested, and if there is a project/team benefit. • Coaching and mentoring on projects • Informal technical guidance, occasional webinar links • I am semi retired. • I teach rather than am taught • Some of it is self directed learning • We deal /learn/grow in this space as projects in this space arise. • Stormwater and slope stability. • I'm a one-man company

	Do you think that engagement with academia on industry-based research leads to improvements in your practice?		
	Yes	**No**	**Maybe, please explain:**
Number	109	15	13
Percentage	80%	11%	9%
			• Connection between academia and industry is not well practiced in Australia • Depends on whether the research has practical applications often it doesn't • Lots of academic research appears to go down detailed rabbit holes the outcome of which are generally overwritten by construction practices. A better focus on research at the practical application level are more useful. • Mixture of research quality • Absolutely, but it never happens! • Incremental steps • Often too theoretical • Only if it includes contractor/builder involvement • Add value with specialist knowledge not normally used • Very often the research is so niche and specialised that it is not useful or relevant to the industry as a whole. • Most academics do not have practical experience. • Yes, in some cases

	Do you have a network of academic contacts who can provide advice on difficult technical issues	
	Yes	**No**
Number	85	51
Percentage	62.5%	37.5%

	If you are a member of the Australian Geomechanics Society (AGS), what is your home chapter?	
	Number	**Percentage**
WA	12	8.6%
Tasmania	2	1.4%
SA/NT	10	7.1%
Victoria	26	18.6%
NSW	31	22.1%
Newcastle	7	5.0%
Qld	35	25.0%
Not a member	17	12.1%

	What is your approximate age?	
	Number	**Percentage**
18 to 24	1	1%
25 to 34	30	21%
35 to 44	39	28%
45 to 54	29	21%
55 to 64	26	19%
65 and above	15	11%

	What professional sector do you belong to?				
	Private company - consultant	Private company - contractor	Public entity	Academic institution (student, teacher, researcher)	
Number	104	11	7	15	
Percentage	76%	8%	5%	11%	

Do you have any other comments relating to the current state of Transportation Geotechnics?

Do you have any other comments relating to the current state of Transportation Geotechnics?

- Thanks and wish you the best with your work/survey and presentation of results.
- I am very concerned about a few things- for instance the advent of state based legislation that either deliberately or possibly accidentally excludes engineering geologists will lower standards, producing lower quality and more expensive work. The "independent verification process" appears to attract a box ticking approach that searches for options that are zero risk to the assessor (who is often out of their depth) but then achieve poor outcomes for everyone from the tax payer to the end user and everyone in between,
- Most of consultancy in this field is done by consulting engineer who are not well connected with academia.
- I work for a geosynthetics product supplier and deliver solutions for ground improvement applications.
- As always you get what you pay for. The quality of the design you get is also very dependent on the practical construction experience the designer has.
- I believe all data collected as part of Geotechnics needs to be captured in a centralised GIS based system as being done in the UK. We need to have the government have a registry for all new boreholes and new data delivered into a database at the end of projects as per the new Construction Playbook adopted in the UK.
- I am partly retired. Only working 5% of the time
- There is an urgent need for better connectivity between private, universities, and government. Things are getting worse and worse each year.
- Field expertise is generally poor.
- You did not mention the importance or any inclination to the use of geophysics
- Same old. No true innovation, to risk adverse (even perceived risk). No incentives from clients.
- Not sure what the future holds for the industry without young practitioners coming on board.
- Your feedback might be improved if an option was "others in my team action this". There is a lot of components I never or rarely look at and dont need to understand the full workings as I have qualified team members dealing with that.
- Your survey include data management aspects. Considering geotechnics is still in many aspects semi empiric, access to data it is essential. The use of AI and ML over data achieved and stored adequately, with quality i mean, need to be explore. Working for over 30 years, in public works, with labs exclusively dedicated to construction, also in transports (railway and roads), i confess many information, its majority, have been wasted, even to those who explore those structures. I participated in some attempts to store such data, through GIS or specific lab databases, but mostly with minor success than that information would deserve. Your concern about all this, is mine also.
- There seems to be less focus on understanding rock fall risk to transport geotechnics in Australasia
- Advised to open Professional body (e.g. International Transportation Geotechnics Society, ITGS)
- There are lots of gaps to be filled.
- Adoption of risk based approaches in the digital age still has a long way to go, particularly between academia and practice however the future seems very optimistic regarding the challenges, interesting solutions and opportunities for collaboration within the discipline of transportation geotechnics.
- Transport authority specifications and requirements appear to adopt geotechnical engineering as a science set in stone, forgetting that much of our field is based on empiricism and thus requires an experienced engineers interpretation when acceptability of earthworks comes into question.
- Has become poorer in NSW due to lack of capability/ Deskilling in government who provide most of the work
- I'm not entirely clear what it means. Does it strictly relate to transport infrastructure & roads/rail engineering?
- Best practice is commonly under valued by conservative clients who believe they are passing their risk to others, less experienced client personnel who assess cost first and by geotechnical consultants who under bid work and rely on traditional methods (as much point data as possible, no understanding of the engineering geology of the corridor) rather than adopting a staged approach which leads to a thorough understanding of the site and its engineering geological condition and history.
- A national reference to good practice would be of benefit. Noting there would need to be section related to specific structures. Why states vary in their contract requirements but there is overall principles applicable.

- Reviews upon reviews upon reviews from people who have very little knowledge on what they are reviewing is incredibly frustrating and detrimental to innovation.
- I act as a peer reviewer related to dams and landslides. I recently had some involvement in a highway project that had a major landslide which resulted in many $millions repair. The potential for that slide could have been identified by good peer review. I feel many problems would be picked up with more use of peer review.
- 1. Many companies (typically larger ones in my experience) are not focusing on developing an EGM (and indeed do not understand what an EGM actually is). Geology is treated as another step in the process, rather than a discipline that underpins the entire EGM. 2. I feel that the understanding of fundamental soil mechanics in the industry is poor, and getting worse. Consequently there seems to be reliance on things like rules of thumb (e.g. su=6N) to define parameters and models. 3. Due to lack of understanding, investigation and testing is poorly prescribed, and rarely challenged and understood. 4. As an industry, we have never had more analytical tools than we do right now, but things still seem to be going wrong. In my opinion, moving the focus back to understanding what we are analysing rather than just analysing would be beneficial.
- I am an ex RTA/RMS employee. I was in charge with running a large team of geotechnical professionals whilst working there whilst also engaging the services of many private sector geotechnical consultants. There are almost no words to describe the destruction of the government road and rail engineering in NSW. Simply put, building and maintaining road and rail infrastructure is a knowledge based practice. You can’t expect to hand this kind of engineering over to private industry and have them produce cost effective road and rail maintenance. The continued loss of experienced road and rail engineers from TfNSW to supervise private industry will only see the current state of transportation geotechnics decline both qualitatively and quantitatively.
- I feel that Transportation Geotechnics involves so many types of geotechnics that it does not warrant a separate “discipline”.

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