Challenges to Digital Transformation in Geotechnical Engineering

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ABSTRACT

The application of digital data and technologies in geotechnical engineering is not new; however, the use is sporadic and inconsistent among geotechnical engineering specialists and firms across the world. Further, this use is often limited to specific areas such as processing of field data during ground investigations and detailed numerical analyses of complicated foundation systems during design. There is a general lack of interoperability among the various digital tools and systems, which is inhibiting efficiency that could have been achieved otherwise using compliant platforms which can readily transfer data and models. This paper examines by way of examples where digital data and technologies are being used to increase efficiency in design and construction and enhance collaboration on construction projects. The paper explores the current state of the art and future potential opportunity to automate the whole geotechnical design process of capturing field data, generation of ground models, analyses and design, and visualisation of final solutions without the need for manual data entry at any of the intermediate stages. The level and stages where human input would continue to be required in geotechnical engineering are also reviewed, given the level of empiricism we still adopt due to significant gaps in our understanding of the variability of natural materials, behaviour of ground under loading and due to its complex interaction with other man-made materials and structures. In addition, a view is taken of the market driven barriers that might be limiting the efficiency of the geotechnical industry and the society in general, which could gain from the ongoing digital transformation.

Keywords: geotechnical, digital, market, challenges, design, construction, risk

1 INTRODUCTION

Digital transformation in geotechnical engineering broadly engenders a feeling of hope in the geotechnical engineers due to its potential strengths. Digital tools and processes can be used by geotechnical engineers to capture the spatial distribution and highly complex characteristics of natural materials; to facilitate prediction of the mechanical behaviour of materials for design purposes and to help visualise a ground model and associated geotechnical solution that can otherwise be difficult to communicate to the end user and non-geotechnical engineers. However, on the other hand, efforts to inculcate the widespread use of digital technology in geotechnical engineering process have yet to meet noteworthy success due to several impediments and challenges. These challenges are both of commercial and technical nature. The main commercial challenges include lack of competition among digital solution providers and geotechnical community itself (supply) as well as lack of appreciation among the end users or clients (demand) of the value that digital transformation can bring to their projects. Impediments of technical nature include uncertainties of dealing with significant variation in characteristics of natural materials (soil and rock), as well as limitations of our understanding of their highly complex constitutive behaviour when compared to other fields of engineering which mainly deal with manmade materials that can be modified to a required specification for design purposes. Due to these factors, it is relatively difficult to reduce the required human intervention and judgement in geotechnical design processes and to rapidly bring digital transformation in geotechnical engineering so that it is on a par with other engineering fields.

In this paper, the current state of digital transformation is reviewed, some of the known impediments are discussed and recommendations are provided to deal with the challenges.

2 STATE OF THE ART

2.1 Data Capture and Storage

Geotechnical Engineering Industry has achieved some good and consistent progress in data capture and storage processes over the last two decades or so, specifically when it comes to the transfer and storage of digital geological information from ground investigations.

Perhaps the most widespread use of digital data transfer within the international geotechnical community has been the AGS data transfer format, which was setup by Association of Geotechnical & Geoenvironmental Specialists in 1991. The AGS Data Format, with periodic updates allows for a consistent and seamless sharing of factual data between the different software used within the geotechnical industry (https://www.ags.org.uk). Recently, AGS have introduced AGSi (https://www.ags.org.uk/data-format/agsi-ground-model/) for ground models and interpreted data. Further, AGS piling (http://www.ags.org.uk/data-format/ags-piling-draft/) has been initiated to capture piling data.

GeoSciML is another example in the data space, which is an international data transfer standard for geological data, developed by the IUGS Commission for the Management and Application of Geoscience Information (CGI). The Government Geoscience Information Committee (GGIC), which represents all the Australian and New Zealand government geological surveys, has endorsed GeoSciML as the Australasian geological data transfer standard (https://www.ga.gov.au/).

For site investigations desktop studies, geological maps are digitally available to public in most states in Australia. Australian Government's Geoscience Australia Portal (https://portal.ga.gov.au/) provides full access to Geoscience Australia data and other publicly available geological data sources. It also provides a suite of analytical and multi-criteria assessment tools to maximise the value of the data. Berg et al. (2011) suggest Geoscience Australia and Geoscience Victoria have been the most active Geological Survey Organisations in Australia.

With the increasing availability of affordable Unmanned Aerial Vehicles (UAVs) / drones becoming available to "access" places otherwise not easily accessible or inherently unsafe on foot. In many cases, they can be used to undertake inspections of cliff faces without the need for scaffolding or roped access. The key limitation being that one can only see the rock without being able to touch or feel it, but often, some level of ground truthing through limited walkover surveys can significantly reduce this deficiency. Photogrammetry techniques enable accurate 3D digital models to be developed from the photographs taken from UAVs.

2.2 Development of Ground Models

Three dimensional geological models are increasingly being used to characterise ground supporting complex structures. Soil, rock, geological structures, such as faults, rock fall zones and slips are often best examined in a 3D domain.

Several geological modelling tools are available in the market with popular software used on Civil Engineering and infrastructure projects, including Leapfrog Geo, gINT and holeBASE. More specialised geological modelling tools are in use by the mining and energy sectors such as IRAP RMS suite and GoCAD Mining Suite. Similarly, specialised hydrogeological modelling tools such as Feflow and Modflow are also available. Berg et al. (2011) provides a useful global synopsis of the available geological modelling software and the list keeps on extending since then. GIS software such as Mapinfo and ArcGIS are also regularly used for 2D and 3D visualisation of site geology.

Table 1: Typical examples of Geological Modelling Software

Usage	**Digital Software**	**Provider**
Ground Model	gInt	Bentley Systems
Ground Model	HoleBASE	Bentley Systems
3D Ground Model	Leapfrog Geo	Bentley Systems

2.3 Geotechnical Analysis and Design

In the geotechnical design phase of a project, not much has changed in terms of the use of some main digital software tools for analysis and design over the past 20 years or so. The use is restricted mainly to few famous analysis software such as those required for 2D and 3D limit equilibrium, and 2D and 3D finite element analysis. Software packages are available to resolve geotechnical problems such as slope stability, ground settlement, pile group analysis, gravity and embedded retaining walls, deep excavations, driveability assessment and liquefaction analysis. Some new analysis and design software tools have been introduced into the market, but there remains just a handful of developers or providers in the geotechnical market whose software is being used by majority of the commercial firms.

Some good progress has been made to make the software tools more user-friendly and increased computing power has allowed improvement in computing speed and graphical user interface. However, very limited progress has been achieved in making the available software more interoperable.

Table 2: Typical examples of Geotechnical Design Software

Usage	**Software**	**Provider**
Slope Stability	Slope/W	Bentley Systems
Various (Finite Element)	Plaxis	Bentley Systems
Retaining Walls	Wallap	Bentley Systems
Settlement Analysis	Settle 3	RocScience
Slope Stability	Slide	RocScience
Rockfall Analysis	RocFall	RocScience
Pile Axial/Lateral	RSPile	RocScience
Pile Group	Group	Ensoft
Axial Pile Capacity	A-Pile	Ensoft
Lateral Pile Capacity	L-Pile	Ensoft
Pile Group Design	Repute	Geocentrix
Retaining Wall	ReWard	Geocentrix
Liquefaction	Liquify Pro	CivilTech
Piles	AllPile	CivilTech
Pile Driveability	GRLWEAP	Pile Dynamics
Piles PDA	CAPWAP	Pile Dynamics

2.4 3D Visualisation of Solutions

Digital visualisation of geotechnical solutions in 3D domain has limited use in the industry but projects with large earthworks infrastructure are making increased use of 3D models during construction for communication purposes among the geotechnical designers, earthworks contractor and the client.

For cut slope design, especially in rocks which require mapping by geologists, a 3D Leapfrog model with Esri's ArcView GIS interface using drone technology has been used successfully during the design and construction of the Manawatū Tararua Highway in

New Zealand. A 3D digital model for the entire project has been developed by Aurecon, including a fly-through during the tender stage which assisted the New Zealand Transport Agency and the local Iwi community leadership to understand the designer's thinking and enabled them to see first-hand how the new highway will integrate into its geological cut slope profiles and environmental context. Virtual Reality (VR) has also been an invaluable tool in conversations with both the local population of Iwi and the ultimate client, the Transport Agency. Within the Alliance, Aurecon's design and construction teams have made use of VR to help them understand how key design elements will integrate and fit in real life – for example, it has helped understand the complex interaction between bridge foundations, significant scale of earthworks, drainage and cultural expression design elements. The 3D models significantly assisted in interaction between the geotechnical engineers and other disciplines.

Figure 1. Digital Visualisation of major cuts on Te Ahu A Turanga – Manawatū Tararua Highway, New Zealand

2.5 Construction Management

Geotechnical design solutions are mostly based on idealised ground models that need to be validated on site in terms of the assumed stratigraphy, and strength and stiffness parameters. This allows the designer to provide economical designs that are not based on worst case ground conditions but the "most credible". The verification of the design requires an on-site presence as well as instrumentation and monitoring during construction. Observational method of geotechnical design is an extreme case example of this scenario, which heavily relies on site observations, and instrumentation and monitoring regime during construction.

A combination of 3D geological digital model, 2D or 3D GIS visual interface and data capture through regular fly-through using drone technology on site allows for management of construction of major earthworks on infrastructure projects. On Manawatū Tararua Highway project, monitoring of cuttings and embankments through drones alongside digital data capture tools on site have been used to feed into a 3D GIS interface in Esri's ArcView. The backend geological model in Leapfrog is then used by the office-based geotechnical engineers to compare with the face mapping results and the model is updated where needed. Verification of design assumptions and any recommendations to modify the design are all provided to the construction team in real time.

This augmented reality, where models and the real world can be visualised together by the decision makers is possible with the available digital tools but could be expanded to other projects if the wider industry adopts its use.

2.6 Instrumentation and Monitoring

Instrumentation and monitoring can assist with the design, construction, and operation of most geotechnical assets. It adds significant value when a high degree of uncertainty is present in the ground conditions, which significantly interacts with the structure being constructed. Geotechnical instrumentation can also be used for operational risk management of a potential geotechnical hazard through the use of an early warning system (EWS).

The last decade has seen the development of cloud-based systems, which can store a vast amount of data generated from monitoring of geotechnical earthworks and structural foundations during and after construction. The information can be made available to designers and to the relevant stakeholders in real time where the effects of ongoing excavations, foundation loading, retaining walls under construction and effects of weather events, for example, can be discussed and decisions made. Real-time data capture, remote monitoring with data loggers and presentation through digital visualisation platforms allow effective, timely and targeted assessment and design of remedial solutions. Spatial survey techniques, and instruments such as inclinometers, vibrating wire piezometers, extensometers, crack meters and digital profile gauge meters are commonly used on large infrastructure projects in Australia for these purposes.

2.7 Geotechnical Risk Management

Managing of geotechnical risks on projects is crucial for the success of any Civil Engineering project. Many Australian infrastructure projects have gone over budget, with a 2020 Grattan Institute report indicating cost overruns of $24 billion on just six current projects (Terrill et al., 2020). Deficiencies and shortcomings in design, ground investigations and the geotechnical interpretation of results are responsible for approximately one third of the total cost for errors (Nylén 1996 & 1999). Unforeseen site conditions are one of the most significant risk factors in causing delays to construction projects (Mbachu and Taylor, 2014).

A general perception within the construction industry seems to be that a higher budget allocation to ground investigation and testing on a project would proportionally improve the project team's understanding of ground and thus mitigate geotechnical risks to the required levels. Although true to an extent, this is just part of the story as capturing and understanding geotechnical risks is much more complex than merely capturing results from in situ and laboratory testing. As an example, based on data from UK's highway projects, around 1% of total construction cost at tender is allocated to ground investigations and even then, the data suggests that cost overruns of up to 100% might be possible

(Figure 2, Clayton, 2001). According to Jaksa (2014), expenditure on geotechnical site investigations on other types of construction projects varies considerably and can be as low as between 0.1 and 0.3% of the total project cost.

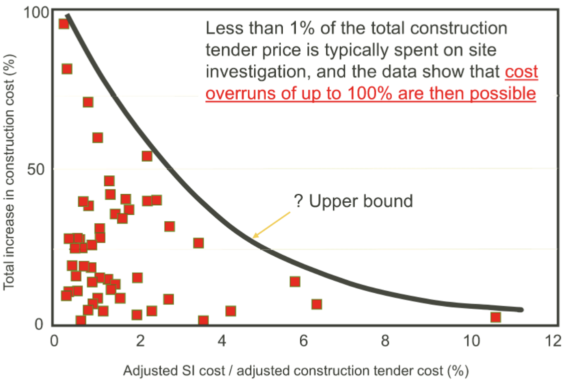


Figure 2. Adequacy of Site Investigations (Mott MacDonald and Soil Mechanics (1994), as referenced in Clayton 2001)

Geotechnical risk is a combination of mainly two types of uncertainties associated with the natural ground (Figure 3). These are risks associated with natural randomness of soils and rocks (Statistical Risks) and risks associated with inaccuracies in our prediction and estimation of reality (Systemic Risks). As such, any significant investment on site investigations beyond a certain optimum limit without properly understanding and mitigating systemic risks also, is unlikely to result in the desired positive outcome.

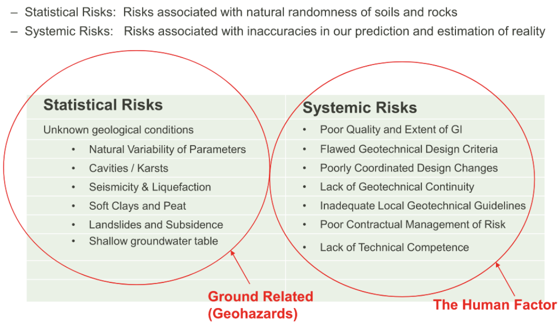


Figure 3. Types of Geotechnical Risks

The current state of the art mainly focuses on digitising information that supports understanding of statistical risks mainly and lack a holistic and systematic approach that captures both types of geotechnical risks during the course of the project.

A qualitative or a quantitative risk assessment can be carried out in practice to assess geotechnical risks; however, the general practice remains to be the assessment of geotechnical risks using a qualitative approach. This is usually done using simple Excel based matrix that determines risk levels using a product of impact and likelihood of the identified risks and communicated using a colour coded ranking system in a risk register for the purposes of mitigation analysis. Use of a more refined quantitative approach, such as Monte Carlo Simulation using digital tools, has yet to gain popularity within the geotechnical industry, although this approach is widely used by contractors on large-scale infrastructure projects.

3 CHALLENGES AND GAP ANALYSIS

3.1 Economics and Competition

Geotechnical engineering is not seen by many as an exact science, but more as an art with significant empiricism involved throughout the design process. As Professor John Burland (2012) says, “With a material as complex as the ground, empiricism is inevitable, and it is (and will always remain) an essential aspect of ground engineering”. Considering this, digitising geotechnical engineering is expected to come with a higher challenge and investment when compared to other engineering fields that have better grounds to formulate into a computer-based routine.

Digital transformation has shown to come with increased efficiency in the construction industry and a general expectation from the clients is a decrease in design time and cost on their projects. However, although geotechnical engineering industry has reaped some benefits when it comes to savings on labour intensive data entry tasks, such as those involving geological data capture, these benefits have not been transformed into an overall efficiency in the interpretation and design process and have not yet resulted in benefits to the ultimate clients in terms of shorter programme and reduced cost. This has resulted in general scepticism among the clients (low demand), and a reluctance to invest in digital transformation within the geotechnical industry.

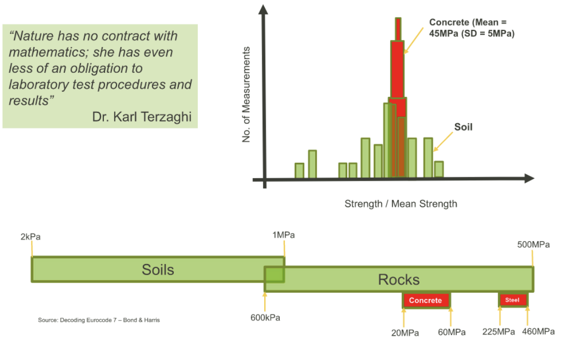
Another impediment is the low level of competition within the geotechnical industry itself to transform the geotechnical design process due to a general lack of appetite to embrace the change. One reason for this is the lack of leadership mainly arising due to digital skill gaps within the generally more influential senior members of the geotechnical community. Most experienced geotechnical engineers who are currently leading teams within major consultant and contracting firms may not have the right level of digital skills. It may not be reasonable or even be realistic to expect every ground engineer to have a similar level of digital skills however, to speed up the transformation, it is crucial for experienced ground engineering experts to be able to communicate with the digital specialists to help progress the transformation.

3.2 Digital Twin

As Seequent (2021) defines it, “A digital twin is a digital representation of the physical system. In addition to the initial geologic model created for the site, the digital twin must also capture the evolving site conditions. A classic example would be the creation of ‘as-built’ drawings for the construction of an earthen dam or tailings storage facility”.

The scale of natural variation in ground is known to be so significant when compared to man-made materials, such as concrete and steel, that the concept of Digital

Twin in geotechnical engineering seems to be a misnomer to many in the industry. The question being asked is “Can the earth really have a Digital Twin”? As Dr. Karl Terzaghi said, “Nature has no contract with mathematics, she has even less of an obligation to laboratory test procedures and results”. As an example, the variation in strength of ground (soil and rock) might vary by a factor of 50 or more compared to a general variation by a factor of 2 to 3 in concrete and steel (Figure 4). Further, additional testing data in soils does not necessarily increase accuracy of measurement of mean strength as can be seen in case of concrete (Figure 4).



Source: Decoding Eurocode 7 – Bond & Harris

Figure 4. Natural Variability in Ground (after Bond et al., 2008)

Despite the high level of uncertainty in soils and rock, the concept of having a digital twin has a lot of promise, as long as the inherent uncertainties and limitations are well understood and catered for in the model. For example, digital twin models should capture additional data related to uncertainties associated with each individual soil or rock layers in terms of its potential variation in both vertical and horizontal domains. Similarly, each individual test parameter and the corresponding derived strength or stiffness parameter should have an associated reliability function. Through this level of information, the geotechnical designer and the end-user should be able to gauge the level of confidence they can have in the digital twin and can carry out sensitivity analysis to fully mitigate any risks associated with the relevant uncertainty and plan for future expansion. As suggested by Phoon (2017), reliability methods can handle complex real-world information (cross and/or spatially correlated multivariate data) and information imperfections (sparse, uncertain and/or incomplete information) more effectively than relying on empiricism and judgement alone. The principle of adopting reliability function is not new, but for use of digital twin in geotechnical engineering, it assumes more importance and any digital tools shall prompt the modellers to ensure this information is made available.

3.3 Quality and Quantity of Data

It is a well-known fact that timely and correct decisions on construction projects can be made when the right level of information is provided at the right time to the right person.

The geotechnical industry has long been using digital data formats to capture ground investigation data. However, the data mostly remains of factual nature. Mostly on large infrastructure projects too much data is available that doesn’t match the expectations of the geotechnical designer, as it is either not available in the right format and at the right quantity, or it is provided too late and doesn’t match the project’s programme requirements.

UK’s AGSi, AGS-piling and AGS Instrumentation and Monitoring seem to be the right way forward to assist with the design process. However, its use has yet to get traction as an industrial practice internationally.

When it comes to automation of the interpretation process of digitally available data, geotechnical engineers feel nervous to let its full implementation happen, as they are aware of the complexity of the process and thus the need for higher level of human intervention. As an example, while reviewing plots of SPT, CPT and other geotechnical in situ and laboratory testing data, the reasons for outliers in the data are not always clear. It could be a naturally occurring localised pocket of soil or rock that might be presenting completely different strength or stiffness characteristics, or it could be a damage caused to the in-situ material through the drilling and testing process, or even disturbance to the laboratory samples during transportation and preparation. Skill of the drilling crew and the methodologies they adopt on site are known to result in highly variable results as can be seen in two RQD results obtained from adjacent boreholes across a reasonably uniform site (Figure 5). The boreholes were carried out by two different ground investigation contractors. Only human intervention in the automation process can make it possible to recognise any such systemic risk that results in anomalies in the available geotechnical data, and hence avoid a potential negative impact on the design outcome.

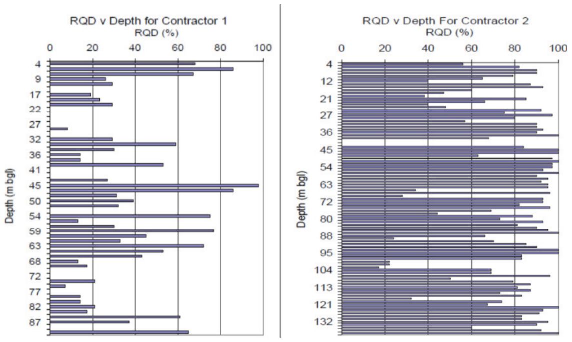


Figure 5. Drilling Induced difference in RQD results

Similarly, interpretation of geological stratigraphy from boreholes is widely carried out by commercially available software; however, final geological model for design purposes requires human intervention to identify features such as faults, buried river channels, historic fill and buried utilities or structures. Nevertheless, case studies exist where comparison of interpretation carried out of insitu test results such as CPTs by AI based digital tools and those made by humans suggested CPT interpretation required relatively fewer corrections after review (Kennedy, 2021).

Safe design requires sufficient and good quality data. It is usual for geotechnical engineers to criticize the scarce data available for design. Limitations in data are usually complimented by experience and judgment. The level of uncertainty or the quantum of perceived risk by a geotechnical engineer in relation to relying on a particular data set cannot always be explicitly conveyed in the design reports or calculations, regardless of whatever the design claims to have achieved as the 'nominated' factor of safety based on standard or codes. For example, geotechnical engineers consider a multitude of factors while selecting a 'design line' based on a given data plot of soil or rock parameters. These might include non-quantifiable risks or factors such as the level of experience the supervision staff had (if there was one present at the time of drilling and testing), skill level of the drillers or the testing team, techniques used to obtain the data, any potential disturbance, quantity of data and sensitivity of the structure being designed to the design parameter in question. Accordingly, the process of selecting the so-called representative, worst credible, spatial mean, local mean or characteristic design parameters can be subjective. The result is that geotechnical engineers are often criticized for producing designs which are supposedly overly conservative or overly safe in the eyes of the party who are bearing the cost of construction, as the uncertainties are not always explicitly conveyed merely through the adopted 'nominated' factor of safety. Yet another issue arises when in some cases there is too much good quality data available, but the conventional interpretation process does not allow any benefit of the abundant good quality data.

Merely digitising the data capture and management process might speed up the overall interpretation process if conventional interpretation rules are followed, but it will continue to miss out on recognising any discrepancy or even benefit caused by the above factors which are mostly related to systemic risks (or opportunities) rather than statistical risks. Use of a reliability approach could potentially help with alleviating some of the issues related to data scarcity as well as provide better results in the situation where data is abundantly available.

In case where data is too scarce, more generic data can be used instead of site-specific data. The main challenges in use of generic data to supplement project specific data are possibly jurisdiction's requirements to share geological data, as well its accuracy and reliability. This also warrants human intervention to consider two different sets of data having a difference in 'confidence level'. These factors can, however, be built-in into the reliability analysis so that both data scarcity and data abundance can be weighted into the interpretation process more objectively.

3.4 Ownership of Data

The nature and size of today's infrastructure projects often require the consultant to work in partnership with joint ventures, alliances or consortiums, which can raise issues regarding the ownership of the project's data. Development of a comprehensive Digital Data Management Plan should be undertaken during the tendering phase to identify these issues. As a minimum, such a plan should agree on a common data environment which will provide a single truth for the development of the federated digital model; agreement on the common data environment for the storage and display of the model (together with associated drawings and reports developed on the back of the models) and the workflow process to ensure the current model is shared between the parties. Such a plan should address the ownership and distribution of the data, but it is important that consideration is also provided to addressing the intellectual property used in developing the digital model.

An example recently has occurred on a joint venture project that Aurecon was part of where the logs and laboratory testing results have been provided from a site investigation partner in an AGS format, however as the interpretation of the geotechnical domain was being undertaken by the joint venture partners, additional functions had to be amended to the data set to allow grouping and characterisation of the data into each of the domains.

3.5 Nature and Life Cycle of Geotechnical Risks

Geotechnical risk management is a highly complex area which requires human intervention at all stages of a project. These risks remain live throughout the project life cycle, starting from bid phase and throughout the design life and de-commissioning phase of the asset.

The process of geotechnical risk identification can be highly subjective, and perception of risks does vary depending on the contractual party or stakeholder identifying or assessing risks. For instance, depending on the procurement type and contractual clauses such as whether a differing ground conditions clause is added, the client's perception of severity of risks can be different to that of the geotechnical consultant or contractor.

Traditionally, geotechnical risks on projects have mostly been assessed via a qualitative approach. A qualitative approach measures the impact and likelihood of the identified risks and ranks the risks in a risk register for mitigation analysis. The qualitative approach mostly used simple excel spreadsheets at most and has hardly gained any noteworthy benefits from the available digital technology.

The quantitative approach is a more involved process compared with the qualitative approach. This approach is usually reserved for larger, more complex projects. Although this approach normally adopts a non-simulation approach using a single variable or factor, recent digital advances have facilitated the use of simulation approach, such as Monte Carlo Simulation, which allows to calculate the combined effect of several geotechnical risk factors. Detailed descriptions of digital simulation methods are in US DOT manuals and other published books and reports. However, to date, the simulation approach is carried out at the overall project level and not exclusively used for geotechnical risk assessment. Further, mostly aleatory, or statistical uncertainties are captured and not the systemic risks, which is a major gap area to be considered in future work. NCHRP Guidelines for Managing Geotechnical Risks in Design Build Projects (Gransberg et al., 2018) does provide preliminary level guidelines to the simulation approach, which can improve the state of the art and more widespread use of digital simulation approach for geotechnical risks assessment.

3.6 Interoperability of Digital Design Tools

In Digital Geotechnics, much of the recent development appears to be heading towards a Virtual Reality end use (Output) or the Data Capture (Input) Stages. In the last couple of decades, many newer software tools have appeared in the market with significant improvement in processing speed and yet analysis time hasn't significantly reduced, mainly due to lack of interoperability among the software tools at various stages of the geotechnical design process.

Most available digital design software tools remain to be operating in a 2D plane strain or axisymmetric domain which are limited in their representation and assessment of a real-world 3D failure mechanisms and ground response. A handful of 3D design software is available; however, these are only used for complex problem solving as the generally acceptable program and cost expectations by the clients do not permit a more widespread use of these tools. Such design software tools mainly rely upon finite element or finite difference routines and although computing speed has significantly increased in the last two decades, lack of interoperability of these digital design tools continue to require significant skilled labour in frequently utilising them for geotechnical design.

Over the last few years, several software developers have worked to enable their software to directly import data from 2D and 3D digital geological models into analysis software however, these functions have yet to become a general practice as they still require human intervention and labour to avoid significant errors and omissions. Further, once analysis is carried out and a solution is developed, there is yet another phase of manual export of information to regenerate the final solution in a 2D or 3D digital model for the purposes of visualisation and production of construction drawings.

3.7 Role of Human Judgement in Design

Judgement is the ability to arrive at sensible decisions about a problem in the presence of incomplete and contradicting information (Jose, 2021). Judgement is the exercise of thinking clearly, logically, and calmly about a problem, weighing the known facts, suppositions, missing information, and consequences, and then taking a decision (Marr, 2006).

Although judgement plays a central role in all phases of geotechnical engineering process, interpretation of geotechnical data for design purposes is the prime area where digital transformation is facing the most resistance out of all other areas.

International geotechnical design codes and standards such as the Eurocode 7 have attempted to implement the same principles of reliability analysis as have been successfully adopted by their counterpart structural design codes for instance, however, they do recognise the role of human judgment in geotechnical design, and thus Eurocode 7 allows the designer a significant degree of leeway when it comes to use of judgement in the selection of characteristic parameters for design purposes. Similarly, the partial factors of safety, as stated in Eurocode 7, are yet to be explicitly calibrated according to reliability principles described in Annex C of the head Eurocode (EN 1990:2002) or Annex D of ISO2394: 2015 (Phoon, 2019).

Variation in the selection of geotechnical parameters could be due to actual natural variability, inherent bias of the sub sampling for testing or due to human limitations of testing and predicting the actual soil or rock characteristics. In addition, the available design methodologies are less than perfect and in fact mostly empirical as principles of exact science haven't yet developed constitutive relationships that fully model the vastly variable behaviour of soils and rock and their interaction with structures under different levels and forms of loading. Numerous constitutive models exist however, selection of the most appropriate model for a specific design purpose requires significant experience and judgement on behest of a geotechnical engineer and cannot be merely left for the machine to decide upon. Whether a plane strain 2D model, an axisymmetric or a more time-consuming (and costly) 3D model is appropriate for a given problem, experience and judgement are crucial.

Even for the so-called simplest of geotechnical design problems such as estimating pile lengths and predicting settlement of an isolated footing, case studies suggest a significant variation might exist among the results produced by different geotechnical engineers. In one case, prediction of pile lengths by sixteen geotechnical engineers all resulted in pile capacity varying by 50% to 200%, when compared with the actual capacity resulted from a pile test on site (Figure 6, Wheeler 1999). Similarly, routine calculations of the settlement of footings on sand can easily be in error by a factor of 5 (Figure 7, Clayton et al 1988).

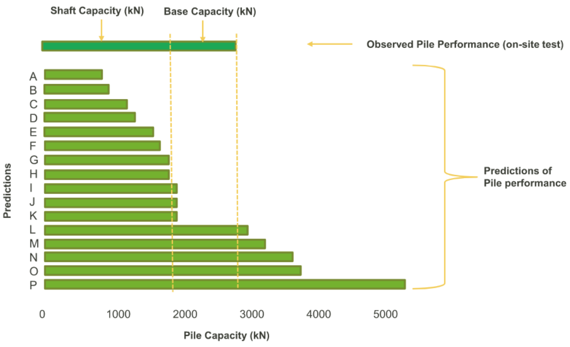


Figure 6. Inaccuracies in Pile Capacity Predictions (Wheeler 1999)

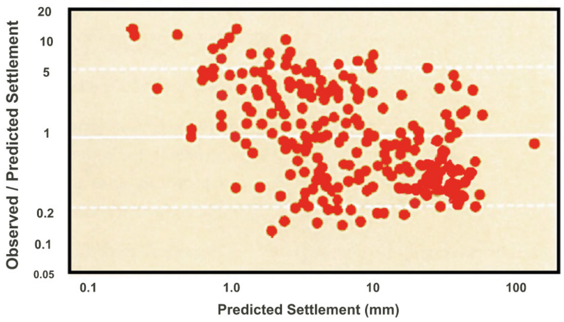


Figure 7. Inaccuracies in Prediction of Settlement (Clayton et al 1988)

Despite the undeniable role that judgement continues to play in seeking geotechnical solutions, its role has indeed evolved over the last century from a more gut feel type approach based on limited and rather crude testing data, to a more informed level of judgement supported by better field and in-situ testing; and analytical, numerical and probabilistic analysis models, as depicted in Figure 8 (Lacasse 1988, Mayne 2012). This is further supplemented by ease of access to digitally available information related to lessons learnt from others. The immense power of computing and digitisation can be exploited by using the available information in a more systematic and transparent manner to support engineering judgement. To speed up the transformation process, digital workflow for geotechnical design will need to be modelled such that stages for human intervention are well defined and so that the geotechnical engineer is prompted, where their input is needed.

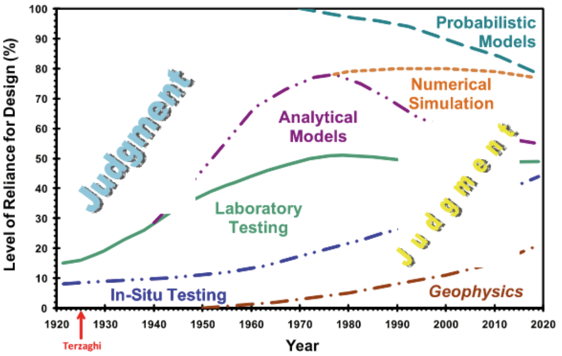


Figure 8. Role of Judgement in Geotechnical Engineering (after Lacasse 1988, as referenced in Mayne 2012)

4 CONCLUSION

Implementation of digital transformation in geotechnical engineering is creating benefits in terms of time savings, cost reduction and transparency to geotechnical design and risk management processes throughout the life cycle of a project. However, it is crucial to understand the limitations and challenges that this transformation engenders, since geotechnical engineering, unlike some of the other Civil Engineering fields, deals with enormous complexity and uncertainty associated with naturally occurring materials. As a result, digital formulations would need to formally adopt and imbed empirical methodologies and human judgement as part and parcel of the geotechnical engineering process.

A systematic and transparent framework is required to implement digital technologies in this field so that some of the concerns of the geotechnical engineers and the broader engineering community can be alleviated. A key challenge is to achieve transformation holistically and not in a particular challenge area to avoid chaos and disruption in the industry. All the challenges associated with digital transformation, such as those related with integration of human judgement at the right stages, holistic risk management, interoperability among digital tools, a shift to reliability approach in design, staff upskilling and investment in digital tools; all need to be tackled together rather than in isolation. This can be achieved by developing digital workflows that clearly highlight the stages and gateways where human intervention is required and also by identifying areas where further rapid transformation can be instigated in the field for the ultimate benefit of the construction industry and society as a whole.

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