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40 years of numerical modelling of soil-structure interaction - how far have we come?

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ABSTRACT: Numerical modelling in engineering has evolved rapidly since the early days of personal computer in the 70s and 80s. The field of soil-structure interaction modelling lags behind general development in other fields numerical modelling due to the fact that complexity of modelling such problems requiring the inclusion of both the underground structure, which has more established material properties; and the soils which, as natural materials, exhibits a wider range of behaviours and high variabilities in their response to different loading and unloading conditions. Today, complex 2D and 3D soil-structure interaction modelling has become a norm in design offices across the globe despite many calls to be cautious with the use of such complex tools. Further advancement in various algorithms has extended the capability of modern computing even more, and the use of automated data processing, efficiency gain via automation and scripting, machine learning, use of surrogate model, implementation of design optimisation etc. have started to gain ground in geotechnical engineering especially amongst research establishments. Increasing reliance on this type of "black box" approaches in geotechnical engineering would inevitably lead to a diminished understanding of fundamental soil mechanics and geotechnical design.

KEYWORDS: Soil-structure interaction, finite element, numerical modelling, 2D 3D models.

1 INTRODUCTION

Complex soil-structure interaction (SSI) modelling in geotechnical engineering using 2D and 3D numerical method (NM) has become a norm today. Simpson *et. al.* (2009) included a brief section on design analysis methods and, at that time, they indicated most of the models typically comprised 2D models with limited full 3D SSI modelling except in more complex situation requiring such consideration. Also, simple Mohr Coulomb model was used in most of the assessments undertaken then. The examples of the 3D analyses presented at the time were based on the works by Yeow (2004), Yeow *et al* (2005) and Simpson et al (2006). Even today it is not uncommon to combine both geotechnical and structural modelling with geotechnical software used to handle the SSI behaviours while the structural software focused more on structural elements and multiple load cases required for structural design.

This paper presents the Author's own experience since early 1990s when he was introduced to numerical modelling and his attempt to present the evolution of SSI in geotechnical engineering and his personal view of the future of our industry in this field. His experience is only limited to his direct exposure to the use of certain finite element (FE) software and while undertaking or involving directly in numerous 2D and 3D SSI modelling in projects throughout his career. This experience covers 23 years in Arup Geotechnics from 1990 to 2013 thereafter with COWI from 2013 to present day.

2 FE SOFTWARE PROGRAMS

2.1 *1990s to 2000s*

Today there are numerous FE software available to geotechnical engineers but 40 years ago this was not the case. Most of these software packages started their life in research establishments and some of them are still confined as research tools. In the early 1990s the Author was using *Oasys SAFE* program to model 2D problems. Ten years later, after a failed attempt to source a long term commercial 3D FE software that led to the decision to commission external subconsultants to undertake the complex 3D model of a suspension bridge foundation for the Metsovitikos Bridge shown in Figure 1 (Dauncey et. al. 2002), a technical and business decision was made to develop an internal 3D program *Oasys LS-Dyna* software. The software originated as a freeware which was developed by Livermore Software Technology Corporation in USA into a versatile multi-purpose program widely used by automobile and aerospace industries. It is available in explicit code which allows significant savings in analysis time. The software has many advanced modelling features but lacking in geotechnical engineering modelling components prior to the efforts by Arup Geotechnics team to incorporate such features. As the distributor of the software in the UK and Ireland, Arup realised the potential of the software and invested in resources in early 2000s to incorporate and upload the necessary modelling features for SSI modelling requirements, e.g. staged construction and advanced soil models. Today it remains the main 3D modelling tool in Arup Geotechnics.

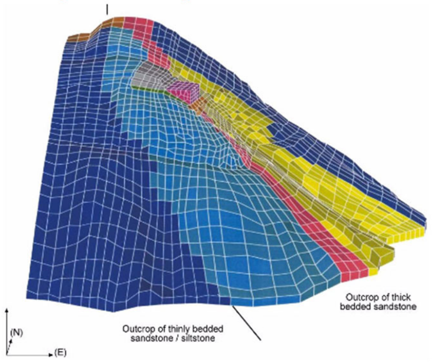


Figure 1. Early 3D model of Metsovitikos Bridge suspension bridge foundation (125,000 elements)

A well known commercial FE program, Plaxis software started as a 2D research tool in the 1980s in Delft University of Technology and became a commercial software in early 1990 (Seequent, 2023). In early 2000 when the need for 3D modelling became apparent, Plaxis started its journey of developing the program by introducing tunnels and foundations, i.e. as a transition algorithm between 2D and full 3D program. It took another 10 years before a full 3D software was released by Plaxis in 2010.

Another well-known software used commercially by a geotechnical consultant in the UK during this time was the Imperial College FE program (ICFEP). The on-going development of this program under the research team of Imperial College added many modelling features unavailable to many commercially available FE programs. The software is only available to engineers in Geotechnical Consultant Group and Imperial College researchers/staff when undertaking external consultancy services. FLAC is another commercial tool used by some in geotechnical modelling of SSI problems. Another FE software known to the Author but not widely used is the CRISP program.

2.2 *2000 to 2010*

As a commercial software provider entity, Plaxis was able to develop its tool to be user friendly under the Windows environment. This has elevated its market share amongst geotechnical consultancies. In 2008, when the need to produce the design of Crossrail's Canary Wharf Station, the Author chose Plaxis 2D as the main design tool in order to facilitate design development stage requirements whereby changes of structural geometries, ground model and type of retaining wall and its supports were necessary. The full 3D component of the software was not available yet at that time.

In early 2000 of *Oasys LS-Dyna* development in SSI modelling, a 3D model with approximately 100,000 elements and multi-stages construction sequence was possible, see Figure 2 (also previous Figure 1). The development progressed rapidly with much larger models achievable with this software, see Section 3.3 of this paper.

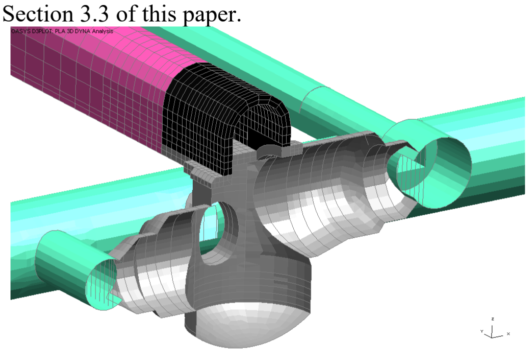


Figure 2. Access tunnel constructed using sprayed concrete lining technique for Kings Cross redevelopment project

At the same time MIDAS was also actively promoting its 3D program where the Author was involved in trial evaluation of its capability. Although such program was easier to use, it was deemed lack of the overall capabilities provided by *Oasys LS-Dyna.*

2.3 *2010 onwards*

In early 2010s the Author joined another consultant firm and Plaxis software forms the backbone of numerical modelling to solve complex SSI problems. As the 3D Plaxis software just started its distribution into geotechnical industry, it was not a smooth transition from 10 years of the use of the *Oasys LS-Dyna* program. The Author found there are certain limitation trying to build and analyse complex and large model using the Plaxis software whereby computation resource could be stretched and the analysis become very inefficient if not impossible. One of such models was the model used for assessment of a major slope stability project that required a model of 300m deep over an area of 1000x1000m shown in Figure 3.

During this time, *Oasys LS-Dyna* program was able to handle massive multi-million element 3D models incorporating detailed structural elements.

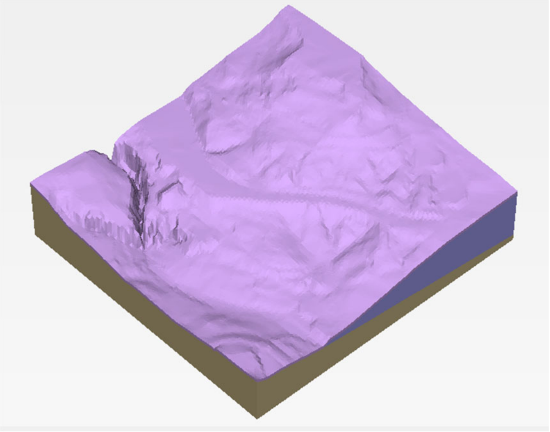


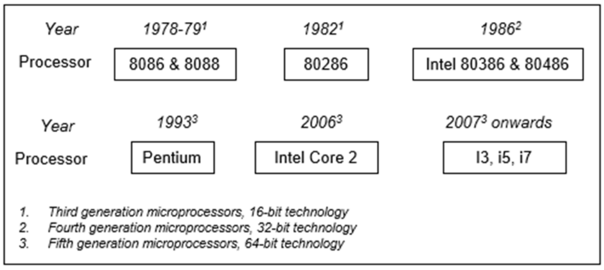
Figure 3. 3D slope stability assessment

3 THE EARLY YEARS OF NUMERICAL MODELLING

3.1 *Late 1980s and early 1990s*

The introduction of microprocessors of 8080 and 8086 in the 1970s led to affordable microcomputer but its wider used in the engineering communities was not realised until the introduction of personal computer (PC) by IBM in the 1980s.

In the late 1980s and early 1990s when more powerful microprocessor 80386 and 80486 were introduced into engineering communities, heavier computing using PC to solve engineering problems became more attractive. Even then, a 2D FE model could only handle a limited number of elements. The Author could still remember having to generate a simple 2D model to design a sheet pile retaining wall and he had to limit the number of elements to a couple of hundred in order to perform the computation effectively. Figure 4 shows the evolution of microprocessors over the early years which affects the gradual increase in the use of NM in geotechnical engineering.



Year	*1978-79*[1]	*1982*[1]	*1986*[2]
Processor	8086 & 8088	80286	Intel 80386 & 80486
Year	*1993*[3]	*2006*[3]	*2007*[3] *onwards*
Processor	Pentium	Intel Core 2	I3, i5, i7

1. *Third generation microprocessors, 16-bit technology*
2. *Fourth generation microprocessors, 32-bit technology*
3. *Fifth generation microprocessors, 64-bit technology*

Figure 4. Evolution of microprocessors (Wikipedia)

3.2 *Mid 1990s to 2000s*

Simpson (1999), in his paper on *Engineering Needs* presented a few images showing the 2D FE models he used in various types of design assessments, revealed the coarseness of the elements used during that time, see Figure 5. He also outlined problems faced while applying simplifications needed to undertake more complex SSI including smearing and introducing axi-symmetry assumptions. In the same paper Simpson presented a full 3D model used in conjunction with advanced small strain BRICK model to assess the ground movement of the caisson foundation of the Millennium Footbridge foundation using *Oasys LS-Dyna* program, see Figure 6.

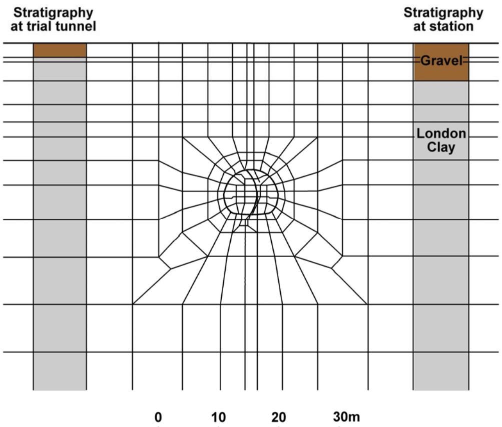


Figure 5. 2D FE mesh modelling sprayed concrete lining tunnel (Simpson 2006)

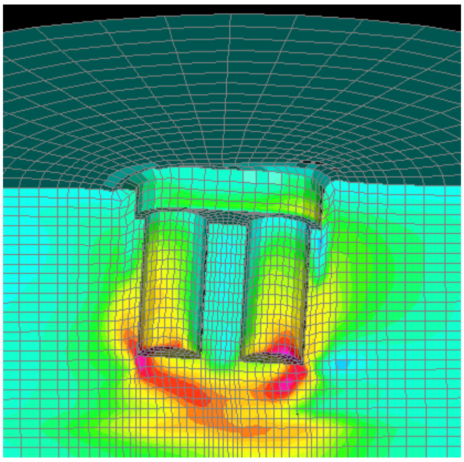


Figure 6. 2D FE mesh modelling of Millenium Footbridge pier foundation (Simpson 2006)

During this period, the use of such complex *LS-Dyna* 3D software was restricted to highly trained individuals which required Unix operating system to provide the flexibility and processing power to solve the SSI analyses.

3.3 *Rapid progress of 2000s*

In the early 2000s it became apparent that SSI had become increasingly complex due to higher volume of construction in populated urban environment globally. Underground construction in the form of redevelopment of existing assets or installing new transport infrastructure within our cities required more and more sophisticated analyses in order to manage risks and ensure safety during such construction.

During this period, as the numerical skills team lead of Arup Geotechnics, the Author was also tasked to promote the development and usage of 3D modelling to solve complex SSI problems, Yeow (2004). It was during this time the Author embarked on a part time Royal Society Industry Fellowship at Imperial College under the supervision of Professor Zdravkovic and Professor Coop in order to build added competencies in advanced soil models and laboratory testing.

One of the first complex 3D model involved the assessment of construction effects of the Grade 1 listed St Pancras station during construction of the Thames Links Box (Yeow et al 2006) as part of the construction of the Channel Tunnel Rail Link project, see Figure 7. Advanced non-linear BRICK soil model was used with the masonry buttresses supporting the ties of the roof truss structure modelled as ubiquitous joint model to allow for weaker mortar joints of the masonry. The model had a total of approximately 650,000 elements with an equivalent 2 to 3 million degrees of freedom at each of the modelling stages.

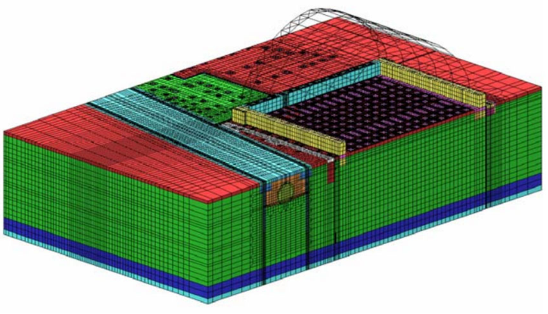
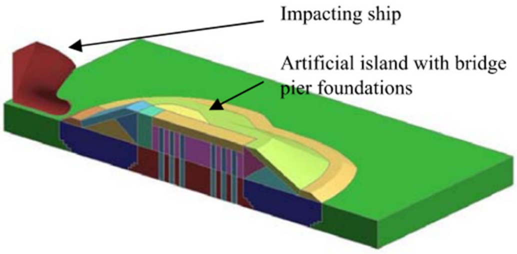
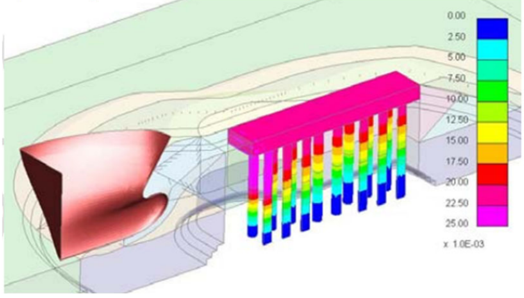


Figure 7. 3D model of St Pancras station

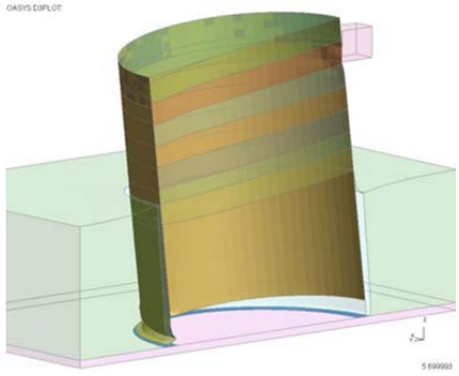
Following the increasing use of 3D SSI modelling in early 2000s, the advanced capability, versatility and efficient nature of the *Oasys LS-Dyna* software also provided the ability to perform optioneering of ship impact protection solutions for a tender design of a major bridge project in the Far East (Yeow 2007), see Figure 8.



a) Image of the artificial island protection



b) Response of bridge pier foundation under impact load



c) Option study of sacrificial dolphin performance

Figure 8. Optioneering for bridge impact protection using an artificial island or sacrificial dolphins

3.4 *2010 onwards*

The experience of Plaxis 3D was mixed. On the one hand it has a very user-friendly interface allowing ease of building a complex model but its limitation to control the mesh generation and extensive computer resources needed for large and complex model could be frustrating for users. For complex 3D sprayed concrete lined tunnel junctions model, Kanagasabai et al (2025) did several initial investigations in order to reduce the need to model the geometry of these structure elements explicitly to manage the computer resources needed when modelling the proposed underground construction of the High Speed 2 tunnels north of Euston Station.

4 THE LAST 10 YEARS

Increasingly NM has been used to design and/or analyse performance of geotechnical structures. Design optimisation could be achieved by more realistic modelling of SSI instead of adopting limit equilibrium approach. Adopting NM could also allow far better understanding of potential development of any complex mechanism that could not be foreseen without the full SSI modelling. When investigating any geotechnical failure it is impossible not to carry out a form of NM to fully understand the source of critical parameter affecting the behaviour of the failed underground structure.

With the upcoming 2^{nd} generation of Eurocodes (Yeow et al 2024), clearer guidance of using NM in ultimate limit state design of geotechnical structure also provides the impetus for wider use of such technique in our works.

In her Rankine Lecture of 2024, Professor Zdravkovic presented the evolution of NM in her works since late 1990s. The pace of progress over the past 10 to 15 years in NM has been phenomenon with the current trend moving towards another new form of SSI analysis approach. Machine learning and artificial intelligence are gaining traction lately with huge benefits gained through their ability to perform “alternative SSI design analysis” at tremendous speed. Such approach requires huge amount of data generation to establish the training dataset. For the believers this method would improve accuracy of SSI modelling by using trained data to produce geotechnical design. Perhaps the golden age of numerical modelling using FE software programs is coming to an end to be replaced with artificial intelligence based type of numerical methods.

5 SOIL MODELS

For many years linear elastic perfect plastic Mohr Coulomb soil model has been the backbone of geotechnical design for the ultimate and serviceability limit states design requirements under Eurocodes. Input factoring of material strength properties or output factoring of the derived forces are the approaches adopted in the UK and, in one form of another, in other countries adopting Eurocodes design. In circumstances where more accurate ground movement assessment is needed, more complex advanced soil models are needed. However, development of advanced soil models is mainly confined to research establishments with very limited models transferred into commercial software even today.

It is also a common knowledge that most of advanced soil models require many input parameters with some of them are arbitrary constants provided to allow better fit to soil behaviour from data of laboratory tests. When these fitted parameters were applied to boundary value problems a further calibration of the soil properties will be needed to mimic the actual performance. Such additional calibration could be due to the need to offset some disturbance of the soil sample affecting the laboratory test results or local inhomogeneity of the ground at the location of the underground structures.

Furthermore, many such advanced soil models are not based on firm theoretical framework and are coupled with other plastic models (Yeow & Coop 2015). There are certain elements of the model parameters introduced to best fit the intended phenomenon of the soil. One such input is the stiffness degradation curve in the BRICK soil model (Simpson 1992) and the non-linear MC model in the ICFEP program (Jardine 1986). Regardless of their simplicity in incorporating such advanced features to the soil models, these two models have been used successfully over many years to model the over consolidated London Clay in numerous projects across London.

It is the Author’s opinion that, regardless of the soil model one uses, understanding how a soil model works is critical to a successful application of NM in any geotechnical analysis. Over the years, misused of soil model be it a simple or an advanced model, is due to a lack of fundamental understanding of soil mechanics principle and/or the appreciation of the constitutive relationship embedded in such model. One such well known case history is the Nicoll Highway Collapse (NHC) incidence in Singapore in 2004. Attempt to best fit soil parameters by back analyses without due consideration of the fundamental meaning of input parameters of the soil model is another unfortunate source of misuse of NM. This is also one of the shot comings identified in the findings of the NHC inquiry.

As more appropriate soil models for different soil types are not readily available to practitioners, increasingly modellers are adapting available advanced soil model in the software available to them to undertake SSI modelling of the underground structure they design. Without extensive calibrations of in-situ and laboratory tests coupled with validation with some case history measurements, such approach should only be adopted with carefully planned site verification in the form of a comprehensive instrumentation and monitoring plan akin to the application of observation method (OM).

6 THE FUTURE

6.1 *Real Time Back Analysis*

The advent of efficient processing tool and the need to react to construction activity promptly have improve delivery of design based on Observational Method (OM). Real time back analysis (RTBA) has increasingly adopted in conjunction of delivering projects using OM design to achieve economy, improve safety and reduce construction duration.

Ying et al (2018) presented some 3D FE back analysis works she did for deep excavations of some station structures of the Crossrail project as part of her PhD study. At the time when most 3D FE software programs struggle with complex models, the model presented for the Liverpool Street Moorgate shaft model incorporated so much details that requires millions of elements to build and days to analyse, see Figure 9.

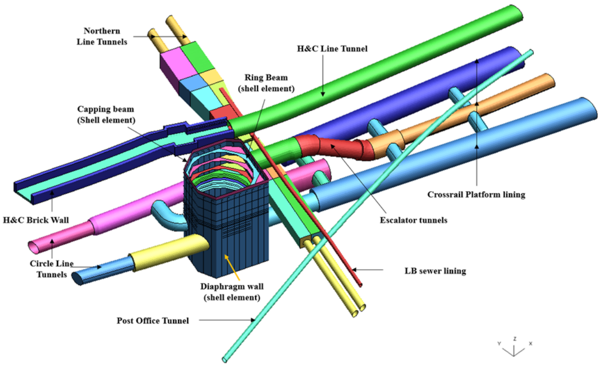


Figure 9. Complex 3D model of Liverpool Moorgate shaft (Ying 2018)

Since her PhD Ying (2018) continues to promote the use of RTBA to make back analysis more efficient and spoke during the mini symposium organised by British Geotechnical Association on OM. Such RTBA approach utilises the benefits of machine learning to produce the most probable parameters that fit site measured data by analysing many combinations of input parameters to produce the best fit set for onwards estimate of the behaviour of the underground structure in next stages of construction works.

Despite reservation of potential mismatch in the machine learnt derived parameters and the actual values, those using such approach are confident the engineer using such tool would have sufficient control of the whom process. The ability to compute huge number of analyses to optimise the selection of most probable parameters has attracted the adoption of OM in geotechnical design. It has also raised the profile of Technical Community 206 (TC206) on their activity to promote the use of RTBA in design using OM.

6.2 *Surrogate model*

Another avenue in the development of future of numerical modelling is the use of surrogate model. Such method uses a mathematic approximation of the computational model constructed using various methods, such as some algebra function for simple models to more complex method for complex models based on machine learning algorithm. This approach would avoid long running time for complex models when analysed based on conventional FE type of analyses.

Such approach will require data generated and trained in the surrogate model mimic closely the actual behaviour. The source of such data could be from numerous numerical simulations and/or real project measurements. Once adequately trained, the model would allow batches of calculations to be carried out rapidly based on the derived mathematical equation.

The Author has no personal and hands-on experience with such approach. However, it is his personal opinion that due to local variations of ground conditions, complexity of various interactions with adjacent infrastructures and possible other construction related effects; any simplified mathematically derived relationship might not be able to capture the actual behaviour of the underground structure. Adopting such approach may risk the ability to adequately modify the work mid-construction when site observation, through measurements or any other means, reveals different response or behaviour. Again, such risk could be mitigated with carefully planned site verification in the form of comprehensive instrumentation and monitoring.

7 INDUSTRY PERCEPTION OF AND APPROACH TO NUMERICAL MODELLING

Since the early 1990s when the Author started his geotechnical engineering career, there is a marked change in the perception of and approach to numerical modelling in the industry. Today pretty much all major players in the industry have the ability to undertake most of the routine analyses using such complex tools with varying degree of appropriateness. Furthermore, major universities and tertiary education establishments have introduced some fundamental theoretical and practical trainings as part of their teaching modules. This equips graduate engineers with basic knowledge, hands-on experience and understanding in the use of such tool at very early stage of their career. Changes in the industry due to more innovative and/or complex construction activities especially in urban environment also require more complicated assessments to mitigate risks even if the complex analysis is not used explicitly in the design, e.g. undertaking ground movement and damage assessment. Long gone the days of unfavourable views of colourful numerical analysis output populated in geotechnical design report. Despite huge efforts to convey awareness of the pitfalls of the use of such complex tool to the industry, the bandwagon of numerical modelling in geotechnical industry is unstoppable.

With the industrywide needs of numerical modellers or analysts many of our younger generation engineers are currently allocated such role at very early stage of their careers. The Author has observed many of these engineers would continue such path without experiencing much practical hands-on of geotechnical activities; even some have never been on site and exposed to the most fundamental site investigation activities. As geotechnical departments of most major players get bigger, compartmentalised working practice further limits individuals to see a project through from desk study to construction. A modeller now accepts ground model and geotechnical parameters prepared by the engineering geology department and the proposed undergrounds structure geometries from the architect or structural designer and his/her sole responsibility is to feedback the output from the analyses. It is a worrying trend and could only made worst with increasing use of digital ground investigation data and the implementation of complex data analysis tools to derive the soil properties.

It is the Author's personal opinion that, in order to face the challenge of geotechnical engineering, a competent numerical modeller would benefit tremendously with hands-on practical experience of geotechnical activities. Observing how a borehole is sunk and in-situ test is performed, how soil is sampled and tested in the laboratory, how a piezometer is installed, how a bored pile is bored, concreted and even tested, how deep excavation is executed and how instruments we installed are monitored; are part of the knowledge an engineer needs. Such wide range of experience in an engineer has become scarce especially within larger organisation with compartmentalised working practice.

8 CONCLUSIONS

NM has advanced in an exponential manner in the past 30 to 40 years in software development and processing power. Despite a lack of widespread use of advanced soil models in the industry, the use of such tool routinely with commercially available soil models in design offices is apparent.

It is the Author's opinion that appropriate level of training in the use of such tool is still lacking in the industry. Those who are competent in this type of work tend to build their career path entirely on providing NM service to colleagues needing some advanced modelling to understand the behaviour of the underground structure they design. This is an unfortunate consequence of readily available commercial NM tools which are designed to be extremely user friendly and accessible to many. The need to have understanding of both the fundamental of soil mechanics and the complexity of the tool one uses is critical in delivering appropriate solution to the geotechnical problem.

The next phase of advanced geotechnical design modelling be it based on the current form of NM or potential incorporation of some form of artificial intelligence (AI) algorithm or machine learning is underway. The backbone to this approach to geotechnical engineering is the collection of case histories or database to be used to train the algorithm. When this approach becomes the norm in the future, we will start to rely on the "black box" to provide the answer to the problem we need to solve. Gradually this will erode the fundamental understanding of what we design as users are relying more and more on the output at the other end of the analysis.

The Author is fortunate enough to be working in the golden age of NM and start to see the transition into the next phase of AI based geotechnical modelling. It is hope that the next generation of practitioners would continue to make sure our fundamental knowledge of geotechnical engineering remains intact and not overwhelmed by the digitisation drive currently spreading in our industry.

9 ACKNOWLEDGEMENTS

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