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Reflections on Some Contemporary Aspects of Geotechnical Engineering Education – From Critical State to Virtual Immersion

M. B. Jaksa

University of Adelaide, Adelaide, Australia
mark.jaksa@adelaide.edu.au

ABSTRACT: This paper documents the 2nd Burland Lecture on Geotechnical Engineering Education. The paper explores three contemporary aspects of geotechnical engineering education. Firstly, critical state soil mechanics, which was developed around 60 years ago, is re-examined and a case is made for incorporating it into mainstream, undergraduate civil engineering education. Online learning, in particular, the flipped classroom, is then discussed briefly. Finally, the emerging technology of immersive learning is explored from the lens of geotechnical engineering education.

Keywords: Critical state soil mechanics, Flipped classroom, Interactive learning modules, Online learning, Immersive technologies

1 Introduction

It is indeed a great honour to have been selected by peers and colleagues from TC306 – the technical committee of the International Society of Soil Mechanics and Geotechnical Engineering which focuses on geo-engineering education – to deliver the 2nd John Burland Lecture on geotechnical engineering education. It is also an immense privilege to follow in the footsteps of the presenter of the 1st John Burland Lecture, Prof. John Atkinson. Both Johns are, without doubt, giants in the field of geotechnical engineering, not only in education, but also in research and practice. Both are heroes of mine and I am indeed humbled to be in such esteemed company.

In this paper, as you will see, I draw inspiration from both Johns. As John Atkinson stated in his 1st Burland Lecture, the focus was on what to teach, rather than the process, in other words, how to teach. John's 1st John Burland Lecture provided great insights in 'what' to teach in geotechnical engineering. Most of my work, in the geotechnical engineering education space, has focussed on 'how' best to teach geotechnical engineering. However, in this paper, whilst most of my attention will be directed to the 'how to teach' paradigm, I will also devote some effort to one aspect of 'what to teach'; that is, on the topic of incorporating critical state soil mechanics in geotechnical engineering curricula.

In this paper, I will examine three topics. First, I'll look backwards in time and (hopefully) present a cogent and compelling case for why critical state soil mechanics is relevant today in the undergraduate curriculum of civil engineers. I will then look to the present time and spend a few moments discussing a pedagogy known as flipped learning which is significantly disrupting higher education. Finally, I'll peer a little forward into the future and explore a technology that also has the potential to benefit geotechnical engineering education; namely immersive technologies.

2 Critical State Soil Mechanics

I'd like to start by exploring the question: "Is there a place for the teaching of critical state soil mechanics in the undergraduate curriculum of civil engineers?" My firm belief to this question is in the affirmative. I'll first begin with an overview of critical state soil mechanics. I'll then explore the views of others, who speak for and against this question. Finally, I will make my own case in favour of the proposition.

Critical state soil mechanics (CSSM) is a soil mechanics framework that coalesced in the 1950s and 1960s, largely as a result of the work of Kenneth Roscoe, Andrew Schofield, Peter Wroth and John Burland from Cambridge University (Roscoe et al., 1958; Schofield & Wroth, 1968). As Jefferies (2019) noted, CSSM was greatly informed by the work of researchers at Imperial College (e.g. Bishop, Cornforth, Gibson, Henkel and Parry), as well as individuals from the US Corps of Engineers, Harvard and MIT, most notably Donald Taylor (Baecher & Christian, 2015). Since then, CSSM has been widely adopted in research, but much less so in undergraduate education and practice.

At its core, CSSM links load, shearing and volume change, as shown graphically in Figure 1. It unifies fine- and coarse-grained soils, drained and undrained loading, and, in the case of fine-grained soil, normally consolidated and overconsolidated soils, and in the case of coarse-grained soils, loose and dense soils; all within a single framework. Anyone who has studied Schofield & Wroth (1968) and Wood (1990) will realise that, whilst being extremely powerful, CSSM is also complex and requires mathematical skills often beyond those of many undergraduate students. It is likely that the complex, theoretical nature of CSSM, as well as the fact that it is underpinned by artificial, rather than natural, undisturbed soils, has alienated CSSM from many in practice and academia.

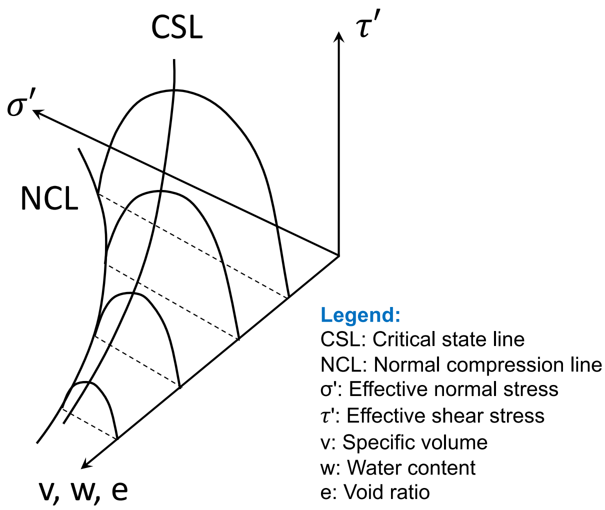

Figure 1. Graphical representation of CSSM – the state boundary surface for soil, adapted from Atkinson (2014)

John Atkinson has done much to demystify CSSM and make it readily accessible to undergraduate students and practitioners, particularly in three of his textbooks: Atkinson & Bransby (1978) and Atkinson (2007, 2014). As Atkinson stated in the preface to the first edition of his elegant textbook *An Introduction to the Mechanics of Soils and Foundations Through Critical State Soil Mechanics* (Atkinson, 1993):

> "The term 'critical state soil mechanics' means different things to different people. Some take critical state soil mechanics to include the complete mathematical model known as Cam Clay and they would say that this is too advanced for an undergraduate course. My view is much simpler, and by critical state soil mechanics I mean the combination of shear stress, normal stress and volume into a single unifying framework. In this way a much clearer idea emerges of the behaviour of normally consolidated and overconsolidated soils during drained and undrained loading up to, and including, the ultimate or critical states. It is the relationship between the initial states and the critical states that largely determines soil behaviour. This simple framework is extremely useful for teaching and learning about soil mechanics and it leads to a number of simple analyses for stability of slopes, walls and foundations."

Airey and Miao (2016) similarly argue that CSSM should be taught to all civil engineering undergraduate students:

> "…the critical state framework underlies our current understanding of soil behaviour. It therefore makes sense to teach the simple critical state framework to introduce students to the important aspects of soil behaviour. The model is able to explain key aspects of soil behaviour and allows a broad understanding of ground behaviour. At the same time, it should be emphasised that this

> is an idealised model and that detailed geotechnical design will require more sophisticated approaches."

However, one merely needs to look at Wikipedia to observe that several in the geotechnical engineering community are not enamoured with CSSM. Furthermore, some strongly oppose the inclusion of CSSM in undergraduate curricula. For example, Wesley (2015) stated:

> "Teaching material that has little or no relevance to practical engineering, such as critical state soil mechanics, should find no place in undergraduate courses."

Jefferies (2019) argues that the reluctance of many academics who have consciously chosen not to teach CSSM, is likely due to the limitations of the original Cam Clay model (circa 1975), which "does not remotely capture the behaviour of soils denser than their CSL [critical state line], which is most soils that you will encounter in practice". Furthermore, he posits that the Cam Clay model was based on "an unnecessary assumption, and with that assumption corrected by the state parameter [see §2.2], CSSM becomes applicable to all soils, all densities, and all loading paths."

From my perspective, Atkinson (1993; 2007) and Airey and Miao (2016) make a compelling case for the inclusion of CSSM in the teaching of undergraduate civil engineering students. They demonstrate that CSSM uniquely unifies the strength, compressibility, density and moisture content of soils, for both fine- and coarse-grained, into a single, unifying theoretical framework. It is incredibly powerful to help explain to students key aspects of soil behaviour, such as soil compressibility, friction and volume change due to shearing (critical state line); the importance of stress path (drained/undrained strengths); and apparent cohesion (Airey & Miao, 2016).

As stated by Airey and Miao (2016), if CSSM is taught in undergraduate curricula, it is often as an afterthought, adding to the students' bewilderment in relation to their understanding of soil behaviour. Atkinson (2007) provides a universal framework for the inclusion of CSSM in geotechnical engineering instruction and Airey and Miao (2016) provide further examples of how educators might implement CSSM in their teaching.

Rather than adopting the common 'siloed' approach to the teaching of soil mechanics, where topics such as soil strength, compressibility, compaction and seepage are often taught in an isolated and disconnected fashion, it is recommended that a more holistic approach be adopted, which includes significant elements from CSSM. It is suggested, for example, that very early on in their instruction of soil mechanics, students might be asked to sketch a series of graphs, with respect to a fine-grained soil, that express the relationships between: soil strength and confining pressure; soil strength and water content and density; and soil compressibility and water content and density. Students beginning their geotechnical engineering education intuitively know that loose soil is weaker and settles more than dense or dry soil. It is not difficult to guide students to postulate on and create a three-dimensional representation of strength, deformation and water content or density, as shown previously in Figure 1.

At this point, I would like to present two, from my perspective extremely important, additional reasons for adopting CSSM in the teaching of soil mechanics to undergraduate geotechnical engineering students; namely, unsaturated soils and liquefaction.

2.1 Unsaturated Soils

Modern experimental studies relating to the shearing of unsaturated soils date back to the 1950s and '60s (Lu & Likos, 2004). Since then, two models have emerged: the *effective stress approach*, which is based on Bishop (1959) and summarised in (1); and the *independent stress state approach*, which is based on Fredlund & Morgenstern (1977) and is summarised in (2).

$$\tau_f = c' + \left[(\sigma - u_a)_f + \chi_f (u_a - u_w)_f\right] \tan\phi' \tag{1}$$

$$\tau_f = c' + (\sigma - u_a)_f \tan\phi' + (u_a - u_w)_f \tan\phi^b \tag{2}$$

where: τ_f is the shear stress at failure; c' is the effective cohesion; $(\sigma - u_a)_f$ is the net normal stress at failure; u_a is the pore air pressure; χ_f is the effective stress parameter; $(u_a - u_w)_f$ is the matric suction at failure; u_w is the pore water pressure; ϕ' is the internal angle of friction; and ϕ^b is the internal angle of friction associated with matric suction.

Largely due to difficulties in explaining the observed collapse upon inundation of unsaturated soils and the perceived lack of a unique relationship between χ and the degree of saturation (Khalili et al., 2004), the effective stress approach fell out of favour. However, largely due to the work of Khalili (Khalili & Khabbaz, 1998; Loret & Khalili, 2002; Khalili et al. 2004), the effective stress approach has been revived and has since gained broader acceptance within the unsaturated soil mechanics community.

A key strength of the effective stress approach is that, through CSSM, it is able reliably to predict strength and volumetric change in unsaturated soils. By analysing many tests performed on unsaturated soils, Khalili et al. (2004) concluded:

> “that the critical state line is unique in the deviatoric stress-effective mean stress plane for both saturated and unsaturated states of a soil. This has a significant simplifying effect on the constitutive modelling of unsaturated soils.”

Hence, CSSM works for both saturated and unsaturated soils.

2.2 Liquefaction

In his keynote paper at the 13th Australia New Zealand Conference on Geomechanics in Perth, Jefferies (2019) stated that the origins of CSSM “lie in the very practical concern of avoiding dam failures caused by liquefaction.” He went on to stress:

> “Today, CSSM (in the wider sense, there being various models within the framework) is the basis of modern understanding of soil behaviour and [is] becoming accessible to practicing engineers through geotechnical software. But why has it taken 50 years? And why is this paper even a keynote, with the implication that CSSM is new to so many engineers?”

In their textbook *Soil Liquefaction – A Critical State Approach*, Jefferies & Bean (2006) state:

> “In summary, a critical state view and associated generalised constitutive model (NorSand) provides a simple computable model that captures the salient aspects of liquefaction in all its forms. This critical state view is easy to understand, is characterised by a simple state parameter (ψ) with a few material properties (which can be determined on reconstituted samples), and lends itself to all soils.”

Finally, in the words of Barnes (2016):

> “[CSSM] assumes that soils behave in an ideal manner, that they have isotropic structures and stress conditions, they are homogeneous throughout their mass and that they have no preferred structure within them, i.e. they are remoulded or reconstituted soils.
>
> Real soils in the ground do not behave in an ideal manner, they have anisotropic structures due to preferred particle orientations of the grains, they are subjected to anisotropic stress conditions and are usually non-homogeneous due to fabric effects such as layering and fissuring. As well as the fabric effects, in situ soils have often developed some interparticle bonding which would be destroyed on remoulding and this is not included in the theories.
>
> Nevertheless, the concepts of a state boundary surface, a critical state condition, the inter-relationships between mean stress, deviator stress and volume, the effects of drainage conditions, elastic and plastic straining, yielding and hardening provide a sound framework for the understanding of basic soil behaviour.”

The research undertaken on unsaturated soils and liquefaction, however, demonstrate that CSSM **is** valuable in representing **real** soils. As such, I hope that I might have been able to present a compelling case that there is great educational merit in including CSSM in the undergraduate curriculum of civil engineers. If not, then perhaps to, at least, consider it and explore it further.

3 Flipped Learning

It is particularly pertinent at this time, when the world, and this conference, has been significantly impacted by the COVID-19 pandemic, to reflect briefly on online modes of learning. Here, I’d like to revisit a topic that I discussed back in 2012 at the *Shaking the Foundations of Geotechnical Engineering Education Conference* (SFGE) in Galway, Ireland. There, I presented the concept of interactive learning modules (ILMs) (Jaksa 2012), as well as an example of how they might be implemented in the context of geotechnical engineering laboratory classes (Jaksa et al., 2012). At that time, the associated pedagogy was known as just-in-time-teaching, but since then it has become more widely referred to as *flipped learning*.

As higher education has moved in recent times to a greater emphasis on mass education (Jaksa et al., 2009) class sizes have inevitably grown. As a result, traditional models of university instruction have been questioned. This has been exacerbated by the fact that, at the same time, technological advances – such as the internet, mobile devices and accessible video recording facilities – have transformed higher education. This led to the flipped learning pedagogy, which grew out of Salman Khan's revolutionary development of short, online instructional videos (TED, 2011) and augmented by just-in-time-teaching (Prince & Felder, 2007). AdvanceHE (2018), defined flipped learning as:

> "A pedagogical approach in which the conventional notion of classroom-based learning is inverted, so that students are introduced to the learning material before class, with classroom time then being used to deepen understanding through discussion with peers and problem-solving activities facilitated by teachers."

In other words, flipped learning is where students watch lectures at home (or elsewhere) and subsequently do their 'homework' at university, as illustrated in Figure 2.

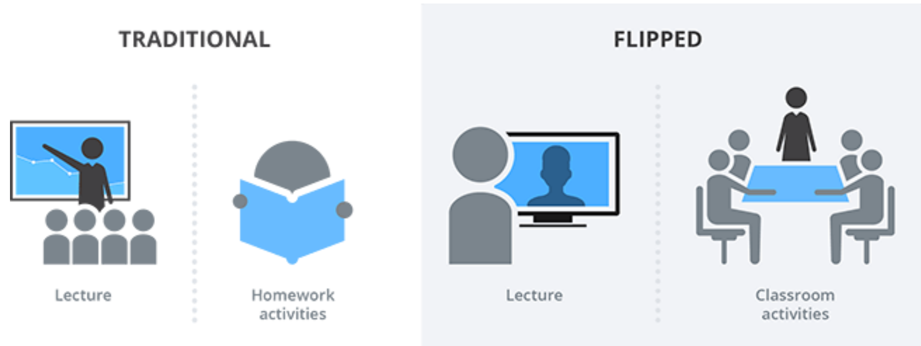

Figure 2. Schematic of flipped learning. Source: www.epiphan.com

Over the last five years or so, in Australian universities, and I suspect in many universities around the world, lectures have been automatically recorded and uploaded to their institutions' learning management systems, so that students can view them remotely. In my university, recording is automatic and mandatory in lecture theatres equipped with the relevant technology, and in my institution, this refers to the vast majority of teaching rooms. There are several advantages to such online learning. For example, students who may have missed a lecture because of illness, a timetable clash or work commitments, can view the lecture at a time that is more suitable to them. Additionally, students who live more remotely and find it challenging to travel to campus, can access the lectures more conveniently. The vast majority of students prefer this option, whereas, in my experience, the greater proportion of academics loathe it. Why? Because lecture attendance has dropped dramatically, in some cases by more than 80%, because the students overwhelmingly prefer it, and they're voting with their feet. Such students will also often speed-up the video by 1.5- or 2-times, so that they can view it more rapidly. On the other hand, some students much prefer face-to-face lectures, and they're the ones who come. It is, however, a fact that the vast majority do not sit in this camp and watch lectures asynchronously and remotely.

What are we, as academics to do about this? One can bemoan the reduction in lecture attendance, and the changing nature of higher education, or one can embrace it and adapt our pedagogies to suit. For example, some academics adopt 'participation marks' to force students to attend face-to-face lectures. I, personally, do not subscribe to this approach; I much prefer a 'carrot' to a 'stick.' If one has to coerce students to attend a lecture, what does that say about the quality of the instruction?

Emeritus Professor Rich Felder, a leading US engineering educator, who delivered a keynote lecture at the SFGE Conference in Galway in 2012, in his learning and teaching workshops, provokes attendees by asking "If you arrived one morning to deliver your lecture and there were no (or very few) students in the room, would you deliver it the same way?" At the heart of Felder's approach is active learning, which he defines as (Felder & Brent, 2009):

> “Active learning is anything course-related that all students in a class session are called upon to do other than simply watching, listening and taking notes.”

Felder provides a rich (pun unintended) set of extremely helpful, practical and accessible learning and teaching resources at his Legacy Website: https://www.engr.ncsu.edu/stem-resources/legacy-site/.

Higher education, and society in general, has benefitted greatly by the move towards online learning. This is especially evident in the present circumstances of the pandemic, where students and teachers are respectively learning and instructing from home. Recently, many of us will have taught students remotely (in my case from home) using a videoconferencing facility, such as Zoom, Skype, WebEx or Microsoft Teams. These are not perfect; they don’t replace face-to-face, but they’ve certainly been helpful. They’re much better than nothing. It is almost a given, that some of the learning and teaching practices that have been adopted during the pandemic will remain with us for a very long time, if not indefinitely.

If your institution has yet to mandate recording of lectures, may I respectfully suggest that you prepare for this eventuality. Online learning is advancing rapidly, and COVID-19 has simply accelerated its pace. The traditional, didactic pedagogy, which is the norm in higher education throughout the world, was initiated when universities sprang into life 800 or so years ago. Little has changed since then (Felder 2006), except for the dramatic rise in class sizes, the accessibility of society to universities, and the availability of technologies that can be adapted to teaching and learning. Flipped learning provides a useful and logical pedagogy for blending online delivery with face-to-face learning. In my view, we as academics are at our best, as is student learning, when the classes are small, and the teachers can address each student’s individual learning challenges. Flipped learning helps to facilitate this.

4 Immersive Technologies

In this section, I’d like to discuss two new technologies – 360-degree cameras and virtual reality – which provide relatively authentic immersive experiences that can aid in education. Here I’ll discuss opportunities for these technologies in the geotechnical engineering context.

4.1 360-degree Cameras

Recently, the price of 360-degree cameras and their associated goggles have fallen dramatically. An example, from Kaiser Baas, is shown in Figure 3. At the time of writing, the cost of the camera is less than $US70 and the cost of the goggles is less than $US20.

What are 360-degree cameras and what do they do? A 360-degree camera is one that enables the user to capture a field of view of an entire sphere. It does so by incorporating two half-spherical lenses, one on the front and another on the back of the camera. When stitched together in a relatively simple fashion, using low-cost software and with the aid of goggles, one can visualise an environment in a relatively basic form of virtual reality. The goggles (also shown in Figure 3) enable the user to slide their mobile phone, in landscape mode, into the front plate. Using an app on the phone, two video images are displayed, one for each eye. When the goggles are worn on the user’s head, by means of the mobile

Figure 3. Example of a 360-degree camera and associated goggles. Source: www.kaiserbaas.com

phone's in-built accelerometers, an almost complete sphere-of-view is observable, simply by moving one's head. Alternatively, one can watch a 360-degree video on a traditional computer screen and navigate using a mouse.

At the University of Adelaide, 360-degree cameras have been used to provide students with virtual site visits to various civil engineering construction activities. Whilst, clearly not as ideal as an actual physical site visit, these virtual visits provide several advantages. For example, over time, a catalogue of site visits can be developed, giving students a wide range of learning experiences. They permit students to visit sites, when they might otherwise have missed the opportunity to attend an actual visit because of illness or some other unforeseen event, such as last-minute, on-site challenges or inclement weather. It also facilitates distance learning.

As the videos can also incorporate sound, by means of the mobile phone's speaker or headphone jack, narration can be provided to augment the learning experience.

In geotechnical engineering, such technology can be used to observe various aspects of site investigations, such as borehole drilling, soil sampling and in situ testing. Students could also visit virtual sites in order to explore various surface features, such as topography, drainage and previous activities that might be useful in characterising a site. Students could also visit various projects, either in construction (e.g. retaining walls, foundations or pavements) or during operation (e.g. Leaning Tower of Pisa, dams, or the after-effects of an earthquake or landslide), in order more accurately to appreciate and learn from these geotechnical engineering topics.

The goggles described above permit three degrees of freedom, i.e. rotation in the three, orthogonal axes (pitch, yaw and roll). They do not, however, permit the user to translate, i.e. move horizontally or vertically. As we'll see in the next section, true virtual reality achieves this.

4.2 Virtual Reality

The Meriam-Webster Dictionary defines virtual reality (VR) as:

> "An artificial environment which is experienced through sensory stimuli (such as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment."

Very recently, VR technology has become much more accessible and affordable to educators. In mid-2019, the Facebook-owned VR technology company, Oculus VR, released a new headset, the Quest (Figure 4), which marked a step change in VR. Up until that point, because of their significant computational demands, VR headsets, such as the Oculus Rift (Figure 5) and HTC Vive, needed to be connected to a high-end graphics computer via cables and used additional, external sensors, which significantly limited the accessibility and functionality of VR. The Quest headset, on the other hand, is equipped with mobile phone type technology, and while the resolution of the image in the headset is not as sharp as previous tethered models, it is cable-free, the sensors are incorporated into the headset, and high-end computing is no longer required, as the software and processing is undertaken within the

Figure 4. Oculus Quest VR headset and hand controllers. Source: www.oculus.com/quest

Figure 5. Oculus Rift VR system. Source: www.vrzone.com

headset itself. Like similar VR equipment, the Quest enables 6-degrees of freedom; i.e. rotation in the three, orthogonal axes (pitch, yaw and roll), as well as lateral movement in the three, orthogonal axes (left-right, forward-back and up-down).

With the release of the Quest, there is now great opportunity to exploit VR technology and adapt it to a wide range of applications, including geotechnical engineering. In this section, I'd like to share, briefly, my initial thoughts and forays into this space.

In 2019, I and a group of four, final year civil engineering Honours students 'dipped our collective toes' into the VR 'pond', in the form of a pilot research project. The question that we asked ourselves was "How might VR be used in the geotechnical engineering educational context?" In a first answer to this, we imagined the underground, in a way similar to that which David Macaulay achieved in 2D, as a series of sketches in his attractive and engaging book *Underground* (Macaulay, 1976). An example from this book is shown in Figure 6. Notice at the bottom of the sketch, presumably a father and his child standing on one of the soil layers peering up and admiring the pile foundations associated with several buildings.

As we know, one of the significant challenges of geotechnical engineering is that the underground is opaque and generally hidden. This presents both opportunities, but also challenges. For example, foundations are, almost always, hidden from view (e.g. Fig. 6), as is soil stratigraphy. In this student project, we explored both of these topics – foundations and stratigraphy – from a VR perspective.

Before examining our early exploration in the VR space, a logical first couple of questions are "Why bother with VR?" and "Is VR helpful in education?" In regard to the first question, VR helps one to visualise the non-visible. It is also immersive, in that one feels like they are truly immersed in that environment, and it is also engaging and modern. VR is useful for the promotion of civil and geotechnical engineering, especially to the general public and potential students. It is also helpful for clients to visualise the underground, in a similar fashion to that adopted by architects when visualising yet-to-be constructed buildings.

With respect to the second question, the 'jury is still out.' As the technology is so new, few publications have explored the educational efficacy of VR. Clearly, VR does not replace the 'real thing'. As with most learning technologies, VR should be adopted to augment, not replace, existing pedagogies. As such, it is hard to imagine that VR would be unhelpful.

Back to the final year Honours research project (Coutts et al., 2019). We set ourselves the task of developing a virtual environment involving three multi-storey buildings in the central business district of Adelaide, Australia. Of course, the students shall take all of the credit for what follows, as they are the ones who 'floated to the surface' of this very deep pond, and who, because of their instruction in Civil & Architectural Engineering, possessed reasonably sophisticated 3D modelling skills. The first building selected was Westpac House, which was Adelaide's tallest at the time. The second and third buildings (Ingkarni Wardli and The Braggs Building) were recently constructed at the University of Adelaide's North Terrace campus. The buildings were selected based on the varied nature of their foundations and the availability of construction drawings, which are essential in the development of authentic 3D models. The three buildings are shown in Figure 7.

Westpac House (Fig. 7a) was constructed in 1988, is 132 m tall and is built on a 3.5 m thick concrete raft foundation, whereas the Ingkarni Wardli (Fig. 7b) and Braggs buildings (Fig. 7c) were constructed in 2010 and 2013, respectively, and are both situated on pile foundations. As mentioned above, the construction drawings associated with each building were used to develop the VR simulation. An important element of the project is modelling the stratigraphy of the ground, and borehole logs from each building site were used in the development of the VR simulation.

The buildings and the ground profile were modelled in 3D using the Revit (Autodesk, 2020) software package. In order to create the VR simulation, files were exported from Revit and then input into the Unreal Engine (Epic Games, 2020) gaming software. Examples of the 3D modelled buildings and their associated foundations, from Revit and Unreal Engine, are shown in Figures 8 to 10. The final step of the process was to port the Unreal Engine output file to the Quest headset.

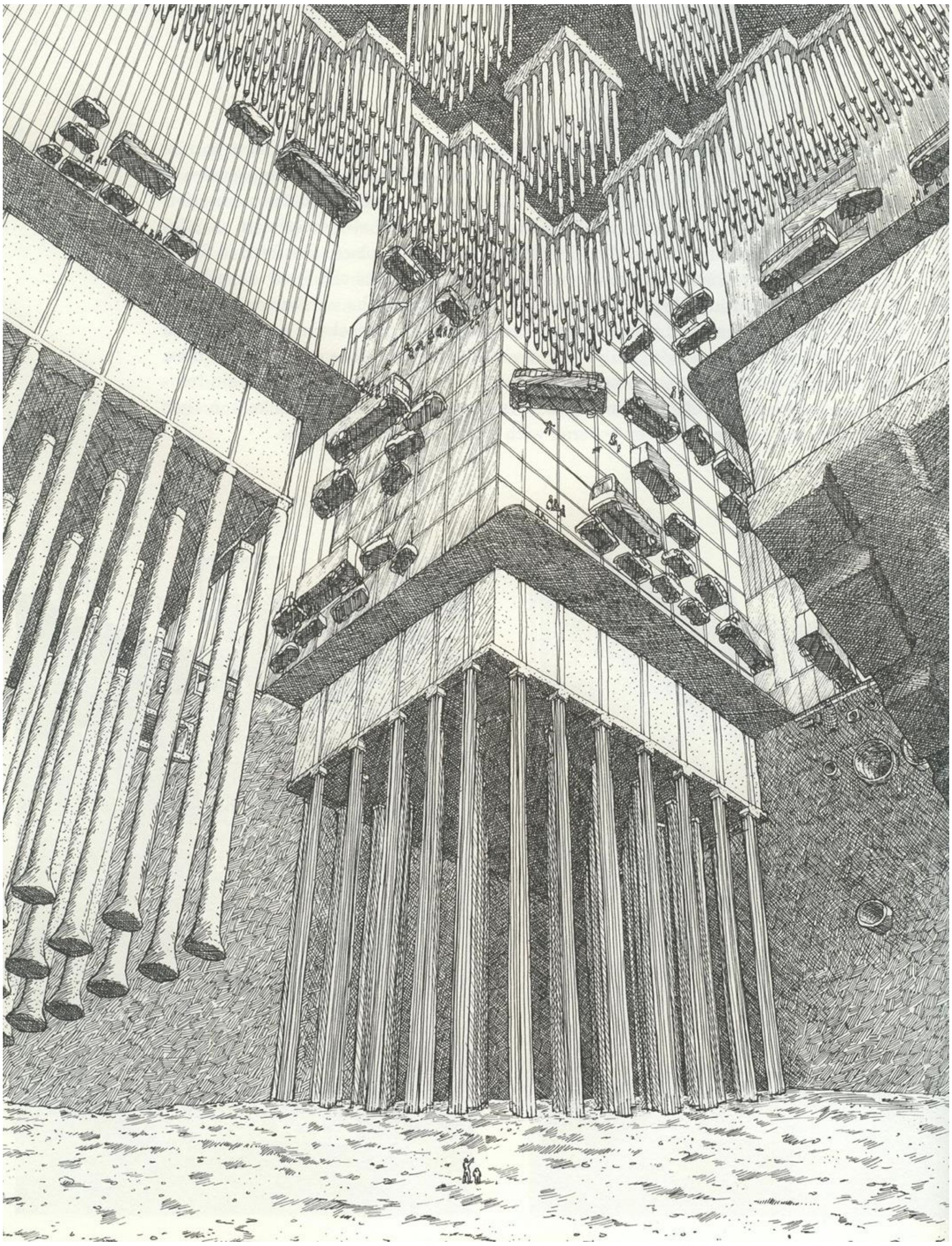

Figure 6. Example of the underground from Macaulay (1976), used by permission

Figure 7. Three multi-storey buildings selected for modelling (a) Westpac House, (b) Ingkarni Wardli, (c) The Braggs Building

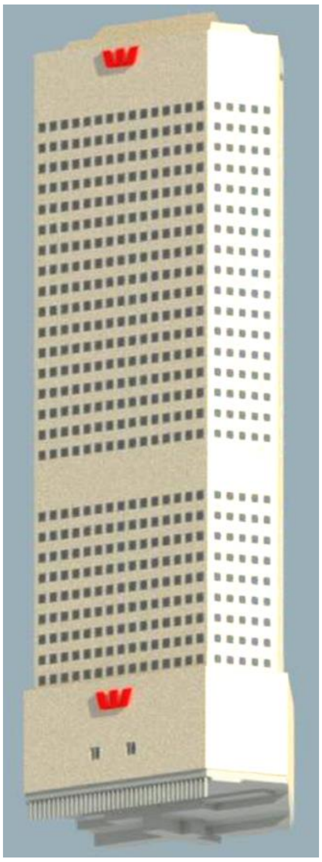

Figure 8. Rendered image of Westpac House from Revit (Coutts et al., 2019)

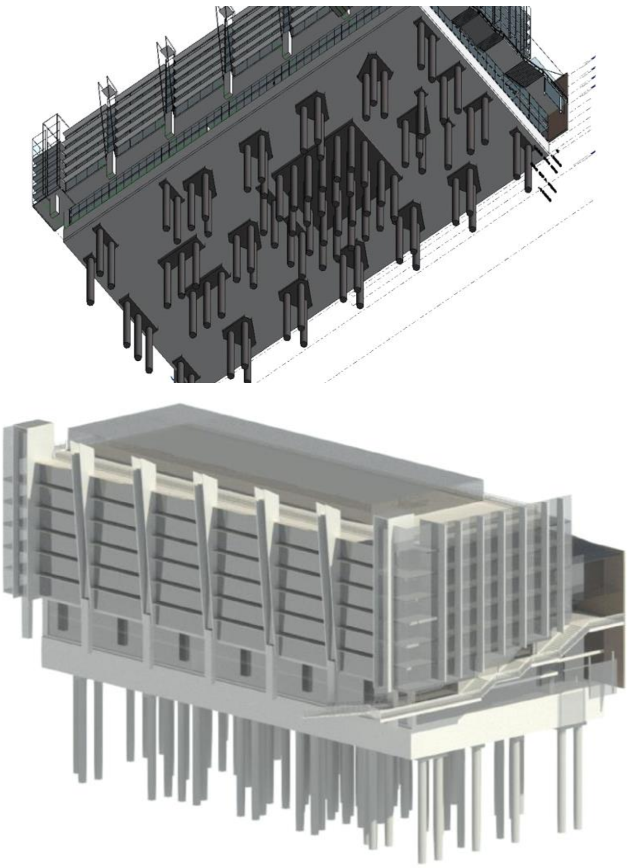

Figure 9. View of the Ingkarni Wardli from Revit: (a) underside, (b) rendered building (Coutts et al., 2019)

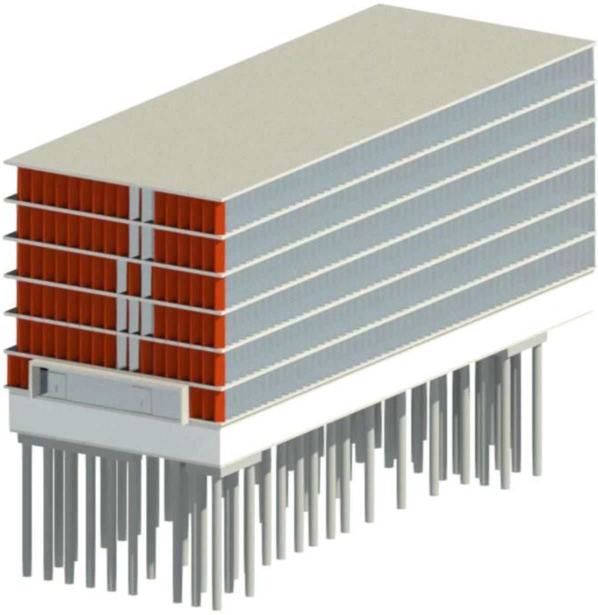

Figure 10. Rendered image of the Braggs building from Revit (Coutts et al., 2019)

The final VR precinct is shown in Figure 11. As Westpac House is located almost 1 km from the two University of Adelaide buildings, a virtual environment was established, where the three buildings are co-located on a single, condensed site, as shown in Figure 11. Even so, as the VR simulation incorporates the buildings at their authentic scale, it is impractical to walk between the buildings within the virtual environment. Hence, a virtual 'teleport' function, which is an element in Unreal Engine, was incorporated into the simulation. Moving the Quest's hand controller joystick up and down, enables the user to move up and down in, effectively, a virtual transparent elevator. This enables the user to be lowered beneath the ground surface. Apart from some modest tinting, in order to highlight the different soil layers, the ground is also transparent, enabling the user to see, and move about, the buildings' foundations.

As one might expect, a 2D paper such as this, is unable to represent appropriately an authentic visualisation of the VR simulation of the three buildings, along with their constructed foundations and associated ground profiles. Nevertheless, in order to provide a sample of what has been achieved within the VR simulation, some images from it are presented in Figures 12 to 16. As can be seen, specific text is also incorporated in the simulation to provide relevant information for the viewer. In future adaptations, this is planned to be replaced by narration.

With this initial exploration into VR, we've only 'scratched the surface' of what might be achieved using this technology. It is expected that the VR simulation will be extended and improved in the future. It has yet to be deployed in a classroom to augment traditional forms of instruction. It has, however, been presented at an exposition of student research work, which was open to the general public, as well as school children. Needless to say, given the cutting-edge nature of the VR technology, as well as the quality of the simulation, it was extremely popular with both school children and the general public.

I'll conclude this brief exposé of VR by imagining where this might lead geotechnical engineering in the future. Just as VR has been incredibly helpful in architecture for visualising yet-to-be-constructed building designs, particularly for clients and the general public, one can imagine that VR would be equally helpful in most sub-disciplines of civil engineering. Various foundation options, and other geotechnical elements, could be visualised prior to construction. Some companies, for example, are using VR to visualise and model cities, such as the Virtual Singapore project (Dassault Systèmes, 2020a), which enhances and unifies city planning and also facilitates the modelling of various scenarios, such as earthquakes and terrorist activities, from which optimal solutions can be derived. Complex civil construction sequences are also being modelled (Dassault Systèmes, 2020b).

VR is also being used as an effective training medium, where, for example, mining engineers can be trained in several aspects including underground mining methods, hazard awareness, working at

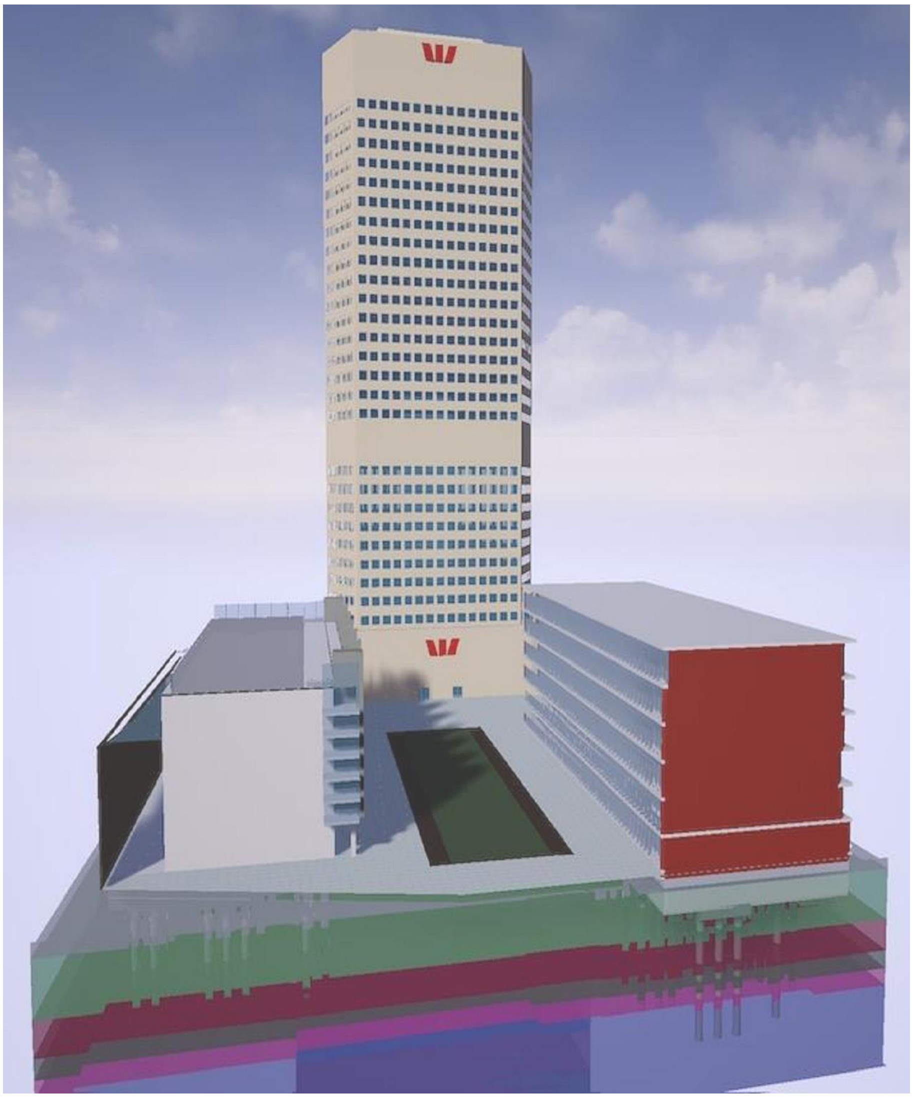

Figure 11. Three multi-storey buildings modelled (Coutts et al., 2019)
(Left to right: Ingkarni Wardli, Westpac House, Braggs Building.)

Figure 12. VR simulation: Precinct (Coutts et al., 2019)
(Left to right: Ingkarni Wardli, Westpac House, Braggs Building.)

Figure 13. VR simulation: View of Westpac House looking up from ground level (Coutts et al., 2019)

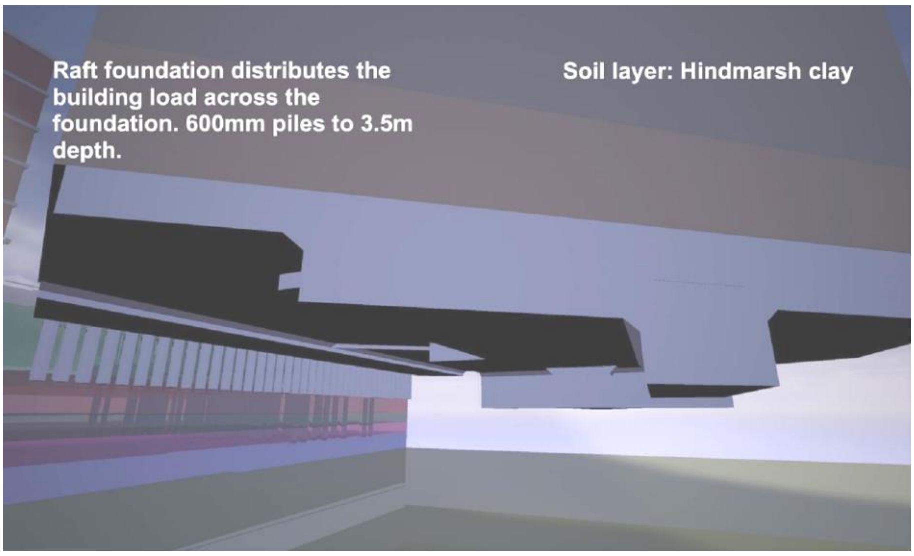

Figure 14. VR simulation: View of Westpac House raft foundation (Coutts et al., 2019)

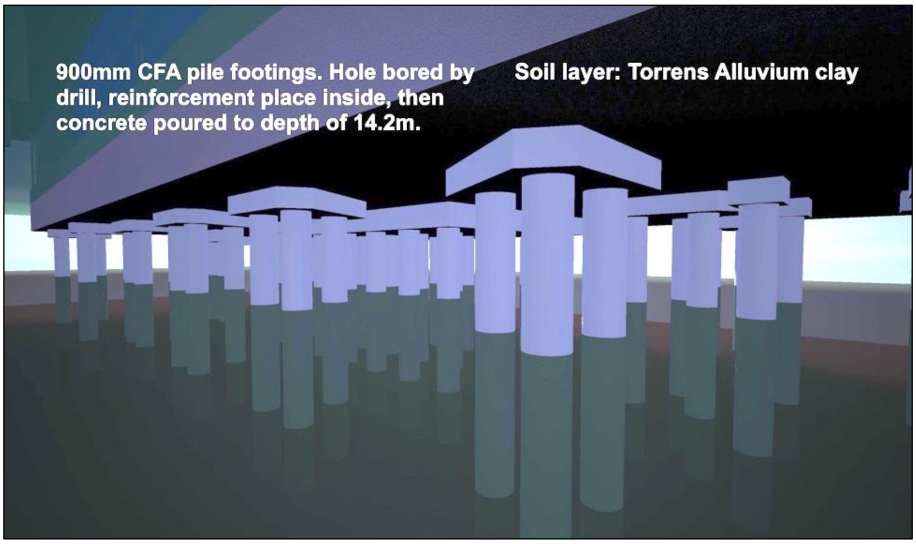

Figure 15. VR simulation: Ingkarni Wardli foundations (Coutts et al., 2019)

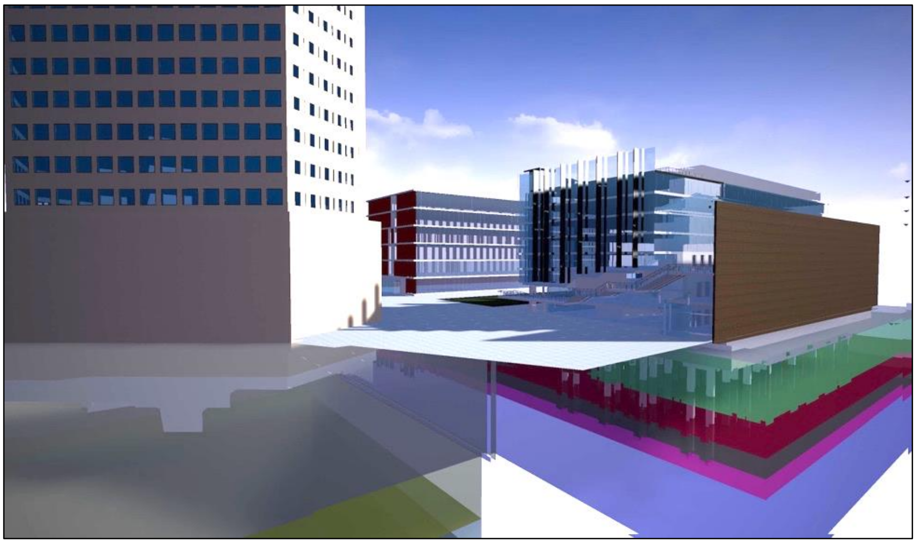

Figure 16. VR simulation: Distant view of precinct (Coutts et al., 2019)

heights, vehicle inspection and data visualisation (Hebblewhite et al., 2013; Mitra & Saydam, 2014). In this way, using an authentic and safe virtual environment, risk of injury during training is effectively eliminated. Similarly, VR is used extensively in construction engineering education and training (Wang et al., 2018). One can also envisage similar training opportunities in the geotechnical engineering context.

VR can also assist with visualising complex stratigraphies and ground profiles in order to better understand the ground, and also facilitate the design of optimal geotechnical structures. In a similar way, complex underground services can be visualised using VR so that, again, geotechnical structures can be designed effectively and efficiently.

A very useful opportunity, but one that is likely sometime in the future, is linking numerical modelling with VR. One can imagine modelling a structure using established geotechnical engineering computer analysis (such as the finite element, finite difference or discrete element methods), modifying a range of geotechnical parameters (such as shear strength, compressibility or stress paths), and modelling the subsequent system performance. By linking these dynamically with the VR system, one could visualise the numerically modelled results. Whilst this would be incredibly valuable in practice, it would also be so in geotechnical engineering education, where students could explore various cause-and-effect scenarios in order to improve their understanding.

5 Conclusions

This paper has examined three aspects of geotechnical engineering education. Firstly, it has been advocated that the principles of critical state soil mechanics (CSSM) be universally adopted in the education, at undergraduate level, of civil engineers. Not the details of the Cam Clay model, or similar, but the linking of load, strength and volume change, which is one of the great strengths of CSSM. It has been argued that CSSM also effectively models real soils, such as those that are unsaturated and those that undergo liquefaction. Secondly, the flipped classroom pedagogy has been briefly examined and it has been argued that it adds value in contemporary geotechnical engineering education. Finally, the immersive technologies of 360-degree cameras and virtual reality have been presented in order to explore whether they might augment learning and teaching in geotechnical engineering. It is concluded that they are likely to be helpful.

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