Applying 3D Geological Modelling Techniques to Geotechnical Engineering Problems – Advantages, Pitfalls, and "Getting the Geology Right"

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ABSTRACT

The geotechnical ground model is the fundamental basis of geotechnical engineering. 3D geological modelling software is now routinely utilised to assist with solving geotechnical engineering problems – this allows rigour to be applied to ground model development, and facilitates early identification and assessment of geotechnical site issues. A good 3D conceptualisation improves connectivity between different engineering disciplines and can improve project efficiency. However, for a model to be useful, it must be founded on robust geological principles, and the value of high-quality input data and expert user guidance cannot be understated. This paper presents several project case studies from Victoria, Australia, demonstrating how the utilisation of 3D geological modelling techniques 1) expanded our understanding of the sites' geotechnical and hydrogeological ground model, 2) aided identification of the geotechnical failure model, and 3) assisted site investigations. We highlight the ways in which modelling played an essential role in clarifying the site geology, geotechnical parameters, and hydrogeology, and where it helped to refine the proposed geotechnical design. When used effectively, 3D modelling can synthesise large datasets to help identify and interpret crucial features and sources of geotechnical risk. We note that while 3D geological modelling tools are now routinely utilised on large infrastructure projects, they remain relatively under-utilised on small- and medium-sized projects, even where the geology is complex and/or the geotechnical risk is high. We demonstrate the value of 3D geological modelling combined with geological/geotechnical knowledge, and how it assists in developing ground understanding for geotechnical engineering projects of all sizes.

Keywords: 3D geological modelling, geotechnical engineering, ground model development

1 INTRODUCTION

The site ground model forms the basis for geotechnical analysis and design (Sullivan, 2010). Ground model development for geotechnical projects is now often done using 3D geological modelling software tools (e.g., Leapfrog Works), which have become increasingly affordable and user-friendly over recent years. 3D geological models are 3D interpretive representations of the earth's sub-surface geology. When used in engineering geology, they are usually deterministic ("explicit") in nature, although they may also be stochastic ("implicit;" IAEG, 2021). However, to be useful engineering tools they must utilise high-quality input data, be founded on robust geological understanding, and should be designed to address a particular engineering problem. Ideally, they should be developed in accordance with the draft guidelines laid out in IAEG (2021).

3D geological models, if used correctly, should form part of the site Engineering Geological Model ('EGM'; IAEG, 2021), which combines and evaluates all available input data to produce an interpretive understanding of the site engineering geological conditions, for the purpose of informing engineering decision-making. Therefore, 3D geological models are not merely 3D data visualisations, but are also a key input to the overall knowledge framework for the site. Key advantages include 1) improved data visualisation capabilities, 2) improved project efficiencies, and 3) improved communication. This tends to result in an improved understanding of the site ground model.

3D geological modelling tools are of most use when used on projects with a combination of 1) large or complex ground investigation datasets, 2) relatively high geological complexity, and 2) a high degree of geotechnical risk. While the up-front cost of model development can sometimes be significant – typically ~0.5–2.5% of total fees for fully-fledged models – modelling effort can be targeted, and development costs are often recuperated later in the project lifespan when efficiencies are realised. In Australia and New Zealand, 3D geological modelling is typically utilised as standard practice on larger engineering projects, where the cost of model development is relatively small compared to the total fee. However, it remains relatively under-utilised on smaller projects, even when the degree of geological complexity and/or geotechnical risk is large. This may be due to the assumption by both practitioners and clients that they are unnecessary, and that the cost of model development (as a proportion of the fee) will be unacceptably high for smaller projects. However, as discussed in Section 4, this is not necessarily the case. The uptake of 3D geological modelling techniques by the geotechnical engineering industry has also likely been hampered to-date by 1) a general lack of applicable industry guidance for the development of 3D geological models (IAEG 2021), 2) inefficient data storage systems and relative inaccessibility of project data, and 3) discomfort with modern digital techniques compared with traditional approaches (e.g., KPMG, 2016) and a perception that models carry additional uncertainties compared to traditional 2D sections.

It is timely to summarise the key advantages and common pitfalls encountered when utilising 3D geological modeling tools, with reference to project case studies.

2 KEY ADVANTAGES

3D geological modelling packages allow for 1) visualisation of geotechnical investigation datasets, 2) 3D visualisation of published data, mapping, digital elevation models (DEMs), and aerial photography, 3) rapid statistical analysis of drilling data and geotechnical analyses, 4) recategorization, complex filtering, and querying of geotechnical investigation datasets, and 5) identification of spatial trends and patterns. Additional advantages and applications include 1) improved process efficiency (e.g., semi-automated section production, software interoperability), 2) estimation of volumes of materials, 3) developing ground profiles, 4) developing an understanding of hydrogeological behaviour, and 5) modelling contamination plumes.

3D geological modelling tools can assist with anticipating the site ground profile prior to intrusive site investigations, which can allow the scope of the drilling program to be optimised and targeted for the expected site conditions. This can help the engineer to make the best use of expensive field investigations. Unfortunately, it is common for 3D geological modelling works to be requested later in the project lifespan, once the full suite of drilling data is available, and when opportunities to adjust the site investigation and proposed design are diminished (e.g., Ranjan, 2017). However, knowledge of the ground profile is especially valuable early in the project lifespan when it is both easier (and cheaper) to adapt the site investigation program to better understand site anomalies. Improved industry awareness of the advantages of 3D geological modelling may help these tools to be more effectively utilised.

3 CASE STUDIES

We introduce three case studies from Victoria, Australia, to demonstrate the value of employing 3D geological modelling tools on small- and medium-size geotechnical engineering projects. All case studies utilise the software Leapfrog Works (version 2021.1.1), developed by Seequent. In all cases, models were primarily ‘deterministic’ in nature (i.e., they are fitted to the available data and guided by the modeller’s understanding of the ground model). Uncertainty was not estimated directly, but was estimated and communicated on the model outputs and within the accompanying documentation.

3.1 Case Study 1: Mount Eliza Landslide

3D geological modelling can assist with slope stability modelling by improving the ability to visualise and query multiple datasets in 3D, and through improved ability to rapidly export geometries to slope stability modelling software. While this workflow is becoming fairly standard practice for slope stability analysis, it is important to emphasise that the slope stability modelling results should be fed back into the geological model to verify and improve the ground model. An example is provided below.

The project comprises a coastal multi-residential property, southeast of Melbourne. The site is located atop an active and very slow-moving landslide complex, which is related to the Manyung fault which itself bisects the site (**Figure 1**). The Manyung fault forms part of the Selwyn fault system, which is an active neotectonic feature (Geoscience Australia, 2022), although no historical ruptures have been recorded. Much of the site surface is hummocky, and numerous scarps cut the site. It had been contended by other parties that the site was previously stable but had undergone recent movements due to recent coastal foreshore erosion. We used 3D geological modelling to improve data visualisation, streamlined determination of the geotechnical failure model, and increase process efficiency through software interoperability with slope stability modelling software.

Published maps and sections for the site indicated that the site is underlain by a combination of Tertiary-aged sediments, with granodiorite and basalt expected from ~20–30 m bgl beneath the site (Gostin, 1966; Peck et al., 1992). The site foreshore comprises beach sand overlying slip debris derived from the Tertiary-aged sediments. The active Manyung fault trace, which runs NE-SW at the rear of the site

(**Figure 1**), was originally interpreted by Gostin (1966) as a west-dipping normal fault that approximately parallels the coastline. Senversa carried out a site investigation in 2021 based on this conceptual site model to investigate slope instability. The investigation included a site geomorphological walkover, mapping of site features, and boreholes and CPTs positioned across the site with target depths nominally at 20 m bgl to confirm rock head. The deepest test location was terminated at 34 m bgl. While extremely weathered granodiorite was encountered in boreholes in the eastern part of the site, unexpectedly these passed downward into Tertiary sediments, representing an unexpected 'age reversal.' This had several important implications for the site ground model: 1) this contradicts the original interpretation of Gostin (1966) that the Manyung fault is a normal fault, 2) it requires the presence of two reverse splay faults within the site, because the location of the main Manyung fault scarp is located further to the east, and 3) the depth to bedrock may be much deeper than that predicted by Gostin (1966). As a result of this information from the 3D geological model, a thorough literature review was undertaken which identified that faults bounding the Mornington Peninsula had since been re-interpreted as reverse faults (Cayley et al., 2002), consistent with our drilling observations.

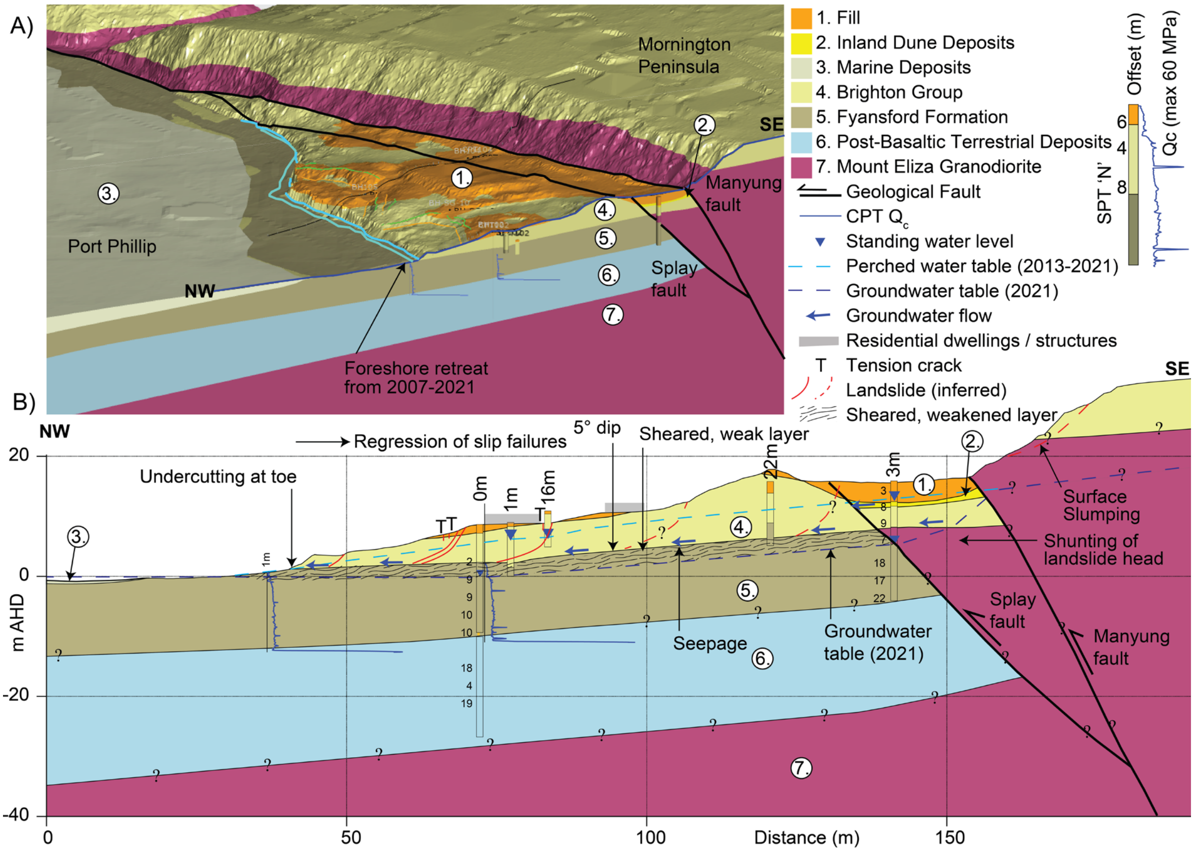

*Figure 1 – **A)** 3D geological model for the Mount Eliza site (natural scale). Note the Manyung fault and its splay fault (black lines), and the extent of foreshore retreat between 2007–2021 (light blue lines) – see text for explanation. **B)** Interpretive ground model for the site, incorporating the results of the slope stability modelling. Note the sheared, softened layer at the top of the Fyansford Formation, which defines an ancient, translational slip surface. A series of regressive, rotational slip surfaces cut the overlying Brighton Group. The Manyung fault and its splay fault define the landward limit of the landslide complex.*

Two aquifers were encountered: one perched within the upper Tertiary sediments, and another located along a softened layer (**Figure 1B**). 3D geological modelling software (Leapfrog Works) was used to visualise shoreface retreat. The literature review indicated that the rate of foreshore retreat was episodic, marked by periods of net foreshore erosion interspersed by periods of net foreshore advancement. Multiple topographic surveys (2007, 2021) were assessed to estimate the distribution of recent foreshore erosion at the site (average retreat rate of 0.2–0.3 m/yr from 2007–2021). However, historical aerial photography indicated that while net foreshore erosion had occurred between 2007–2021, foreshore erosion had been variable since 1946, with net shoreline movement sometimes being seaward.

A 3D geological model was developed for the site (**Figure 1A)** to assist with determination of the ground model and slope failure mechanism. This was useful, as the failure surface could not be definitively identified from the boreholes or CPTs, and time did not permit the installation of inclinometers. Modelling effort required was modest, incorporating both surface and sub-surface data. Cross-sections were computed along critical sections, and geometries were exported to the software GeoStudio 2021 for slope stability analysis. The slope stability model was calibrated using existing active slope failures located near the coast, and material parameters were estimated based on laboratory analyses and published correlations. Separate analyses were conducted for the 2007 and 2021 site surveys, to show the effects on slope stability of ongoing foreshore erosion and erosion of the toe over that period. The slope stability modelling showed that the ancient surface was brought closer to failure by net foreshore erosion between 2007–2021. It was also demonstrated that beach nourishment (i.e., placement of sand material on the foreshore) would slightly improve the stability of the site. The results of the slope stability modelling were then recombined with the 3D geological model to refine the model, and modelled slip surfaces were compared against the field data.

The data are consistent with a basal, ancient translational failure surface that occupies the ~5° seaward-dipping contact between two Tertiary-aged soil layers (**Figure 1B**). Repeated reactivation of that surface has resulted in development of a sheared, weakened layer there. A series of smaller, arcuate slips cut upward from the sheared layer, and are marked at the surface by back-scarps and tension cracks. Together with the historical aerial imagery, this indicates episodic movement of the landslide system. It is speculated that periods of activity on the basal, ancient landslide are triggered by a combination of 1) erosion of the landslide toe due to foreshore erosion, 2) loading of the landslide head (e.g., due to landscaping earthworks, surface slumping from the upper slope, or movement on the Manyung fault), 3) increased groundwater pressures (e.g., in response to heavy rainfall events), and 4) seismic activity or tectonic shearing (e.g., on the Manyung fault). Periods of slip on the Manyung fault would load the landslide head. Slow landslide movement results in net seaward mass movement, which loads the landslide toe. Ongoing movement on the basal landslide would then continue until the toe had been sufficiently loaded. This is followed by periods of quiescence, during which time stability is improved through shear strength healing of the softened layer (Stark and Hussain, 2010). Together, this process results in episodic periods of movement, interspersed by periods of relative stability. Based on this interpretation, Senversa was able to demonstrate that the site stability was governed by the presence of an ancient, but intermittently active, basal landslide.

3.2 Case Study 2: Brickworks Quarry

The project comprises an active quarry located in Central Victoria. Two phases of work were conducted: 1) a preliminary 3D geological model for the site was developed based on limited drilling data, and 2) the design of multiple landfill cells including a limited drilling program. The key advantages of 3D geological modelling were the ability to use the preliminary model as a data visualisation to anticipate the materials present in different parts of the site, and assistance with developing an understanding of groundwater seepage behaviour and impacts of surface water in the various quarry pits.

The site is located on a large exposure of Silurian Dargile Formation (siltstone), surrounded by Quaternary Newer Volcanic Group (basalt flows; **Figure 2A**). A preliminary 3D geological model was developed in Leapfrog Works using limited historical borehole data, geological mapping, aerial imagery, multiple topographic surveys (2007–2008, 2021), and surface water measurements. Only modest effort was required to generate the model. The two surveys were compared to determine the extent of excavation and stockpiling of fill across the site – this enabled identification of a fill embankment between the creek and the West Pit (**Figure 2B**), which had previously been incorrectly logged as alluvium.

Additional drilling was later requested by the client to investigate the ground conditions for a proposed landfill containment facility in the northern area. The location for the proposed facility had been formulated without accurate knowledge of the local ground profile – it was not known that significant filling had occurred, and the proposed footprint had been assumed to be underlain by a single stratum. However, the existing preliminary 3D geological model was able to demonstrate that the ground conditions were likely to be variable across the footprint (**Figure 2B**). This knowledge was then used to scope the drilling investigation and ensure that the thick fill and variable ground profile were adequately targeted. In this way, we were able to provide advice regarding the risks of differential settlement across the proposed footprint. Ultimately, the design solution was to strip the existing fill and adjust the proposed layout, to avoid founding partly atop fill, siltstone, and residual basaltic clay. The 3D geological model was then able to rapidly estimate the volume of fill materials to be removed.

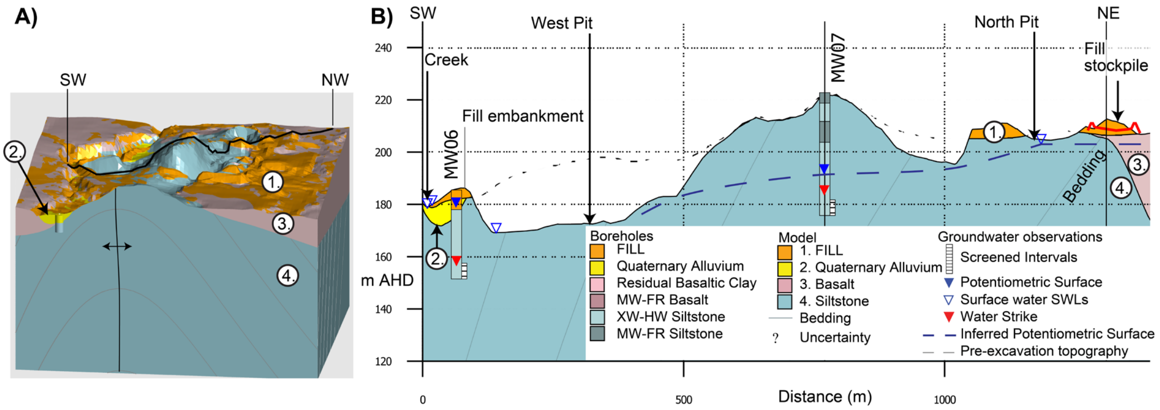

*Figure 2 – **A)** 3D geological model of the brickworks quarry site (5x vertical exaggeration). Note the section alignment (black line). **B)** Cross section through the brickworks site. Note the pre-excavation topography (dashed line), present topography (black line), fill stockpiles indicated by the difference between these surfaces, and the proposed design footprint for the containment cell (red line).*

3.3 Case Study 3: Former Fire Training Facility

The project comprises an inactive former fire training facility located in Central Victoria. Pliocene basalt flows are underlain by Tertiary sediments. A 3D geological model was developed for the site to synthesise approximately 10 years' worth of site investigation data, which had previously only been reviewed in 2D. The 3D modelling enabled the extent of the geometry of a paleochannel to be rapidly determined, and assisted with planning of the ongoing drilling investigation.

A preliminary model (**Figure 3**) was developed in Leapfrog Works using 32 boreholes, supplemented by surface mapping within deeply eroded gullies to the east and west of the site. Initial model development required only modest effort, and the model was able to be updated efficiently based on subsequent rounds of drilling data. 3D visualisation of the data and ground model immediately revealed multiple paleosols developed within the basalt, separating multiple, distinct basalt flows. Paleosols have the potential to act as aquitards, and at the time it was suspected that they may control site groundwater behaviour. However, visualisation of the groundwater dataset in 3D against the paleosol layers revealed that this was not the case, and that groundwater levels were instead controlled by vertical, highly fractured zones of higher permeability in the basalt. The 3D geological model was also able to define the extent of the paleochannel, and highlighted data gaps and areas of uncertainty. This information was used to guide further site investigation works, with each phase of works being used to update the model in real-time. In this way, the locations of new boreholes were able to be optimised based on the latest understanding of the ground model. The model itself also served as an invaluable tool for guiding client presentations and discussions and improving collective understanding of the site.

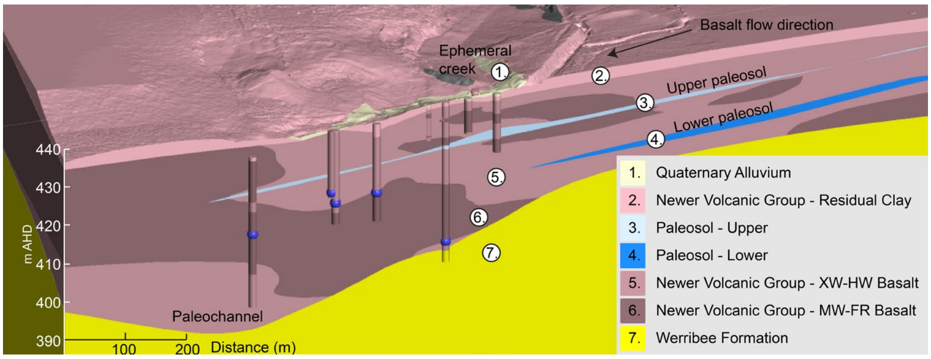

Figure 3 – 3D geological model for the former fire training facility site (5x vertical exaggeration). Note the two paleosols, paleochannel feature, and standing water levels (blue dots).

4 COMMON PITFALLS

Robust 3D geological models should incorporate geological data from a variety of sources. Typical inputs include topographic DEMs, boreholes, CPTs, piezometer data, geological maps, and aerial imagery. For sites that may have undergone cutting/filling or change over time (e.g., landsliding), multiple topographic surveys collected at various times should be used to construct the model, so that changes to the site topography can be accurately quantified. For all three case studies described herein, multiple surveys were assessed to develop the site understanding.

3D geological modelling is not a substitute for sound engineering geology expertise. Inadequate geological understanding can limit the modeller's ability to *'get the geology right'* (e.g., Fookes, 1997), which can result in incorrect understanding of the site geotechnical risks. The modeller must have a good understanding of the geological principles and site setting, which should form the basis for the site conceptual model. The 3D geological model must be consistent with the mapped geology, and must be consistent with the geological processes and stratigraphic relationships expected at the site. For Case Study 1, lack of recognition of the "age reversal" encountered in the drilling investigation, and lack of knowledge of the Caley et al. (2002) interpretation of the Manyung Fault orientation, would have led to the assumption that the Manyung fault dipped in the incorrect direction, which would have led to a reduced understanding of the slope failure mechanism.

The modelling approach should be flexible, and the modeller should be prepared to modify the model as required by the input data (Sullivan, 2010). Multiple model hypotheses should be explored early on, and each tested, with the goal of converging on the final site conceptual model based on the evidence. The modeller also needs to understand the limitations of the dataset. It is generally unacceptable to omit data or information that do not fit the model – while 'outliers' may potentially be excluded, this must be justifiable. Ultimately, the model should be based on the facts, rather than reverse-engineering the model from a preconceived answer. Ideally, the 3D geological model should be continually refined based on the latest available data and site understanding. This is particularly the case when new data are not consistent with the predictions of the preliminary model (as was the case for Case Study 1).

It is often assumed that 3D geological modelling is unnecessary and/or too expensive for use on small- and medium-sized projects (refer Section 1). However, these techniques are potentially of great benefit to such projects if the geology is relatively complex, and if the geotechnical risk is high. It is important to note that a fully-fledged model need not be developed for all projects – the amount of modelling effort can be readily tailored to suit the project requirements, and modelling focused on key elements. For small- and medium-sized projects, it is often possible to invest only minimal modelling effort to obtain an improved understanding of the ground model. Modelling effort is regularly recuperated later in the project lifespan when additional efficiencies are realised (e.g., semi-automated section development).

5 CONCLUSIONS

3D geological modelling can be a valuable tool for geotechnical engineers. Advantages include improved site understanding, enhanced visualisation and communication, improved planning of drilling investigations, and improved efficiencies. However, 'over-enthusiastic modelling' can lead to a misuse of such tools and there are several common pitfalls, including inadequate recognition and incorporation of the available input data, and an inadequately developed site conceptual model. Finally, while 3D geological modelling tools are now routinely used on large infrastructure projects, there is significant opportunity for increased utilisation of these techniques on small- and medium-sized projects, where they can improve site understanding and improve efficiencies, in many cases with only modest modelling effort required. We argue that improved industry awareness of the key advantages (and potential pitfalls) of these tools will enable them to be more effectively utilised on small- and medium-size projects.

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