Spatial variability of pile founding layers: a case study

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ABSTRACT

This paper explores the design and construction of a single span road bridge, highlighting the impact of geotechnical spatial variability on deep foundation projects. Due to various project constraints, the geotechnical boreholes used for initial design were located a considerable distance from the proposed bridge abutments. As the project progressed, and further geotechnical investigations were carried out, it was observed that the proposed pile founding layer showed signs of spatial variability in both thickness and strength. To address potential risks, the design was revised to extend the piles into a deeper layer of very dense sand, and proof bores were planned at the abutment locations to verify ground conditions before construction. This study incorporates 3D geological modelling, adopting the previous investigations and the latest proof bore data and provides a clearer representation of the variable properties of the pile founding layer, supporting the pre-construction design changes. The findings underscore the critical nature of geotechnical spatial variability and the need for strategic placement of investigative efforts. The paper also details observation and monitoring activities undertaken during construction to ensure that design intent and local government compliance criteria are met, and steps taken to manage potential risks during pile excavation in dense sands below the groundwater table, which are envisioned to be useful for deep foundation projects under similar conditions.

Keywords: Geotechnical spatial variability, 3D geological modelling, Pile construction, Segmental casing, Pile design

1 INTRODUCTION

As part of the level crossing removal works carried out in the Southeastern suburbs of Melbourne, a single span road bridge over a creek with one trafficable lane in each direction was proposed to be constructed. The integral bridge was designed to be supported on reinforced concrete abutments on each end that are founded on a single row of five piles. The geotechnical design for the bridge included the evaluation of ground conditions and the design of bored piles to support the bridge structure.

Limited geotechnical information was available during the early stages of design, which led to an initial design to include provisions for additional geotechnical information to be obtained and reviewed as design progressed. The initial design considered a shallower dense to very dense sand layer as a suitable pile founding layer. The risk of reinterpreting ground conditions and revising pile design was noted in the initial design, assuming that spatial variability would likely be low owing to the geological history of the site. However as more geotechnical investigations were completed, noting that these new borehole locations were still distant from the actual abutments due to ecological restrictions and access difficulties, spatial variability turned out to be higher than anticipated and this led to a risk of not being able to achieve the required pile capacity. This was deemed a critical scenario and therefore, it was collectively decided to revise the pile design to use the deeper residual sands as the founding layer.

This paper presents high-level details of the design process that illuminate the importance of spatial variability. Field observations during pile construction and results of 3D geological modelling conducted post project illustrate the issues faced, shedding new light to support the design change. The results of this paper are expected to be useful in scoping out geotechnical investigations for similar projects, evaluation of investigation results and highlight the importance of location and frequency of geotechnical testing.

2 DESIGN SUMMARY

2.1 Project setting and background

The project is located in the Southeastern suburbs of Melbourne, and the ground conditions comprise Red Bluff sandstone presented as stiff to very stiff sandy Clay and dense to very dense clayey Sand, underlain by the Lysterfield Granodiorite formation encountered as very stiff residual Clay and very dense residual sand before encountering highly weathered or better Granodiorite rock. The depth to rock was 29–30m, with varying thicknesses of residual material above.

As the creek is located in an ecologically sensitive area and due to restrictions from asset owner easements, early geotechnical boreholes were not placed close to the bridge abutments. As the project progressed and some of the required clearances were obtained, the main focus was to comply with local government authority requirements in regard to investigations, but the actual abutment locations were still inaccessible.

With limited geotechnical information during the early stages of design, the dense to very dense sand layer within the Red Bluff Sandstone unit was deemed a suitable pile founding layer on the condition that it met the minimum strength and thickness criteria to be confirmed by additional geotechnical investigations. It was noted that the residual Granodiorite clay layer underlying this sand unit was less competent in end bearing than the sand. The risk that reinterpretation of ground conditions would need to be done if the sand layer was found to be less competent was noted in the initial design stage. With new borehole information being received and reviewed, this initial founding layer that was being considered showed signs of being weaker and thinner.

The in-situ strength of the materials was assessed with standard penetrometer tests (SPT). The histogram of the SPT-N values recorded only within the initial founding layer (the Red Bluff Sandstone geological unit) for all boreholes is shown in Figure 1. The SPT-N numbers greater than 50 and refusal were included in the last bin of 50.

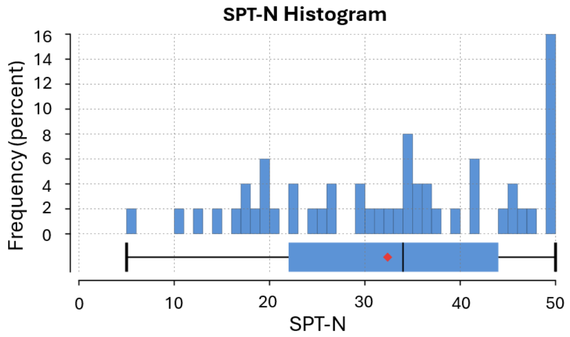

Figure 1. SPT-N histogram for initial founding layer within the Red bluff Sandstone unit

It can be seen that while most SPT-N numbers are greater than 35, indicating dense or better material, lower values were also recorded. This prompted the possibility of inconsistency within the sand unit, which led to the investigation of potential effects of spatial variability in both the strength and thickness of this initial founding layer.

Interbedded clay seams were also noted in the newer boreholes, which made it less suitable as a founding layer.

Furthermore, pile capacities had to be reduced to account for pile spacing changes to avoid clashing with buried utilities near the abutment.

Considering all these issues, a collective decision was made to increase the pile lengths to found within the rock. Further detailed review of the last stage investigations led to founding the piles within the very dense residual sand directly above the rock instead (in the Granodiorite geological unit). Spatial variability being a critical factor in the decision process, the following sections describe the latest findings made using the closest and latest data considering the design changes.

2.2 Spatial variability of initial founding layer thickness

Review of the boreholes indicated a potential trend of gradual lowering of the pile founding sand layer towards the creek. In addition, the SPT-N numbers within the sand layer turned out to be variable and interbedded clay layers were observed within the unit. Considering these issues and given the tight timeframes involved in design finalisation and construction, a collective decision was made by all parties to revise the design to lengthen piles to a deeper founding layer.
The following analysis and results were developed from a 3D geological model created in the Leapfrog Works modelling software package (with OpenGround integration for data import), post project, that support the decision made to revise pile lengths. This post project review intended to capture finer details of ground interpretation that may be useful for future projects.

Figure 2 shows the 3D geological model created with all the relevant boreholes in the area and the 3D model of the bridge structure overlain.

The model was created within Leapfrog Works using formation lithologies in boreholes. Leapfrog Works uses a mathematical algorithm developed from radial basis functions for 3D interpolation (Seequent, 2020).

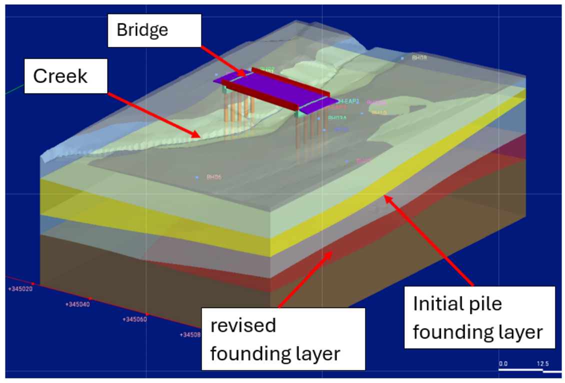

Figure 2. 3D geological model with bridge structure overlain

For the modelling of ground units, the logged soil layers were classified into their main soil type (whether sand or clay) and their geological unit (Red bluff Sandstone or Lysterfield Granodiorite). Fill was considered as a separate unit. A surface chronology based on a depositional model starting from the bed rock (Lysterfield Granodiorite) was used.

The created soil/rock contact surfaces and lithological volumes were compared against boreholes to ensure general validity of the ground model. Results indicated that the initial pile founding layer show signs of thickness change especially when closer to the creek, where bridge abutments were to be constructed.

Figure 3 shows a section drawn across the bridge alignment.

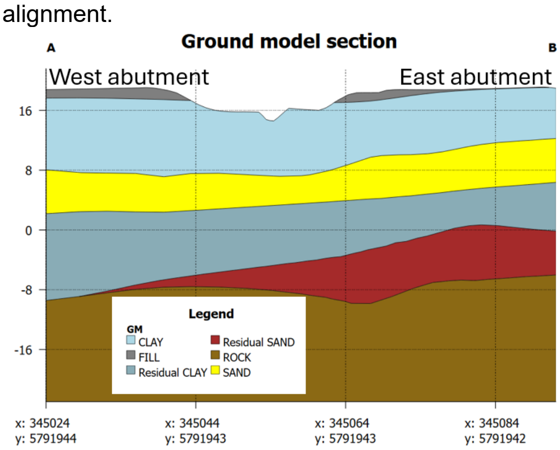

Figure 3. Ground model section across bridge alignment

The yellow layer in Figure 2 depicts the initial pile founding layer in the Red Bluff Sandstone unit. The thickness variation is not very apparent as the interpolation does not consider the interbedded clay layers within the sand unit, which was part of the reason for revising the design.

Figure 4 shows the isolated initial founding layer, with boreholes that illustrate the interbedded clay layers observed.

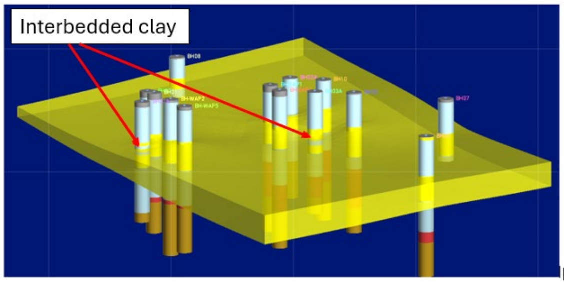

Figure 4. Interbedded clay within initial founding layer

In addition to the thickness variation, the other concern that led to the design change was the variation of the SPT-N numbers. The following section outlines the spatial analyses carried out on SPT-N results.

2.3 Spatial variability of strength

The SPT-N numbers were imported into Leapfrog Works as a numeric value that represents soil strength together with their spatial coordinates. The numbers were then subject to an interpolation based on radial basis function (RBF interpolant). This was done through the numerical model generation functionality within Leapfrog that generates surfaces and 3D volumes of interpolated ranges, which allows for interpretation. Both the spheroidal and linear interpolant functions were assessed, and the linear interpolant function was found to produce a realistic profile of spatial variation of SPT-N. The Leapfrog Works manual (Seequent, 2020) describes the linear interpolant function as a useful general-purpose interpolant for sparsely and/or irregularly sampled data and indicates that it works well for lithology data. Therefore, this method was deemed suitable for the purposes for the present analysis.

Figure 5 shows the 3D interpolated SPT-N range separated into volumes that capture separate SPT-N ranges. Examining the 3D volumes revealed that signs of spatial viability were present in lateral directions across both abutments (across bridge width) and along the bridge alignment. Figures 6 – 8 show images from the model depicting the variability for the above cases, with the bridge structure shown for reference.

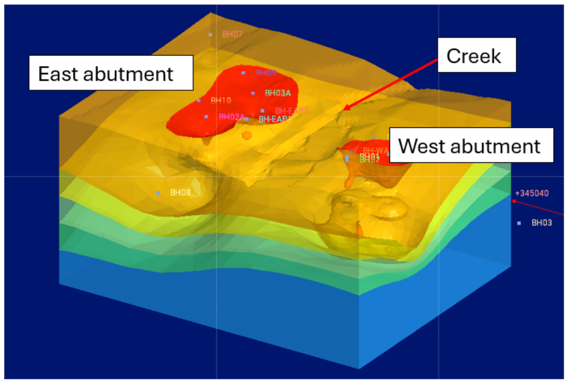

Figure 5. 3D interpolation of SPT-N numbers

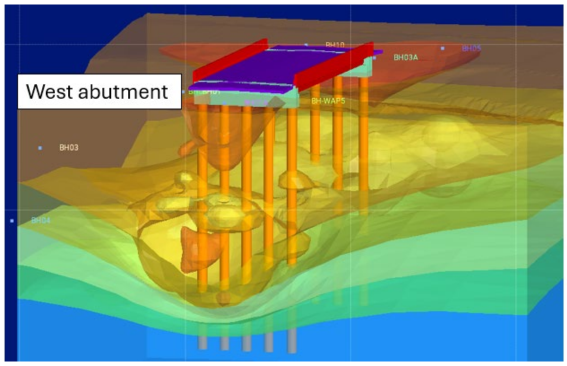

Figure 6. View of the West abutment showing variability in SPT-N across the abutment

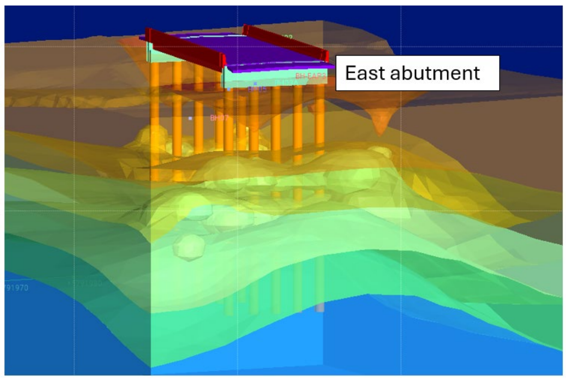

Figure 7. View of the East abutment showing variability in SPT-N across the abutment, but generally of higher strength than the West abutment

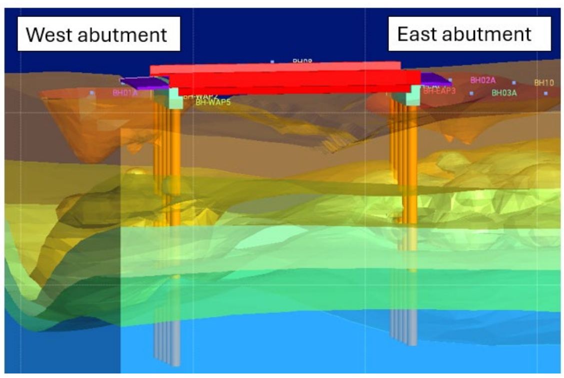

Figure 8. View along the bridge alignment showing variability in SPT-N

The colour scales indicate numerical values of the interpolated SPT-N with red, orange and yellow being weaker than the green and blue regions. It can be seen that while both abutments exhibit variation of strength across abutment, the West abutment region generally has a lower soil strength compared to the East, which was further assessed by examining a 2D long section along the bridge.

Figure 9 shows the 2D long section drawn along the bridge alignment, showing the same SPT-N ranges and their respective colour scales. The numbers along the depth indicate SPT-N numbers recorded within the boreholes. Note that only the boreholes with closest offset to the alignment are shown for clarity.

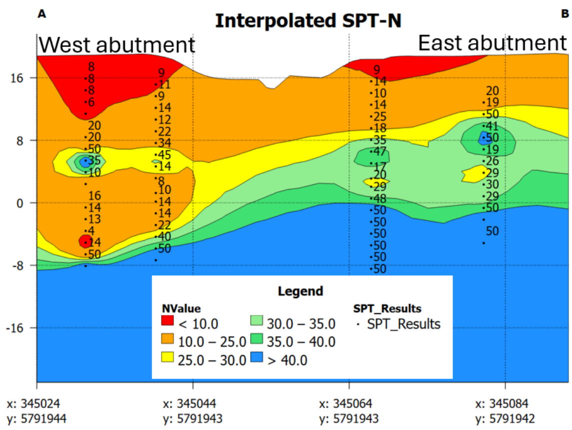

Figure 9. Section drawn across bridge alignment showing variability in strength along the bridge alignment

Figure 9 shows that the interpolated SPT-N numbers within the initial founding layer are lower closer to the creek, where the piles are located. In addition, it confirms that the general strength of the West abutment is lower than that of the East abutment, mirroring initial design advice. This also supports the final design advice with slightly longer piles on the West abutment during final design, as discussed in the following section.

3 DESIGN REVISION

The decision to socket the piles into rock was made upon a review of borehole information as the project progressed. However, once the boreholes at the actual pile locations were reviewed, the design was further optimised to reduce the length of the piles to found on the dense residual (Granodiorite) sand instead. The final pile design considered the founding material to be very dense sand of SPT-N>50. This residual sand was present with some variability across the site and was underlain by highly weathered or better rock. Therefore, to minimise potential differential settlements due to lateral variability, the following founding criteria were proposed:

Table 1. Final design criteria

Pile location	**Reduced level at pile toe (RL m)**	**Total pile length below pile cap (m)**	**Founding material**
East abutment	-8.6	26.1	3D into Very Dense Sand (SPT-N>50) or better
West abutment	-11.6	29.1	
Piles shall be installed to the greater depth of the pile founding material and the estimated pile toe level			

This founding criteria ensures that the piles achieve a minimum depth even if the founding sand layer was encountered earlier.

4 CONSTRUCTION OBSERVATIONS

As the founding material is very dense sand below groundwater level, temporary steel casing was recommended in design advice to avoid potential collapse of the pile bores. Methods considered for construction of piles included continuous flight auger (CFA), and temporarily cased bored piles. Due to constructability considerations, bored piles with casing were selected. The contractors opted for segmental casing, which allowed for gradual advancement of casing segments as boring continued to the target depth.

The final meters of each pile were observed during pile construction onsite. The founding conditions were confirmed by observing the spoil material removed from the bore. Once the pile bore achieved that target depth and was supported with the segmental casing, a cleaning bucket was used to remove debris from the base. As the base of the excavation contained water, a weighted tape was used to confirm the base was suitably clean and to record the final depth of the pile. It was observed that the rock level varied across each abutment, and the pile length in this case was governed by the minimum depth specified in the final design founding criteria. Therefore, all piles terminated in rock reducing the likelihood of differential settlement.

5 CONCLUDING REMARKS

The geological modelling presented within this paper supported the pre-construction design changes that were undertaken when we accounted for the new geotechnical investigation data.

Although this analysis was done post project, the methods used for modelling spatial variability in Leapfrog Works with OpenGround integration are envisioned to be useful for future projects of similar or larger scale.

The findings highlight the importance of carrying out adequate investigations at the correct locations during early stages of the design process.

In addition to complying with local government requirements for scoping out investigations, the value of considering potential spatial variability of likely founding materials within a site in relation to proposed structures to be built is demonstrated and the importance of a suitable investigation frequency throughout the design process to minimise the risk of ground variability, even over short distances is highlighted.

6 ACKNOWLEDGEMENTS

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REFERENCES

Seequent Limited. (2020). “User Manual for Leapfrog Works Version 3.1.” https://help.seequent.com/Works/3.1/en-GB/LeapfrogWorksUserManual.pdf