Atypical Observations of Pore Pressure Dissipation Tests using Silicone Oil

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ABSTRACT: Piezocone preparation includes saturating the piezocone assembly. Without such preparation, the results of the pore pressure trace are unreliable, leading to erroneous assessment of outputs that rely on the excess pore pressure or dissipation test results. In addition, even after a piezocone is properly saturated during assembly, it can be affected by air entrainment while advancing the cone, especially through unsaturated or dilatant material. Traditionally, de-aired water or glycerine was utilised as a saturating fluid. However, more recent practice has expanded to include silicone oil as the saturation fluid. The silicone oil reportedly produces a more responsive excess pore pressure trace, is more robust in its resistance to desaturation effects when compared to other saturating fluids, and in most environments is inert. However, in certain depositional environments, the silicone oil has been found to result in atypical dissipation test results characterised by a delayed onset of rapid pore pressure increase following an otherwise typical dilatory dissipation test curve. The authors have investigated and ruled out causes other than a chemical reaction between the silicone oil and in situ material. The findings indicate a cautionary approach to using silicone oil as a saturating fluid.

KEYWORDS: CPT, CPTu, Piezocone, Medusa DMT, Dissipation Testing, Saturation Fluid, Silicone Oil, Glycerine

1 INTRODUCTION

Geotechnical investigations were carried out across a number of sites located within the Bowen Basin in Queensland, Australia. The purpose of the geotechnical field investigations was to collect information on the characteristics of the soil profile and groundwater conditions. The field investigations included boreholes, test pit excavations, Cone Penetration Tests (CPT) and Medusa Dilatometer Tests (DMT). The CPTs were paused at selected locations and depths to carry out pore pressure dissipation tests.

This paper describes the atypical dissipation test results observed at some locations and depths when using silicone oil as the saturating fluid. The authors have investigated and ruled out causes other than a chemical reaction between the silicone oil and the in situ material. The atypical response did not occur when using glycerine as a control.

2 PIEZOCONE PENETRATION TEST

2.1 *General Description*

In the Cone Penetration Test (CPT), a cone on the end of a series of rods is pushed into the ground at a constant rate and continuous measurements are made of the resistance to penetration of the cone and of a surface sleeve along the side of the cone. A standard electronic cone has either a diameter of 35.7mm or 43.7mm (i.e. 10 or 15 cm^2 cross-sectional area), with an apex angle of 60 degrees (Robertson & Cabal, 2022).

Most CPT systems today also include pore-pressure measurements (CPTu). To have good pore pressure response during a CPTu test, the piezocone must include a pore pressure measuring system that is properly saturated.

2.2 *Saturation Fluids for CPTu Testing*

2.2.1 *Published Standards*

At the time of writing, the Standards provide the following guidance regarding saturation fluid:

- ISO22476-1-2012, Annexure D states when performing penetration tests in unsaturated soils, dry crust and dilative soils (like dense sands), the filter should be saturated with de-aired glycerine or a similar fluid, which makes it easier to maintain saturation throughout the test.
- ASTM D5778-20 states pure glycerine or silicone oil is most often applied for de-airing elements that are used to measure the dynamic response. These stiff viscous oils have less tendency to cavitate, although cavitation may be controlled by the effective pore size of the element mounting surfaces.
- AS 1289.6.5.1-1999 does not provide any guidance associated with the use of saturation fluid.

2.2.1 *Industry Practice*

Lunne at al (1997) indicate the fluids used for saturation are either de-aired water, silicon oil or glycerine. Considering Lunne et al (1997) and the authors' experience, the advantages and disadvantages of each are:

- De-aired water presents problems at low temperatures and it can be difficult to maintain saturation before penetration below the water table or when penetrating very dense sand or over-consolidated clay layers.
- Glycerine may be harsh on equipment and personnel. It's vulnerability to desaturation is less than that of de-aired water, but in the authors' experience it remains somewhat vulnerable and results in a more sluggish pore pressure profile relative to Silicone Oil.
- Silicon Oil is not miscible with water, so some surface tension between the oil and the water may result in small errors in the measured fluid pressure. In addition, the preparation may be harsh on equipment and personnel. However, the authors' experience indicates the use of Silicone Oil is the least likely to suffer desaturation during pushing, and results in a superior pore pressure response.

3 SUMMARY OF FIELD WORK

3.1 *Equipment and Procedures Adopted*

3.1.1 *Cone, Sleeve and Filter Location*

The CPTu scope of work was generally carried out using a compression probe with a $15cm^2$ cross-sectional area and a porewater pressure filter element located behind the shoulder of the cone of the probe in the u_2 location. Sensor data consisted of soil tip resistance (q_c), sleeve friction (f_s), porewater pressure measurement (u_2), inclination and temperature (in some tests).

The cone sensor data was transmitted back to the surface using an electrical signal. The system collected sensor data at 1 cm intervals throughout the sounding depths. The CPTs were pushed into the ground at a constant rate of penetration of 20 ± 5 mm per second.

This equipment was subsequently varied as part of the trouble-shooting process employed to decipher the cause of atypical dissipation tests; this will be discussed in more detail in further sections herein but changes included use of a subtraction cone, use of a fully cabled system, use of a larger cone tip.

3.1.2 *Calibration*

The authors' experience shows that CPTu sensors all drift slightly with use, and therefore the operator provided:

- Fresh calibrations for every cone used at the start of the project
- Re-calibration to the ISO standard at the end of the project.
- Re-calibrations compared to pre-job calibrations to confirm CPT accuracy during the project.

Calibrations included qc, fs, u and NAF (Net Area Factor). In addition, the cone was calibrated while hanging free before and after testing. All calibrations were within tolerance.

3.1.3 *Saturation Fluid*

The cone and filter were initially saturated using silicone oil. This was subsequently varied to glycerine as part of the trouble-shooting process employed to decipher the cause of atypical dissipation tests.

3.1.4 *Dissipation Testing*

The coefficient of consolidation of the soil can be estimated by interpreting the dissipation test results. For a detailed explanation on the interpretation of the coefficient of consolidation from dissipation test results, the reader is recommended to refer to Robertson & Cabal, 2022. In addition, the tests can be used to establish the location of hydrostatic water table.

Dissipation testing was carried out at numerous selected depths and locations. The penetration of the cone was paused and measurement of the decay of excess pore pressure was recorded. For each dissipation test, a data acquisition system measured and recorded the variation of the pore pressure measurement with time.

Typically the tests were minutes to hours, but in addition, selected tests were run overnight. The atypical test results were observed in overnight tests only.

3.2 *General Ground Conditions*

The geotechnical investigations were carried out across a historical tailings dam. The inferred geotechnical ground model is shown in Figure 1. The subsurface conditions can be broadly classified into four material units: Residual Soil, Embankment Fill, Tailings and Uncontrolled Fill. The Embankment Fill is underlain by Residual Soil. Tailings were placed against the Embankment Fill. A significant thickness (>10m in some locations) of Uncontrolled Fill, inferred to be excavated mine overburden, was placed above the Tailings.

3.3 *Test Locations*

The CPTs were carried out at 19 locations across a total site area of approximately 250,000 m^2. A total of 61 dissipation tests were undertaken at these 19 locations at various depths. This paper focuses on the testing undertaken at three particular locations, shown on Figure 1, where atypical responses in the dissipation testing were observed.

4 RESULTS

4.1 *Full Traces using Silicone versus Glycerine*

4.1.1 *Comparison Traces*

CPT traces for the three locations are shown in Figures 2 to 4 (graphs produced using CPeT-IT developed by GeoLogismiki). The CPT traces include total cone resistance, friction ratio, pore pressure and soil behaviour type (SBT) index are shown on the plots. Depths at which the atypical dissipation test results were observed are also shown on these figures. At Location 1 and 2, the CPTs were initially undertaken using silicone oil, and subsequently glycerine at a duplicate location 1m offset from the initial test. At Location 3, the CPT was only undertaken using silicone oil.

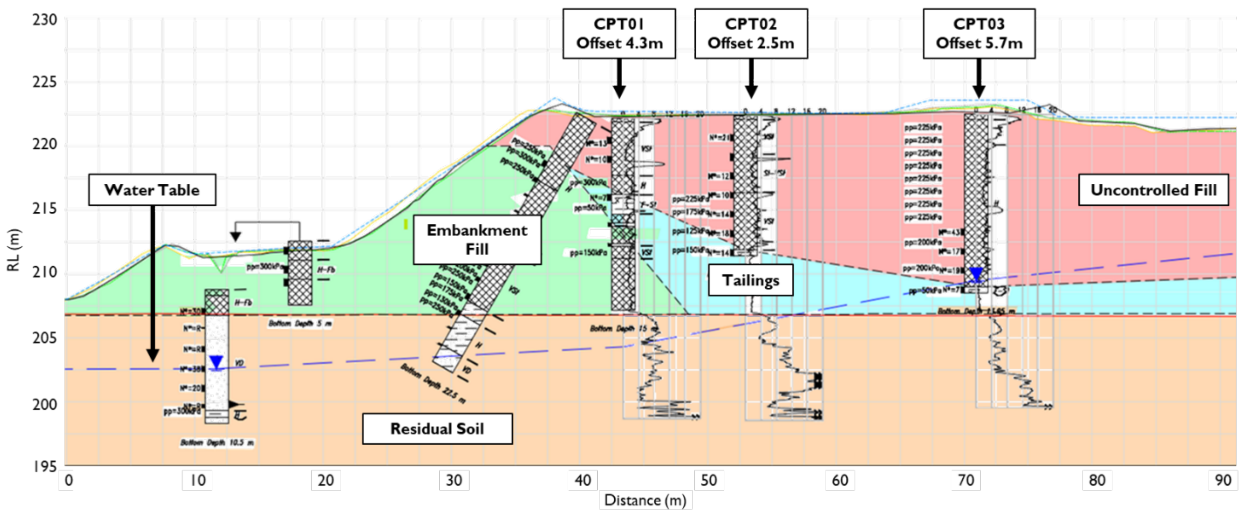

Figure 1. General Ground Conditions

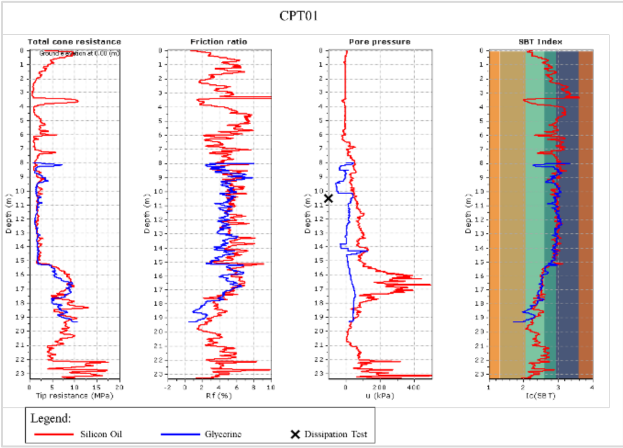

Figure 2. Location 1 – CPT Traces

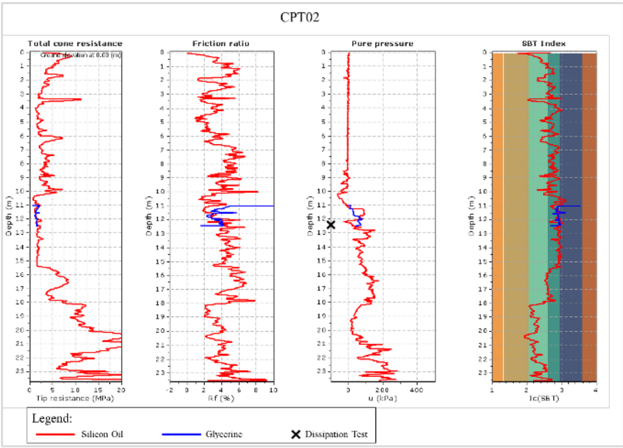

Figure 3. Location 2 – CPT Traces

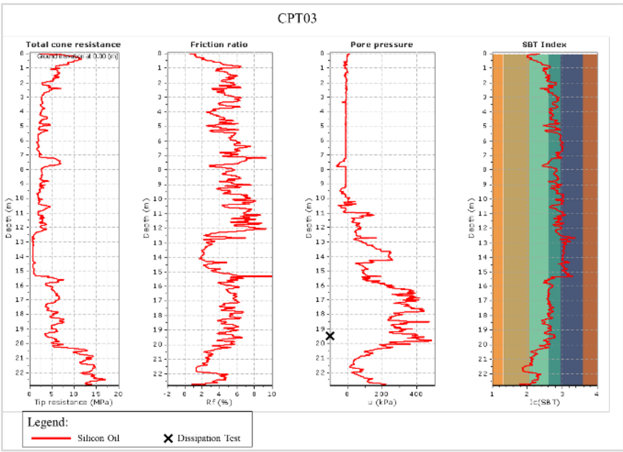

Figure 4. Location 3 – CPT Traces

4.1.2 *Discussion of Comparison Traces*

From the results shown in Figure 2 and Figure 3, the use of glycerine or silicon oil as the saturation fluid results in:

- Insignificant differences in the cone resistance and friction ratio readings.
- Significant variation in pore pressure responses, which can be clearly observed in Figure 2.

For the Location 1 test undertaken using glycerine, it appears that the pore pressure was negative between the depth of 8m to 10m. This has likely resulted in partial de-saturation, a condition in which it appears to remain for the remainder of the test. In addition, the pore pressure response appears sluggish for the remainder of the test. Conversely, the test undertaken using silicone oil did not experience negative pore pressures and appeared to be more responsive.

These observations are generally in line with the commentary by Lunne at al (1997) and the authors' experience, where the use of glycerine as the saturation fluid resulted in a more vulnerability to de-saturation, and a more "sluggish" pore pressure response relative to silicone oil.

4.2 *Dissipation Test Results*

4.2.1 *Typical Dissipation Test Results*

In a typical dissipation test, the pore pressure is expected to decay with time towards the equilibrium pressure. This may occur in monotonic or dilatory curves depending on the state of the soil.

Typical dissipation test behaviour observed on this site, expressed in both log time and root time plots, are shown in Figures 5a and Figure 5b, respectively.

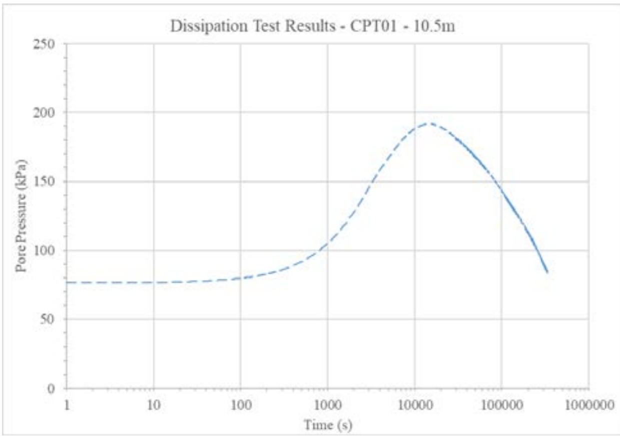

Figure 5a. Typical Dissipation Test Results in Log Time.

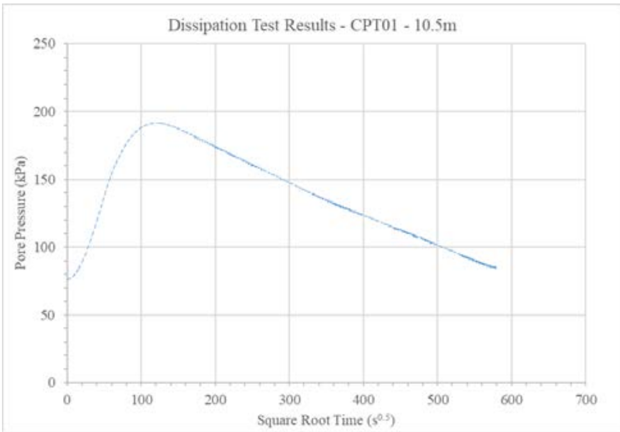

Figure 5b. Typical Dissipation Test Results in Root Time.

4.2.2 *Atypical Dissipation Test Results*

The dissipation test results using silicone oil as the saturation fluid expressed in both log time and root time plots at three different locations are shown in Figure 6a/b, Figure 7a/b and Figure 8a/b.

Compared to the typical dissipation test behaviour shown in Figure 5a/b, a stark contrast can be observed. In the results shown in Figure 6a/b, Figure 7a/b and Figure 8a/b, it can be seen that the pore pressure initially decays with time towards the equilibrium pressure. After some time, however, the pore pressure rapidly increases. This fluctuation in pore pressure is atypical of the behaviour expected in a dissipation test.

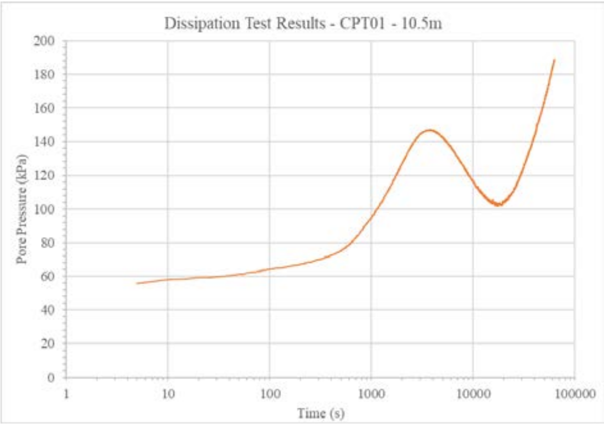

Figure 6a. Location 1 - Dissipation in Log Time, using Silicone Oil.

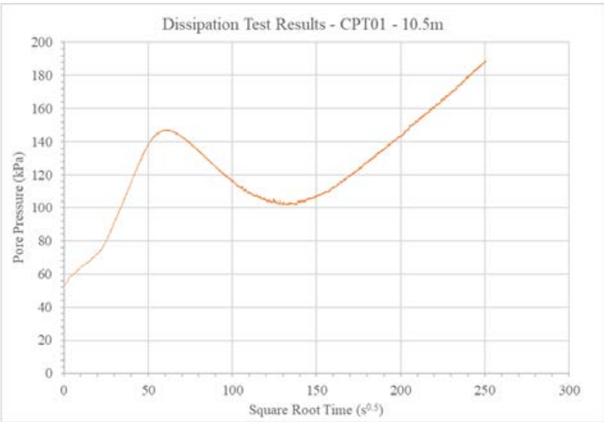

Figure 6b. Location 1 - Dissipation in Root Time, using Silicone Oil.

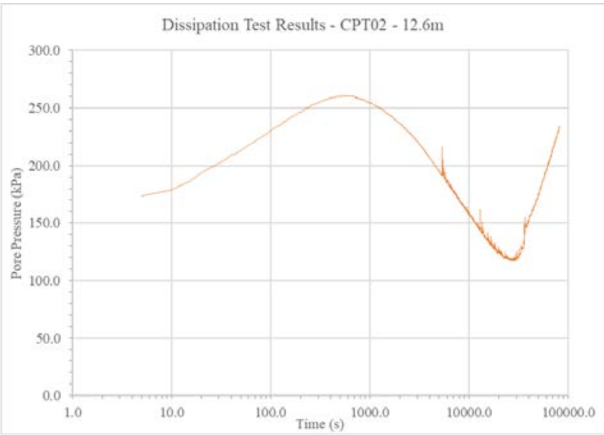

Figure 7a. Location 2 - Dissipation in Root Time, using Silicone Oil.

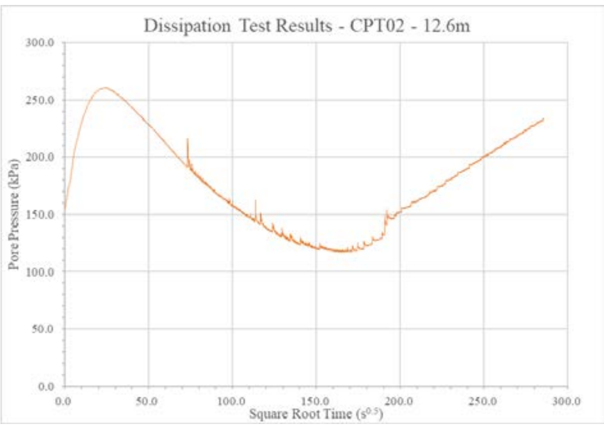

Figure 7b. Location 2 - Dissipation in Root Time, using Silicone Oil.

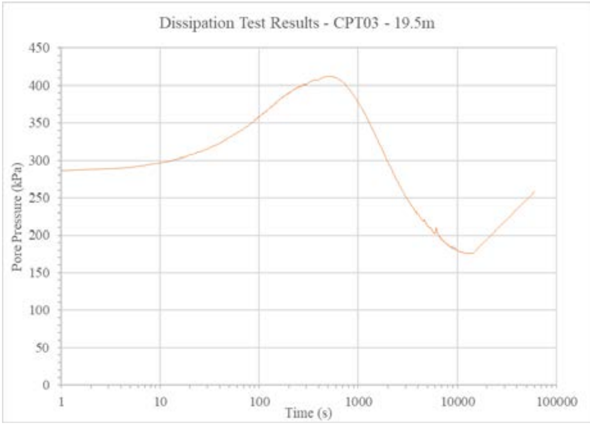

Figure 8a. Location 3 - Dissipation in Log Time, using Silicone Oil.

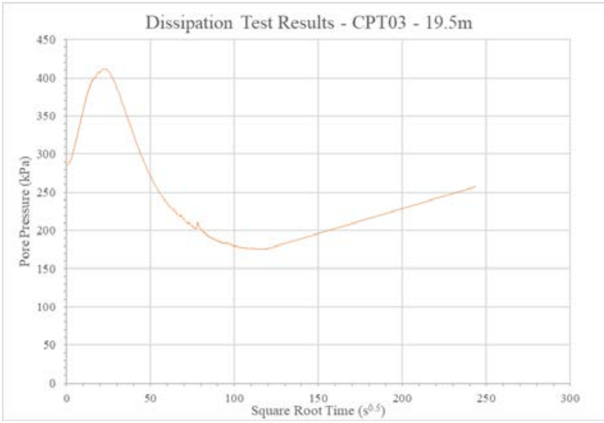

Figure 8b. Location 3 - Dissipation in Root Time, using Silicone Oil.

From the results collected, it was observed that the increase in pore water pressure was observed at around 20,000 seconds (5.5 hours) after the start of the dissipation test.

4.2.3 *Troubleshooting Considerations*

When this atypical behavior was observed, several possibilities for the underlying cause were investigated and ruled out.

- Movement of the cone penetration rig during the test period – Dissipation tests were repeated with the CPT pushing rig moved away from the hole during the testing. Results did not change. In addition, the cone tip data, did not fluctuate significantly during the test.
- Calibration errors in the cone – Dissipation tests were repeated at the same location using different cones. Results did not change.
- Faulty equipment – Dissipation tests were repeated using different set of cones, cables and data acquisition devices. Results did not change.
- External vibrations – Records confirmed no blasting was undertaken on the days of dissipation testing.
- Operator error – Dissipation tests were repeated using a second independent CPT operator. The second CPT operator used a different rig, cones and data acquisition device. The same atypical behaviour was observed.
- Chemical reaction with stainless steel cone shell or internal parts – Visual inspection of the cone indicated no evidence of corrosion or discolouration on any of the cone components.
- Chemical reaction of saturation fluid with the surrounding soil – All initial dissipation tests were undertaken using silicone oil as the saturation fluid. As part of the troubleshooting process, the saturation fluid was substituted with Glycerine. Upon substitution with Glycerine, the atypical behaviour was no longer

observed. A detailed comparison of the results using silicone oil and glycerin as the saturation fluid will be discussed in Section 4.2.4.

4.2.4 *Results with Glycerine*

A comparison of the dissipation test results from the two CPT operators, using glycerin and silicone oil as the saturation fluid, at Location 1 and Location 2 are shown in Figure 9 and Figure 10 respectively.

When silicone oil was used as the saturation fluid, atypical behaviour in the test results was observed. When glycerin was used as the saturation fluid, typical behaviour was observed. This was consistent at both locations with both CPT operators.

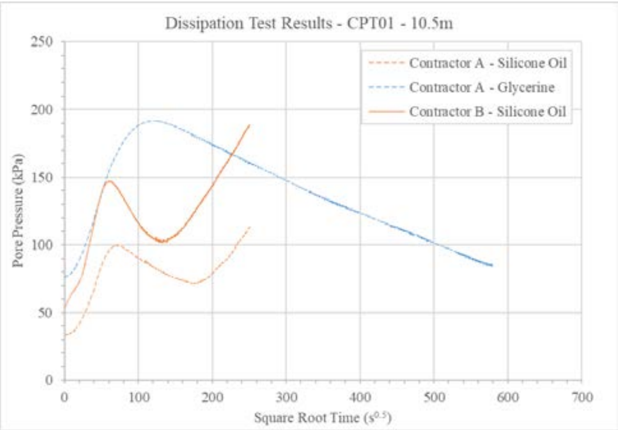

Figure 9. Dissipation Test Results at Location 1 (in Root Time).

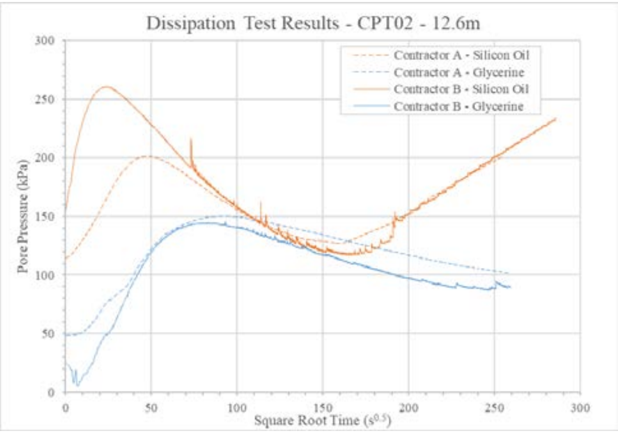

Figure 10. Dissipation Test Results at Location 2 (in Root Time).

4.3 *Changes in Temperature*

Out of the 61 dissipation tests, 39 tests also contain temperature measurements. Changes in temperature were observed at Location 1, 2 and 3 where atypical dissipation tests results were observed. At Location 1, the recorded temperature increased by approximately 3 degrees over the duration of the dissipation test. At Location 2 and 3, the recorded temperature increased by approximately 2 degrees over the duration of the dissipation test.

The observed change in temperature is most readily explained as a result of a chemical reaction. None the less, the authors do not believe there is sufficient evidence to draw definitive conclusions from the available data.

5 DISCUSSION

5.1 *Hypothesis of Chemical Reaction*

Based on the results collected, the authors are of the opinion that the atypical behaviour observed in the dissipation testing is due to the use of silicone oil as the saturation fluid. The authors believe that silicone oil, whilst usually relatively inert, underwent a chemical reaction with the soil surrounding the tip of the cone, resulting in volume change within the cone and thereby introducing extra pressure on the pore pressure transducer. This is supported by:

- Increased temperature at the tip occurring at the time of the increased pore pressures.
- Delayed onset of the increase in pore pressure as may be expected of a chemical reaction.
- Inability to replicate the atypical test results using glycerin.
- Process of elimination, whereby other viable hypotheses have been tested and not supported.

Previous studies have shown that silicones can be degraded by the catalytic effect of certain clay minerals (Moretto, H.H. et al. 2005). Soil moisture content was identified as the most important factor influencing silicone oil degradation rates (Xu, S et al. 1998). When added to air-dried soil or clay minerals, silicone oil undergoes extensive hydrolytic degradation. This degradation process is moisture sensitive and in moist soil proceeds at a slow rate. As the soil gradually dries from moist to air-dry, the siloxane polymers rapidly hydrolyze to oligomeric silanols and eventually to a water-soluble monomer known as dimethylsilanediol.

Clay minerals also varied substantially in their catalytic activity. Kaolinite, beidellite and nontronite were the most active and resulted in the fastest degradation of silicone oil. Geothite and allophane were the least active. We have elected not to undertake a comparison of the degradation rates measured by Xu, S et al. (1998) with our site observations, as their methodology involved spiking the clay with silicone oil in the laboratory, and as such is not directly comparable with the fieldwork undertaken.

Xu, S et al. (1998) stated that although much progress has been made in understanding the degradation of silicone oil, the rates of silicone oil degradation in various soils cannot yet be predicted. This is partly due to insufficient knowledge of the catalytic mechanisms of soil.

5.2 Potential Alternative Approaches

5.2.1 *Selective application of Silicone Oil*

As silicon oil has a reaction with clays, the geotechnical practitioner should consider the viability of using silicone oil as a saturation fluid, especially for long overnight dissipation testing (where there is sufficient time for the silicone oil – clay reaction to progress as described above).

5.2.2 *DMT Dissipation Testing*

Dissipation testing using the flat dilatometer test (DMT) may be considered. The DMT system is typically advanced into the ground using a CPT rig. The flat dilatometer is a stainless steel blade with a flat, circular steel membrane mounted flush on one side. A gas tank supplies the gas pressure required to expand the membrane. Compressed nitrogen or compressed air are typically used as the gas pressure source.

A DMT dissipation test consists of stopping the blade at a nominated depth, then monitoring the decay of the total contact horizontal stress with time. Flow parameters such as the coefficient of consolidation are then inferred from the rate of decay. For a detailed explanation on the DMT and interpretation of the coefficient of consolidation from DMT dissipation test results, the reader is recommended to refer to Marchetti, S et al. 2001.

8 FURTHER WORK

Unfortunately, this case study did not include collection of samples at the test locations. Collection of such samples and testing in the laboratory for clay minerology and onset time to commencement of chemical reaction would assist geotechnical engineers in understanding when the use of silicone oil should be restricted.

Future revisions to Standards, such as ISO, should include consideration of this phenomenon and consider adding commentary surrounding this topic as a factor in selection of saturation fluid.

9 CONCLUSIONS

Geotechnical investigations were carried out within the Bowen Basin in Queensland, Australia. The field investigations included CPTu testing, and dissipation testing. The testing equipment, methods and preparations were all in accordance with published Standards and industry practice.

Despite using Standard prescribed methodology and industry best practice, atypical dissipation test results were observed when silicone oil was used as the saturation fluid. This unusual behaviour was not observed when glycerin was used as the saturation fluid for the dissipation tests.

The evidence suggests the atypical behaviour observed in the dissipation testing is due to a chemical reaction between the silicone oil and soil surrounding the cone tip. This is supported by literature from outside the field of geotechnical engineering, where environmental papers document the reaction between silicone oil and clay minerals.

The intention of this paper is to raise awareness within the geotechnical industry of potential atypical observations in pore pressure dissipation testing when silicon oil is used as the saturation fluid and to offer alternate solutions and recommendations for future work to better understand and document this phenomenon.

9 REFERENCES

American Society for Testing and Material. 2020. D5778-20. Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils. *ASTM International.*

Australian Standard. 1999. AS 1289.6.5.1-1999. Methods of testing soils for engineering purposes, Method 6.5.1: Soil strength and consolidation tests - Determination of the static cone penetration resistance of a soil - Field test using a mechanical and electrical cone or friction-cone penetrometer. *Standards Australia.*

GeoLogismiki. CPeT-IT v.3.0 – CPT interpretation software.

International Organisation for Standardisation. 2012. ISO 22476-1. Geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone penetration test. *International Standard.*

Lunne, T et al. 1997. Cone Penetration Testing in Geotechnical Practice. *Soil Mechanics and Foundation Engineering.*

Marchetti, S et al. 2001. The Flat Dilatometer Test (DMT) in soil investigations. *A Report by the ISSMGE Committee TC16.*

Moretto, H.H. et al. 2005. Silicones. *Ullmann's Encyclopedia of Industrial Chemistry.*

Robertson, P.K. and Cabal, K. 2022. *Guide to Cone Penetration Testing*. Signal Hill: Greg Drilling LLC.

Xu, S et al. 1998. Degradation of Polydimethylsiloxanes (Silicones) as Influenced by Clay Minerals. *Environ. Sci. Technol.*