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The importance of accurate pore water pressure measurements when conducting CPTu as exemplified using data collected in Christchurch following the Canterbury earthquake sequence

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ABSTRACT

Piezocone penetration testing (CPTu) is a widely used investigation method for geotechnical analysis and liquefaction assessments. In addition to recording tip resistance (q_c) and sleeve friction (f_s), pore water pressure (u) is measured by a pressure transducer via a porous filter commonly located behind the cone tip. In this paper, data collected in Christchurch following the 2010-2011 Canterbury earthquake sequence is used to exemplify the variable quality of CPTu data, focusing on pore pressure response. It has been found that if the probe is not properly maintained or prepared prior to testing, it can have undesirable effects on the measured CPTu data. A skilled operator could improve the quality of the CPTu sounding by monitoring the data and pausing the test to verify the pore pressure response. With accurately measured pore pressure response, dissipation tests can be conducted during CPTu. Dissipation tests can provide important geotechnical parameters such as ground water level and soil permeability. Accurate pore water pressure data can improve liquefaction analysis results by providing a representative groundwater level and providing a mean for a more accurate estimation of liquefiable layer thickness. Inaccurate pore pressure response during CPTu sounding can lead to incorrect interpretation of the data when describing soil behavior, especially for fine grained soils such as those found in Christchurch. Quality control is important when conducting CPTu to assure accurate pore pressure response recordings and effective dissipation testing.

1 INTRODUCTION

The Piezocone penetration test (CPTu) has become a popular in-situ test for site investigations, liquefaction analysis and foundation design in Christchurch, following the 2010-2011 Canterbury earthquake sequence. In addition to recording tip resistance (q_c) and sleeve friction (f_s), pore water pressure (u) is measured by a pressure transducer via a porous filter commonly located behind the cone tip. CPTu data can provide important geotechnical parameters. This paper discusses factors which hinder the quality of pore pressure data, and suggests ways to remediate them. The aim of this paper is to demonstrate the importance of pore water pressure data in distinguishing between soil behaviour types, for liquefaction analysis, and the effect of poorly collected porewater pressure data on geotechnical analysis.

Following the 2010-2011 Canterbury Earthquake Sequence, the Ministry of Business, Innovation and Employment (MBIE) released guidelines titled “Guidance: Repairing and rebuilding houses affected by the Canterbury earthquakes”. These guidelines are used by geotechnical engineers to investigate ground conditions for rebuilding and repairing all sites zoned residential in the greater Christchurch area. The guidelines promote CPTu as the preferred ground investigation method, where conditions permit. This has resulted in thousands of CPTu in the greater Christchurch area since 2010.

The advantage of using CPTu is that the high resolution of the data can detect layers in the scale of tens of centimetres. This is particularly useful in Christchurch, which is known to be underlain by a series of inter-bedded coarse and fine grained sedimentary deposits (Forsyth et al 2008). Geotechnical parameters, such as soil behaviour type (SBT) and liquefaction potential index (LPI), change both horizontally and vertically showing a significant variability at the scale of metres. CPTu may be applied to a variety of soil types but for sites with increased gravel content or gravel layers, the probe may not be able to penetrate with the potential to damage the cone. It is common practice in Christchurch to conduct piezocone tests up to a specific target depth or until probe refusal, which is generally at the underlying gravel layers or dense to very dense sands. CPTu may be performed in soft soils following drill-out through a gravel layer, but more commonly, borehole drilling with standard penetration tests is used for estimating the strength and the density beneath impenetrable gravel layers.

2 FACTORS AFFECTING THE COLLECTION OF PORE WATER PRESSURE DATA

In Christchurch, several tests have been performed and although tip resistance and sleeve friction results are consistent and more or less comparable, pore water pressure is often not. This disparity may be attributed to a number of factors, some of which are described in the following sections.

2.1 Insufficient or Improper Maintenance of Equipment

There are many companies that manufacture CPTu equipment, each with their own specifications. It is important for the CPTu operator to understand the limits of their equipment, so that they can obtain high quality data. Regular maintenance is important for data accuracy, and includes properly cleaning the probe after each use, inspection for wear and lubrication of the seals. The probe’s electronic parts can be damaged from exposure to water if worn seals are not replaced, which could result in a seemingly functioning probe collecting inaccurate data.

A transducer in the probe measures the pore water pressure through a porous filter. If the porous filter is damaged, it can change the pore water pressure response and reduce data quality. Due to the varying amounts of fine and granular soils in Christchurch, it is common practice to use the robust sintered metal porous filters, rather than the more fragile plastic or ceramic filters. The sintered metal porous filters can be reused but must be inspected regularly for damage by the CPTu operator (see Figure 1). Over time, the metal may “smear” and become less porous as it is pushed through abrasive soils. It may also become more porous if dented by gravel. After each sounding, the porous filters must be inspected for damage by the operator, deemed reusable or not, and if reusable, must be cleaned in an ultrasonic device, saturated and stored in an appropriate saturation fluid such as glycerine.

Figure 1: Wear on porous filters. From left to right: a new porous filter, a worn filter which may be reusable at the discretion of the operator and an unusable worn filter.

2.2 Improperly Saturated Pore Water Pressure System

The pore water pressure system on the CPTu probe must be properly saturated prior to testing. Entrapped air in the system can slow the pore water pressure response. An effective way to saturate the system is to prepare the probe in a cup of warm glycerine. The porous stone should be stored in cold glycerine and then transferred to the cup with the probe, along with the conical tip. The operator should inspect the components to make sure they are free of air bubbles. Once all components are submerged in glycerine, the probe can be screwed together. Between each sounding, the probe must be cleaned and prepared again using a fresh saturated porous filter.

2.3 Cavitation

Cavitation occurs when the pore pressure system is exposed to air, or when it is subjected to extreme negative pore water pressure values during testing. It can be due to an improperly saturated pore water pressure system, or when pushed through a dilatant soil without stopping in order to allow the negative pore pressure to recover to hydrostatic equilibrium. When cavitation occurs, air bubbles are formed in the fluid, which produces a slower pore water pressure response. This can occur in dilatant soils, such as dense granular sands or fine grained clay-like cohesive soils. It is possible to avoid cavitation by momentarily pausing penetration and allowing the system to recover from the extreme negative pore water pressure.

2.4 Lack of Dissipation Tests

During testing, it is recommended to stop pushing at least once to allow the pore water pressure to recover to the hydrostatic equilibrium pressure at the stopped depth by performing dissipation tests. During testing in soils that are relatively undrained, pore water pressure fluctuates from the hydrostatic equilibrium pressure, and it may be difficult to identify the true hydrostatic gradient without any dissipation tests. The rate at which excess pore water pressure dissipates can provide useful geotechnical parameters, such as soil permeability (k) and coefficient of horizontal consolidation (c_h). Noting the depth at which a test was conducted together with the final equilibrium pore water pressure allows for the calculation of an accurate groundwater level (see Section 4.1 for discussion on the importance of groundwater level in liquefaction analysis).

2.5 Operator Skills

It has been found that skilled operators with some knowledge of soil mechanics can help avoid the issues mentioned above. An operator with a better understanding of the recordings during testing could identify malfunctions in the equipment, erroneous data, depths where a dissipation test should performed, or where a simple pause of thrust should be done to allow pore water pressure to recover back to equilibrium. A skilled operator will properly maintain and setup the CPTu equipment in order to provide accurate and repeatable data. To avoid misinterpretation of CPTu results at a later stage, it is important to mitigate these issues during testing.

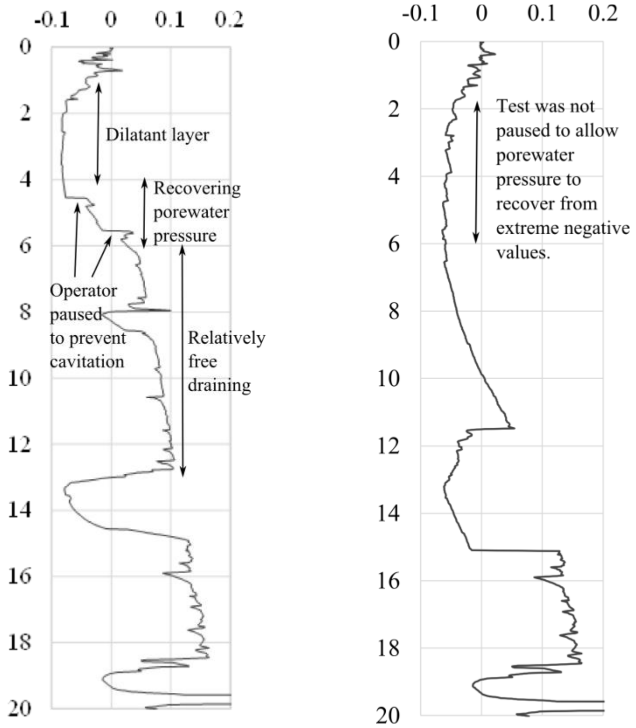
3 EFFECTS OF INACCURATE PORE WATER PRESSSURE MEASUREMENT

Several CPTu results in similar soil formations, conducted after the 2010-2011 Canterbury earthquake sequence, were used and compared in order to demonstrate how the factors discussed in Section 2 affect the recorded pore water pressure. In each pair of results, the tests have been conducted by different contractors and within a distance of 50 m from each other. Cone resistance and sleeve friction traces were comparable in each pair of tests, suggesting that the soil conditions were similar. It would be expected that the pore water response should also be similar, however significant variation was observed. It is proposed that these differences are due to improperly saturated pore water pressure systems with a resulted cavitation effect, a slower pore water response and the lack of pauses during sounding.

3.1 The Effects of Cavitation

Once cavitation has occurred, subsequently collected pore water pressure data is compromised and is likely to have unrealistically high negative values.
Figure 2 illustrates pore water pressure data from two different test locations in Woolston, Christchurch, separated by 25 m. For the trace on the left, the pore water pressure response was

instantaneous, facilitating an accurate interpretation of the soil behaviour. A dilatant layer was encountered from approximately 1 m to 4 m below ground level (bgl). Between 4 m and 6 m bgl, the pressure started recovering to the hydrostatic pressure, and the test was paused at least twice to prevent cavitation and to allow for pore water pressure to recover. Between 6 m and 13 m bgl, there was relatively free draining soil where the pore water pressure remained mostly around the hydrostatic equilibrium. The record on the right represents a poorly collected data and does not provide an accurate representation of the pore water pressure response. The test was not paused to allow for pore water pressure recovery from the extreme negative values encountered in the dilatant layer near surface. In the relatively free draining layer between 6 and 13 m bgl, the trace on the right shows a slow recovery of the pore water pressure, but never actually reaching the hydrostatic line, which is an indication that cavitation has occurred.



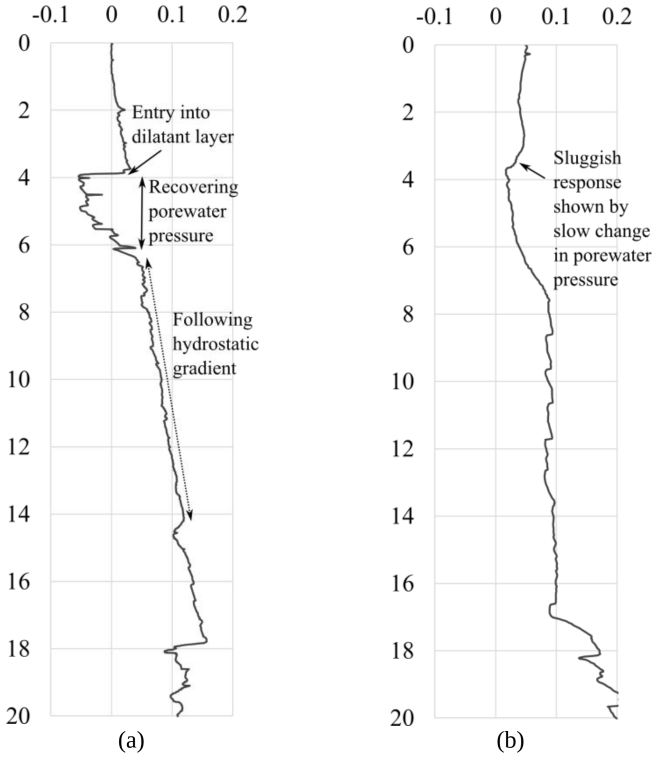
(a) (b)

Figure 2: Pore water pressure (MPa) traces for two sites shown to 20 m bgl depth. (a) an accurate trace of pore water pressure response and (b) a trace of record with cavitation effects.

3.2 Sluggish Pore Water Pressure Response

When the pore water pressure response is slow to change, it is referred to as a sluggish pore water pressure response. This is usually due to an improperly saturated pore water pressure system that contains some air. The effect on the test may not be as significant as with cavitation, but the quality of the data is still compromised.

Figure 3 illustrates pore water pressure data from two piezocone cone penetration tests, separated by 1 m in New Brighton, Christchurch. The results shown on the left illustrate a properly saturated system. At 4 m bgl a dilatant band is encountered where an instantaneous drop in pore water pressure is visible. As expected, once the probe penetrated the layer and encountered relatively free draining soil, pore water pressure recovers until and following the hydrostatic gradient from approximately 6 to 14 m bgl. In the trace on the right, the same dilatant soil layer is encountered at approximately 4 m bgl. The transition into and out of that layer is sluggish, suggesting that the probe has not been properly prepared prior to testing.



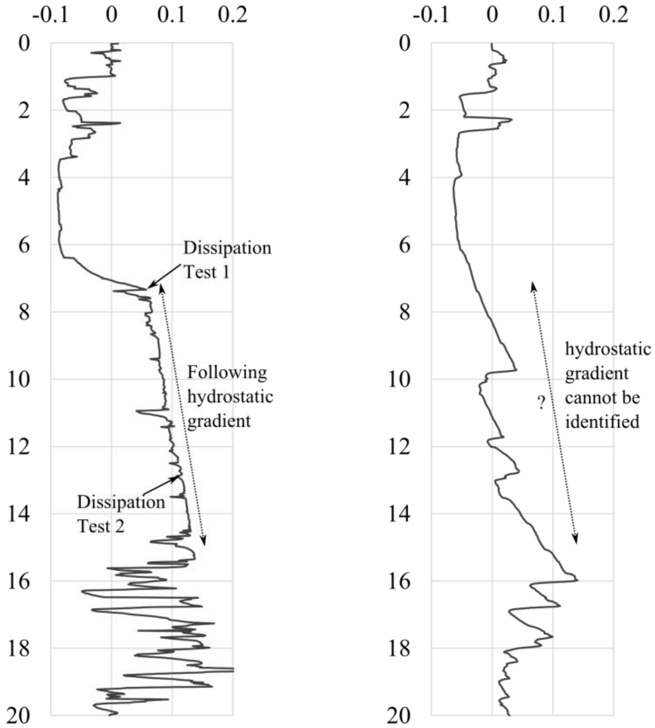
(a) (b)

Figure 3: Pore water pressure (MPa) traces for two sites shown to 20 m bgl depth. (a) an accurate trace of pore water pressure response, and (b) an example of sluggish pore water pressure response.

3.3 Lack of Hydrostatic Equilibrium Reference Point

In a relatively free draining soil, pore water pressure trace will follow the hydrostatic line. Upon entry in a relatively undrained soil, the pore water pressure may fluctuate from the hydrostatic gradient (see Section 2.4). A penetration rate of 20 mm/s is usually appropriate to allow for the pore water pressure to equilibrate to hydrostatic equilibrium upon entry into a free draining soil.

Figure 4 shows pore water pressure data from two CPTu separated by 50 m in Edgeware, Christchurch. The trace on the left is the result of a properly saturated system, with dissipation testing conducted at 7 m bgl and 13 m bgl. The hydrostatic gradient can be identified on the trace from approximately 8 to 15 m bgl. The dissipation tests conducted provide the hydrostatic pressure at the tested depths, which confirms the location of the hydrostatic gradient. An accurate groundwater level and / or soil permeability can be interpreted from this data. The trace on the right does not appear to follow the hydrostatic gradient and the data was presented without any evidence of dissipation tests having been conducted.



(a) (b)

Figure 4: Pore water pressure (MPa) records for two sites shown to 20 m bgl depth. (a) an accurate trace of pore water pressure response, with a reference to the hydrostatic line, and (b) data without a dissipation test and the equilibrium gradient cannot be identified.

4 CONSEQUENCES OF INACCURATE PORE WATER PRESSURE MEASUREMENTS ON GEOTECHNICAL ANALYSIS

The following sections describe why accurate measurements and results of pore water pressure are important for geotechnical evaluation and analysis.

4.1 Pore Water Pressure Data in Liquefaction Analysis

A representative groundwater level is required for liquefaction analysis. This can be determined by using good quality pore water pressure data, by providing the hydrostatic equilibrium pressure at certain depths, as discussed previously in Section 3.3. The groundwater level determined from the piezocone tests can be used together with the seasonal fluctuation data in order to select a representative groundwater level for liquefaction analysis purposes.

Quality pore water pressure data can be used to identify layers with different soil behaviours. Figure 6 illustrates the CPTu data from a site in Edgeware, Christchurch. The transition zones when the probe enters different soil layers (e.g. 10 m and 12 m bgl) are gradual in the cone resistance and friction sleeve data. This is an expected response from the probe, as the conical tip “feels” the change in resistance in advance before actually penetrating it, while the 10 cm friction sleeve is too long to pick up intricacies in the soil column. The pore water pressure response, however, is instantaneous when entering different soil types provided the probe is maintained, properly prepared and the sounding is correctly supervised. These sharp changes in the pore water pressure response may help in identifying contacts between soil types and thin soil layers. This could be a useful analysis tool when evaluating and estimating the liquefaction potential, in order to better understand when a transition zone correction is required. Volumetric strain rates calculated during liquefaction analysis may be applied over the actual thickness of the liquefiable layer, and can be better estimated using the pore water pressure response, rather than the gradual transitions in the cone resistance and sleeve friction values.

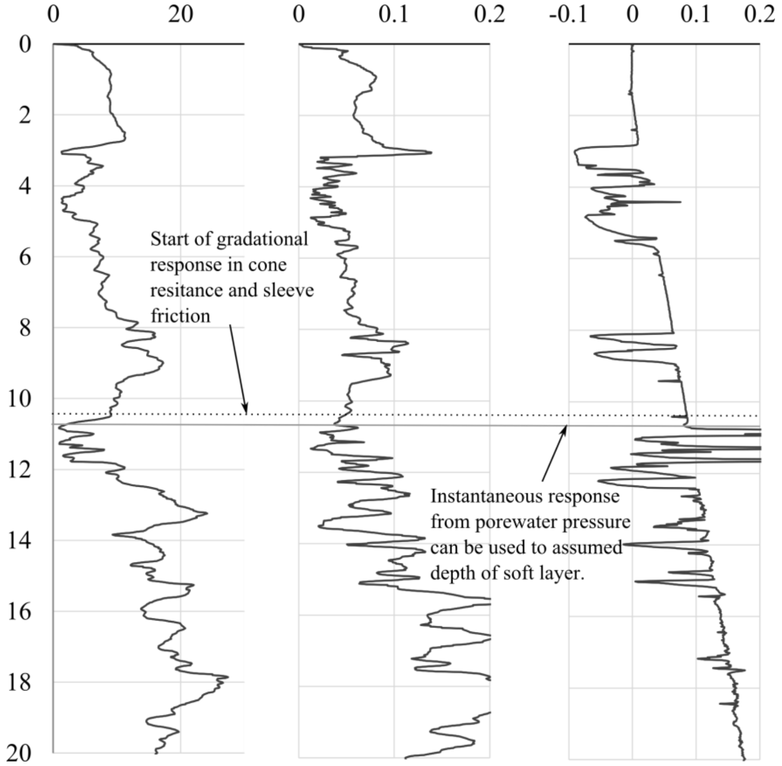


Figure 5: From left to right: cone resistance (MPa), sleeve friction (MPa), pore water pressure (MPa) traces for a site shown to 20 m bgl depth.

4.2 Pore Water Pressure Data and Soil Behaviour Type

Accurate identification of soil behaviour is important for liquefaction analysis and foundation design in geotechnical evaluation process. When a piezocone penetration test is conducted in Christchurch, it is not a common practise to extract soil samples for laboratory testing, and estimation of the soil type. Therefore, piezocone data is essential and used to provide insight into the soil behaviour type. Using the proposed soil behaviour type chart as defined by Robertson (1990, Figure 6), most of the soils encountered in Christchurch fall into categories 4 and 5 of silt and sand mixtures. The soils that fall in these categories can exhibit either dilative or contractive behaviour, and drained or undrained behaviour (Robertson 2012).

A study by Bol (2013) shows that pore water pressure data can be used to differentiate soil behaviour in fine grained soils. The new parameter proposed by Bol, which uses the rate of change in pore water pressure to adjust the Robertson & Wride (1998) soil behaviour type model, could be applied in Christchurch to differentiate the soils plotted in zones 4 and 5 above, using credible pore water pressure data. A parameter such as the one described by Bol could aid in the accurate identification of soil behaviour when differentiating soil behaviour using only tip resistance and sleeve friction is problematic.

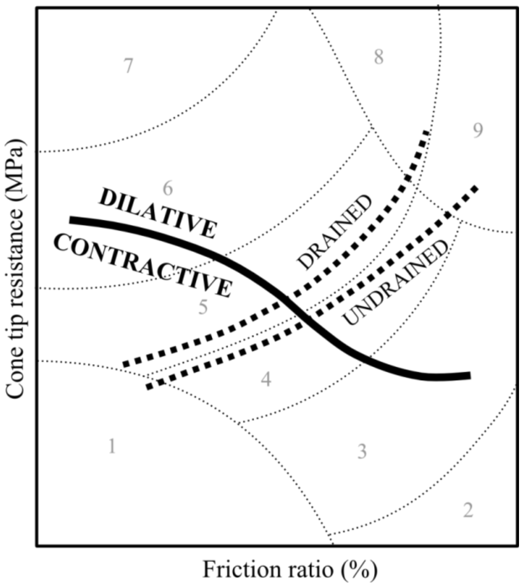


Figure 6 Approximate boundaries between dilative-contractive behaviour and drained undrained CPTu response (after Robertson 2012). The majority of soils in Christchurch plot in zones 4 and 5.

5 CONCLUSIONS

With qualified and well trained CPT operators, it is possible to achieve repeatable high quality pore pressure data by doing the following:

- Properly maintaining equipment
- Properly saturating the pore water pressure system before each test
- Conducting dissipation tests
- Preventing cavitation of the pore water pressure system

Erroneous or unusual data must be identified in the field, before or during testing, and mitigated appropriately. Inaccurate data cannot always be identified by the geotechnical engineer and an initial interpretation during testing is essential to assure that the data provided is of high quality. Accurate pore water pressure data can improve liquefaction analysis by providing a representative groundwater level during testing and determining more accurate the liquefaction potential. Inaccurate pore pressure response during piezocone testing (CPTu) can lead to incorrect interpretation of the data when describing soil behavior, especially for fine grained soils such as those found in Christchurch.

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