Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Back analysed interpretation of yield pressure from CPT using B_q

Richard Kelly[†]

[†] *SMEC Australia,*
Priority Research Centre for Geotechnical Science and Engineering, The University of Newcastle Australia
Level 6, 480 St Pauls Terrace, Fortitude Valley, Brisbane, Australia
DrRichard.kelly@smec.com

ABSTRACT

A sand and gravel quarry has been backfilled with clays and silts washed from the quarried materials. The quarry is now being repurposed for an industrial development. Prefabricated vertical drains and surcharge have been installed to consolidate the soft sediments. Settlement plates and vibrating wire piezometers were installed to track the performance of the surcharge. CPTs have been performed adjacent to the settlement plate / VWP installations in order to confirm thickness of soft soils and to assess their yield pressure in order to facilitate back analyses. A Medusa dilatometer test was also performed as an independent measurement. Correlation between the CPT and DMT showed that N_{kt} was much smaller than the normal range and the N_{kt} factor appeared to be consistent with B_q interpretations. Similarly, the coefficients used to interpret yield pressure lay at the high end of the range and could be justified through correlation with B_q.

Keywords: CPT interpretation, pre-consolidation pressure

1. Introduction

A sand and gravel quarry is being repurposed for an industrial development. The quarry was excavated to about 15m depth and the extracted material washed through a cyclone to separate the sand and gravel from the finer grained material. When an area had been quarried the finer material was pumped back into the quarry. Similar to tailings dams, this process formed a beach area around the pumping point and layers of fine grained sand, silt and clay away from the pumping point. The more distant a point in the quarry was to the pumping point, the finer grained the material that was deposited there.

The industrial development set performance requirements of 100mm total in-service settlement over 30 years for the buildings, 30mm for the roads and culverts as well as differential settlement limits. In order to achieve these limits surcharge and vertical drains was used to consolidate the backfilled material. A rolling surcharge strategy had been developed so that one area of the site is initially fully surcharged and later the stripped surcharge is reused as fill in another area of the site. Settlement plates and vibrating wire piezometers had been installed to monitor the performance of the surcharge over time.

The surcharge in the first area had been designed to lie in place for 12 months after filling. During this period the author was requested to perform an alternate surcharge design taking advantage of the monitoring data to that date. The author requested additional CPTs be performed at the locations of the monitoring instruments partly to obtain an exact measure of the thickness of compressible sediments and partly to contribute to a back analysis of the settlement plate and vibrating wire data. Some additional CPTs were also performed away from the area being surcharged to provide more detail on the thickness of compressible material around the site. At one of these locations a Medusa DMT was also performed to help calibrate the N_{kt} factor to an independent estimate of strength. A shear vane was not available at the time the testing was performed.

The process of using CPT data to contribute to the performance assessment of the surcharge was to estimate the pre-consolidation pressure at the time of testing and to compare it to:

(a) Profiles of in-situ effective stress prior to surcharging and if the total stress increment had been fully transferred to the soil. The purpose was to estimate the average degree of consolidation that had been achieved at that time; and
(b) The effective stress estimated from the excess pore pressures inferred from the vibrating wire piezometer data. The purpose was to verify if the interpreted pre-consolidation pressures were consistent with measurements.

2. Material properties of the backfill

Boreholes away from the surcharged area were drilled to obtain soil samples for laboratory testing. The soils were sampled using U75 tubes. While tubes can cause sample disturbance, in this case their use was deemed acceptable because hydraulically placed backfill will not have structure sensitive to disturbance. Classification, index tests and oedometer tests were performed on samples taken from three depths within one of the boreholes.

Results of the classification and index tests are presented in Table 1. Here, w is the moisture content, w_L is the liquid limit, w_P is the plastic limit and PSD is the particle size distribution. The data indicates that the materials are a combination of clayey silts and sandy silts. It is likely that there will be some areas where silty clays are present. The sample taken from 5.3m to 5.7m depth has a moisture content in excess of its liquid limit. Given this material had not been subject to surcharge and should not have been under-consolidated, it suggests that the Australian Standard procedure of drying the sample in an oven prior to testing had affected the result. The liquid limit should be greater than the moisture content for non-sensitive soils as were present at this site.

Results of the oedometer tests are presented in Table 2 for a load increment of 200kPa to 300kPa. The coefficient of compression (C_c) parameters were maximum for this load increment. The creep parameters (C_α) as a proportion of C_c lie below the usual 2% to 8% range for clays. An estimate of C_c from the index tests at 8.5m to 9.5m depth using Equation 1 was 0.28 which is similar to the value measured in the oedometer. However, the same approach provides very different values for the sample at 5.3m to 5.7m depth which supports the notion that the liquid limit was underestimated but the soil in this tube may have been layered and the portion of the sample used for oedometer tests may have had a higher clay content than the sample used for index and classification tests.

$$C_c = 1.35 \frac{PI}{100} \tag{1}$$

3. CPT tests, DMT tests and their interpretation

The CPT tests were performed using a Geomil 15cm^2 subtraction cone. The pore pressure filter was located in the shoulder and was saturated with silicone oil. The Medusa DMT tests were performed at 1.0m depth intervals adjacent to one of the CPT tests. The interpreted CPT data is presented in Figure 1. The friction angle (ϕ) is interpreted using Equation 2, undrained shear strength (s_u) using Equation 3, pre-consolidation pressure (p_c) using Equations 4 and inverting Equation 5. Marchetti (1981) was used to interpret undrained shear strength from the Medusa DMT using Equation 6. In these equations, q_t is the net cone resistance, σ_{atm} is atmospheric pressure, σ_v is total vertical stress, σ'_v is effective vertical stress, K_D is the dilatometer horizontal stress index, k, N_{KT} and m are constants. Parameter m was set to a value of 0.85 in all interpretations.

$$\phi = 17.6 + 11 log\left(\frac{q_t/\sigma_{atm}}{\sqrt{\sigma'_v/\sigma_{atm}}}\right) \tag{2}$$

$$s_u = \frac{(q_t - \sigma_v)}{N_{KT}} \tag{3}$$

$$p_c = k(q_t - \sigma_v) \tag{4}$$

$$s_u = \frac{\sin\phi}{2}\left(\frac{p_c}{\sigma'_v}\right)^m \tag{5}$$

$$s_{uDMT} = 0.22\sigma'_v(0.5K_D)^{1.25} \tag{6}$$

Table 1. Index Test Data

Depth (m)	**W (%)**	**W$_L$ (%)**	**W$_P$ (%)**	**PSD (%)**			**Classification**
Sieve (mm)				**0.002**	**0.075**	**2.36**	
5.3 to 5.7	52.2	41	19	27	88	100	Clayey Silt
8.5 to 9.0	52.6	55	24	48	99	100	Clayey Silt
13.0 to 13.7	32.1	Not Plastic		15	60	100	Sandy Silt

Table 2. Oedometer Test Data

Depth (m)	**Load increment (kPa)**	**e$_0$**	**C$_c$**	**C$_v$ (m^2/yr)**	**C$_\alpha$**
5.3 to 5.7	200 to 300	1.63	0.86	2	0.0017
8.5 to 9.0	200 to 300	1.23	0.33	2	0.0019
13.0 to 13.7	200 to 300	0.81	0.055	2.5	0.0058

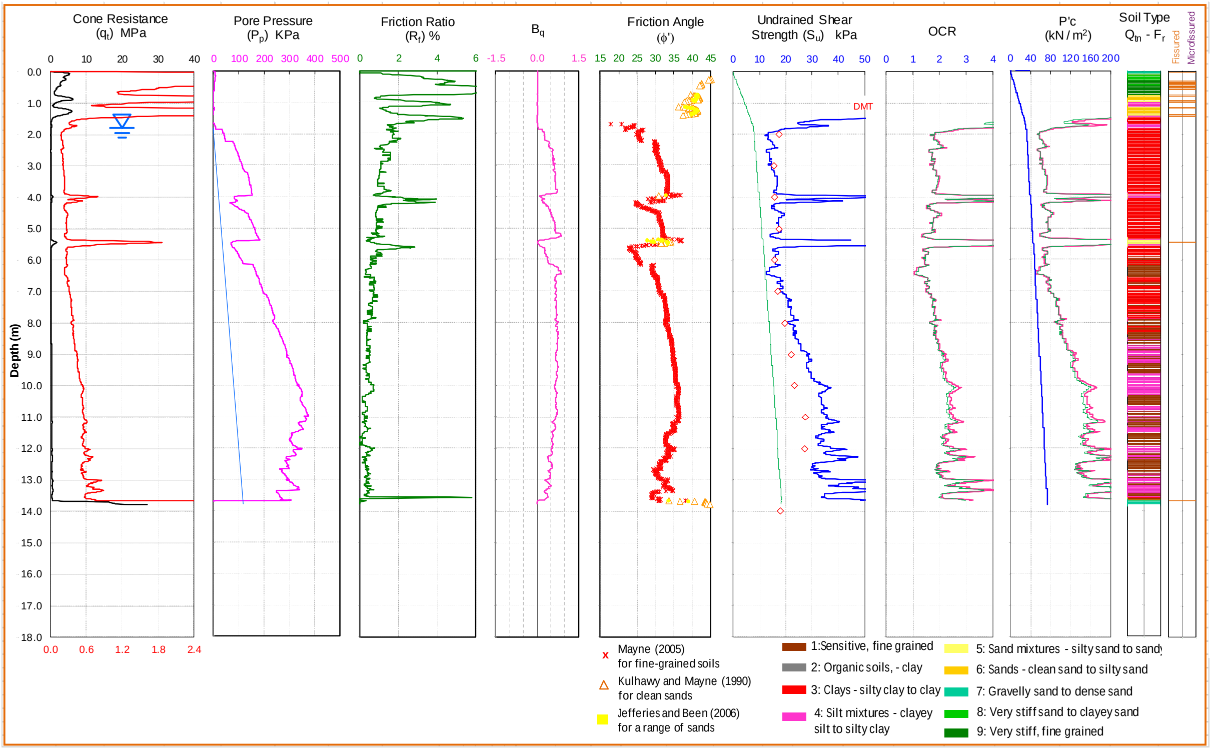

Figure 1. Interpretation of CPT and DMT tests

Equation 5 shows that s_u and p_c are proportional to each other. Therefore, from Equations 3 and 4 the k and N_{KT} parameters should be inversely proportional. N_{KT} values were obtained from B_q data using Figure 2. The k parameter was obtained by fitting p_c interpreted from Equation 4 to that inverted from Equation 5 using s_u derived from Equation 3.

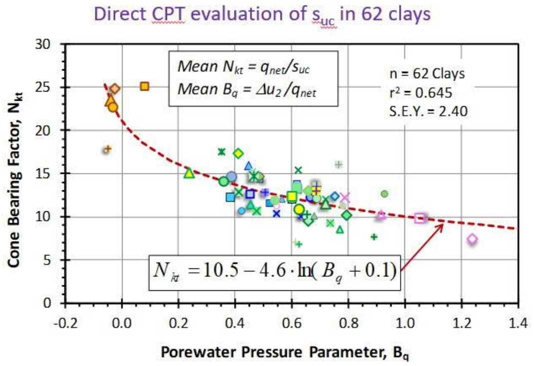

Figure 2. N_{KT} from B_q (Mayne and Puechen, 2018)

In order to validate that N_{KT} was a function of B_q, s_u interpreted from CPT16 and DMT were compared. In Figure 1, undrained shear strength interpreted from the DMT is shown with red diamonds and s_u interpreted from the CPT is shown with the blue line. From Figure 1, a B_q value of 0.72 was adopted which gives N_{KT} of 11.4 from Figure 2. Adopting a friction angle of 30 degrees in the upper 5m in Figure 1, sinϕ / 2 was assessed to be 0.25. Using Equation 4 to fit p_c with Equation 5 results in a k value of 0.38. This value lies at the higher end of the expected range (Robertson and Cabal, 2014). The same procedure was used for CPTs 2 to 4 and the results are summarised in Table 3. Values in brackets in Table 3 assume that the soil is normally consolidated and k can be estimated using Equation 7 which is derived from Equations 3 and 4. The difference between the k fitted to s_u interpretation and k in brackets is due to some overconsolidation of the soil and fitting k by eye. Never-the-less there is a broad trend of increasing k with B_q.

$$k = \frac{1}{N_{KT}\frac{\sin\phi}{2}} \tag{7}$$

Table 3. CPT Interpretation

CPT	B_q	N_{kt}	Sinϕ / 2	k
CPT 16	0.72	11.4	0.25	0.38 (0.35)
CPT 2	0.9	10.5	0.23	0.38 (0.41)
CPT 3	1.5	8.6	0.23	0.47 (0.51)
CPT 4	1.0	11.0	0.23	0.38 (0.40)

4. Use of CPT to help interpret progress of consolidation

The principle of consolidation is summarized in Figure 3 where the fill (load) is constructed over time, excess pore pressures from vibrating wire piezometers (L2B5 T, M and B) and theory (blue line) increase with load and dissipate with time resulting in an increase in the effective stress increment to equal the total stress (load) increment. Pre-fabricated vertical drains were spaced at 1.5m in a triangular configuration, a coefficient of horizontal consolidation of 4.5m^2/year was adopted along with a smear ratio of 5 and a permeability ratio of 5 for the smear zone.

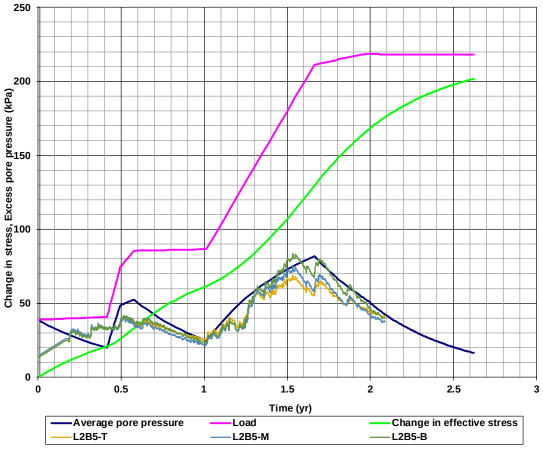

Figure 3. Excess pore pressure interpretation adjacent to CPT2

Effective stresses obtained from the vibrating wire piezometer interpretation are plotted against p_c interpreted from the CPT tests using the *k* values reported in Table 3 in Figures 4 to 6. The CPT interpretations were similar to the piezometer interpretations in Figures 4 and 6. The interpretation in Figure 5 is also reasonable given the piezometers appear to have been installed in or near sand lenses.

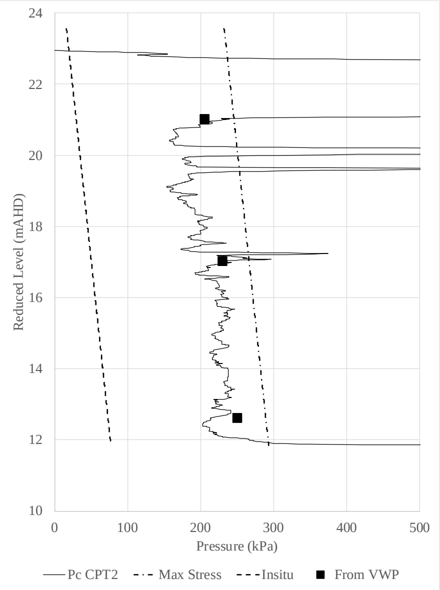

Figure 4. Interpretation for CPT2

The B_q values for CPT3 were unusually high and the pre-consolidation pressure is unusually low. It is not clear why these values are different from other locations around the site but might relate to the magnitude of the cone tip resistance readings.

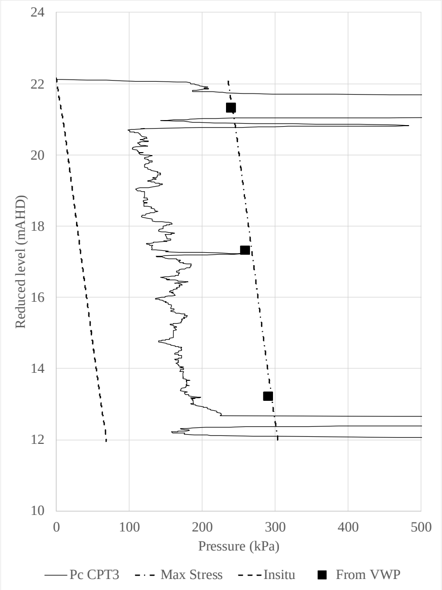

Figure 5. Interpretation for CPT3

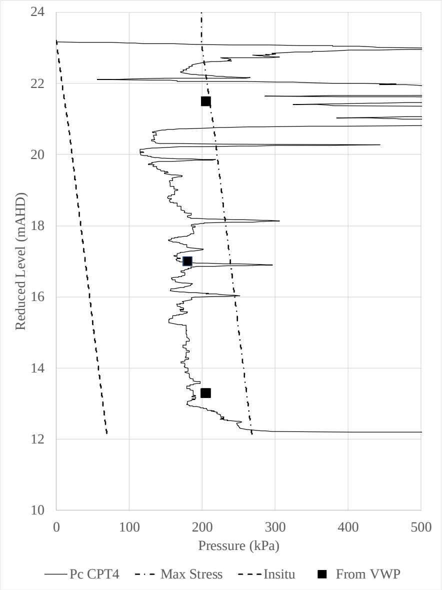

Figure 6. Interpretation for CPT4

The overall degree of consolidation for the compressible materials was assessed from settlement plate data (not reported in this paper), the average of the piezometer data and the average of the CPT interpretation. The aim was to achieve consistency in the interpretations to increase confidence in making decisions about whether or not to remove surcharge. If the conventional *k* factor of 0.33 had been adopted it would have resulted in a 13% reduction in pre-consolidation pressure which would have been less consistent with the other data sets and decreased certainty in the interpretations.

5. Conclusions

CPT data can be used to help confirm the progress of consolidation during surcharging. It provides an extra data set to complement interpretations from piezometers and settlement plates. However, if the default value of 0.33 for the k parameter shown in most CPT guides is used then an inconsistency can be created between the CPT interpretation and other forms of data. This inconsistency can be mitigated by interpreting undrained shear strength and hence pre-consolidation pressure coefficients using the B_q data as well as comparing the undrained shear strength data to an independent measurement.

As a guide, a k value of 0.33 with $\sin\phi / 2$ equal to 0.25 is consistent with an N_{KT} value of about 12 for normally consolidated soils. This in turn is consistent with a B_q value of about 0.62. Higher values of B_q would be consistent with higher values of k and vice versa.

References

Mayne, PW and Puechen, J, 2018. "Evaluation of CPTU N_{kt} cone factor for undrained strength of clays" Fourth International Symposium on Cone Penetration Testing (CPT'18), Delft, Netherlands

Robertson, PK and Cabal, KL, 2014, Guide to Cone Penetration Testing for Geotechnical Engineering 6th edition, Gregg Drilling and Testing Inc