Evaluation of the CPT for assessing ground improvement by dynamic replacement

L.J. Bates & R.S. Merifield
University of Newcastle, Callaghan, Newcastle, Australia

ABSTRACT: Dynamic replacement was chosen as a preferred method of ground improvement for the purpose of providing adequate foundation for construction of coal loading infrastructure on a site underlain by soft estuarine sediment, at Newcastle, Australia. Dynamic replacement is an extension of dynamic compaction used in cohesive soils, whereby suitable granular fill is driven and compacted using high energy pounders to form large diameter columns. Cone penetrometer testing (CPT) was initially engaged to characterise the site for column design and then utilised as a gauge to assess the improvements achieved during initial site calibration trails. Finally, along with the flat plate dilatometer (DMT) the CPT was used as a quality assurance tool during the construction phase. This paper presents an assessment of the capability and reliability of the CPT for assessment of ground improvement and provides comparison with measurements obtained using the DMT.

1 INTRODUCTION

Kooragang Island is situated 5km north of the city of Newcastle, Australia and forms part of the Port of Newcastle. The island which separates the north and south arms of the Hunter River was formed by reclamation of a number of smaller islands.

The Port of Newcastle is the largest coal exporting terminal in the world, currently exporting 90 million tonnes of coal per year through existing infrastructure. An area of land on Kooragang Island adjacent the south arm of the Hunter River was chosen for construction of a new coal loading facility by the Newcastle Coal Infrastructure Group (NCIG). Construction of stage 1 of the new loading facility is due for completion in 2010 and will increase total export volumes to 120 million tonnes of coal per year.

A portion of the new loading facility site, where a coal stockpile pad and associated machinery berms are to be constructed, is underlain by a layer of soft compressible estuarine clay of variable thickness. A crucial aspect to the design of the new infrastructure was to satisfy stringent post construction settlement criteria adequate for machinery operation.

Keller Ground Engineering (KGE) was contracted for the design, construction and verification of dynamically replaced, control modulus columns. The design was required to provide a cost effective and timely solution to the likely settlement problem. The coal stockpile pad area was divided into three sections 30R, 30C and 30L each approximately 90,000m^2. Approximately 2500 1.25m diameter columns were constructed in each area at a spacing of 6m. This paper presents the results of verification testing of sand columns constructed exclusively in area 30R. Rock columns were chosen for construction in areas 30C and 30L, the results of which are outside the scope of this paper.

1.1 *Pre construction subsurface profile in area 30R*

A series of 34 cone penetration tests (CPT), additional to previous investigations works, were undertaken to provide a detailed evaluation of the subsurface conditions prior to construction. The general underlying geotechnical conditions are summarised in Table 1 below.

Layer	**Name**	**Description**	**q_c (MPa)**
1	Hydraulic Fill – Dredged Sand	Fine to medium sand with some silt and shell fragments, ranging in depth from 1.8 to 2.4 m	12- 20
2	Estuarine Clay	Silty clay and clay with some shell, soft to firm, ranging in thickness from 1m to 4m	0.2 -0.5
3	Sand	Fine to medium sand, medium dense becoming dense to very dense to a depth of 9m to 12m	10-25
4	Residual Clay – EW Bedrock	Siltstone and sandstone, low strength, extremely to highly weathered, becoming less weathered with depth.	10 + Refusal

Table 1 Existing subsurface profile in area 30R

Typical preconstruction CPT tip resistance profiles are shown in Figure 1. Pore pressure’s indicated the presence of a confined aquifer in the lower sand layer as evidenced by a difference in the actual and projected hydrostatic pore pressure values measured beneath the clay layer. Figure 1 clearly shows an upper layer of hydraulic fill sand underlain by soft clay which is in turn underlain by dense to very dense sand. Interpretation of the CPT data suggested the undrained shear strength of the clay layer was around 15-50kPa.

A contour diagram indicating the thickness of the clay layer is shown in Figure 2, constructed from the 34 preconstruction CPT’s.

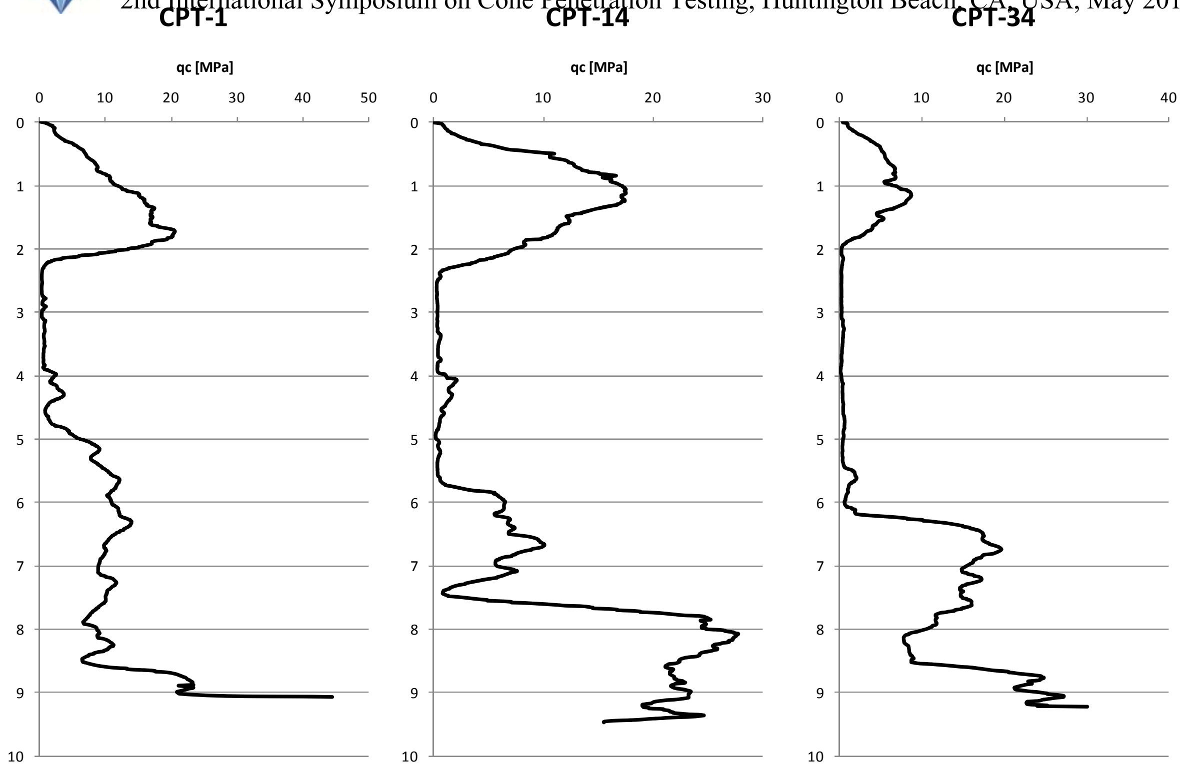


Figure 1 Typical subsurface profile across area 30R

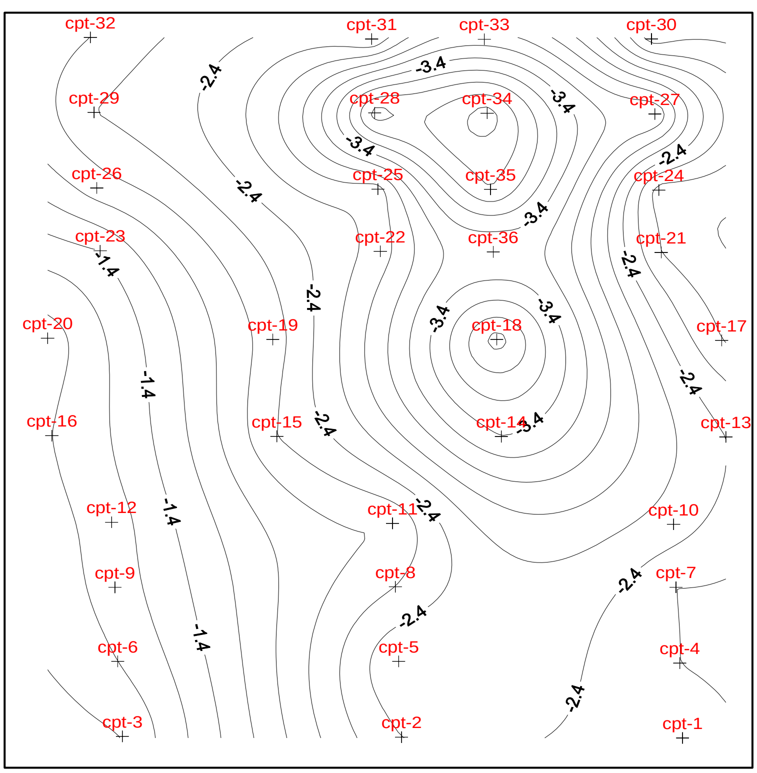


Figure 2 Thickness of clay contours in area 30R

1.2 *Sand column construction and verification techniques*

Construction of sand columns by dynamic replacement involved dropping a heavy steel weight or pounder from a significant height onto the sand surface layer, creating a crater as the sand was punched into the underlying soft clay, ideally displacing the clay. Additional sand was used to fill the imprint as the clay was displaced. A number of trial calibration columns were initially constructed, the effectiveness of the technique was verified using CPT and the optimum pounder mass, drop height and number of drops was confirmed. The accepted column construction required a minimum of 10 blows with a 20 tonne, 1.5m square pounder, dropped from a height of 20m. An additional ironing pass using a 2.4m diameter octagonal pounder dropped ten times from a height of 10m was required to compact the sand in the upper part of the column.

Construction in section 30R, comprised of 2519 sand columns on a grid spacing of 5.0m x 6m, was completed within a 3 month period. Post Verification testing consisted of 73 CPTs, 48 flat plate dilatometer tests (DMTs), and 6 plate load tests (PLTs). CPTs and DMTs were conducted by NewSyd in situ testing facility from the University of Newcastle. PLTs were undertaken by Keller Ground Engineering (KGE).

The CPT was the main in-situ test used to assess the quality of the columns during the construction phase by means of undertaking tests through the centre of the sand columns. A comparison of some typical pre- and post-construction CPTs is shown in Figure 4. A number of CPTs were conducted at different time intervals to after construction to investigate any post construction time effects.

Post construction DMTs where undertaken at a test interval of 0.2m depth, typical results are shown in Figure 3. A number of the DMTs where conducted in the same column as the CPTs allowing a direct comparison of results. Plate load tests (PLT) were conducted using a 1.2m diameter circular plate, the construction crane was used as a reaction load.

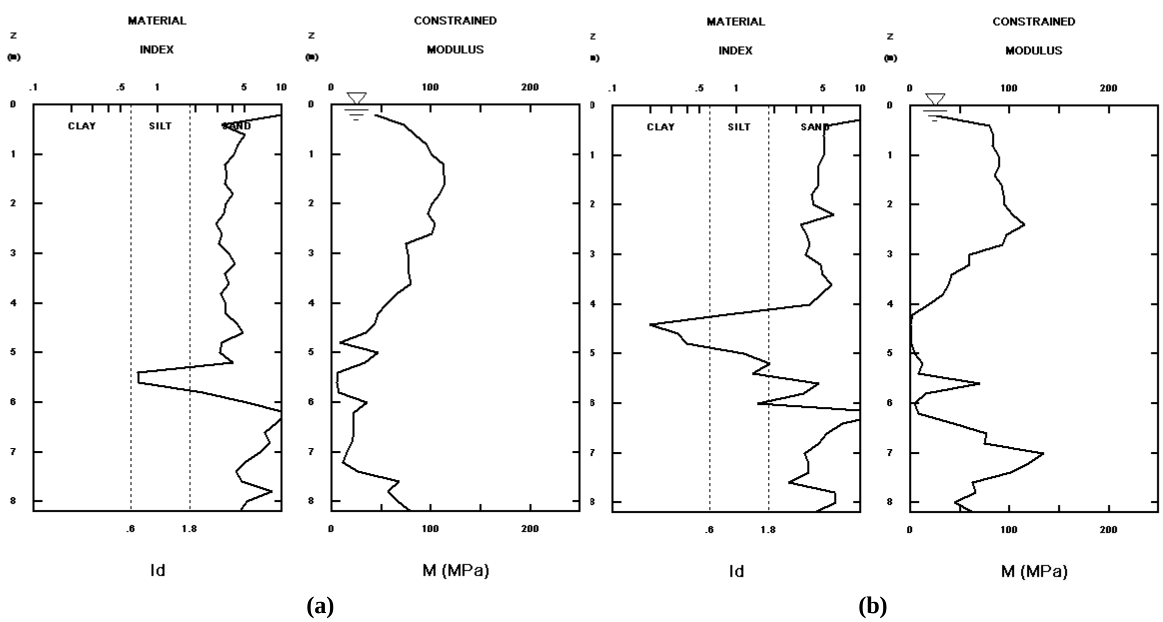
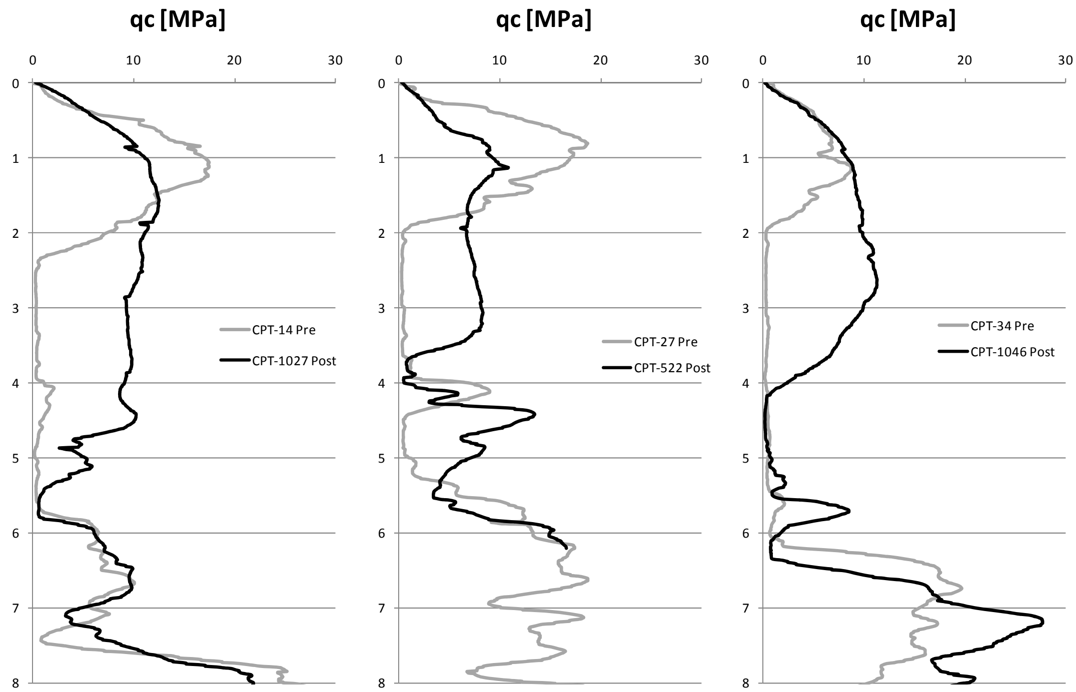


Figure 3 Typical Dilatometer profile through (a) Column 1027 and (b) Column 1046

2 RESULTS AND DISCUSSION

2.1 *Sand column installation verification*

The CPT provides excellent stratigraphic profiling detail (Lunne 1997) which proved effective for determining the extent of the clay displacement. The post construction CPT's also provided a measure of compaction achieved in the sand in the columns. A number of pre and post construction CPT plots for tip resistance (q_c) are shown in Figure 4.



(a) (b) (c)

Figure 4 Typical Pre- and Post-CPT profiles at and through sand columns, respectively

Overall the dynamic replacement technique was deemed to be very successful. Figure 4 indicates that the majority of the soft clay was displaced and an effective sand column was installed. At locations where the clay was particularly deep (i.e. >3m, Figure 4(c)), the post construction CPT indicated the presence of clay below several columns. In this respect, the CPT was able to provide an excellent level of quality control to ensure adequate sand placement and indicate where more pounding was required.

2.2 *Comparison of CPT, DMT and PLT modulus through sand columns*

The basic DMT data reduction formulae (Marchetti, 1980) was used to estimate the soil parameters from the DMT. The constrained modulus E_{oed} (or M_{DMT}) and the undrained shear strength are believed to be the most reliable and useful parameters obtained from the DMT. The constrained dilatometer modulus was estimated from equation 1.

$$E_{oed} = M_{DMT} = R_M E_D \quad (1)$$

Where E_D is the dilatometer modulus and R_M is a function of the material index I_D (Marchetti, 1980).

Estimates of the constrained modulus from CPT through the sand column was made using a well used correlation to penetration resistance (Schmertmann, 1978b; Jamiolkowski et al., 1985, Mayne, 2006) given in equation (2).

$$m_v = \frac{1}{\alpha_c \left(q_t - \sigma_{vo} \right)} \qquad \alpha_c = 6 \pm 2 \tag{2}$$

and

$$M = E_{oed} = \frac{1}{m_v} \tag{3}$$

Given the likely overconsolidated nature of the sand within the column a value of $\alpha_c = 8$ was used throughout the profile. The comparison between the CPT and DMT estimates of E_{oed} are shown in Figure 5. Overall the comparison was favorable and indicated $E_{oed} \approx 25 - 100$MPa for the dynamically placed sand. It should be noted that the DMT tests were performed between 4 - 14 days after the CPT tests and the modulus estimates may be higher due to possible ageing (see section 2.3 below). When compared with the DMT prediction, the CPT tends to over predict the modulus of the in-situ sands below the columns. This suggests a smaller value of α_c may be more appropriate for the in-situ sands.

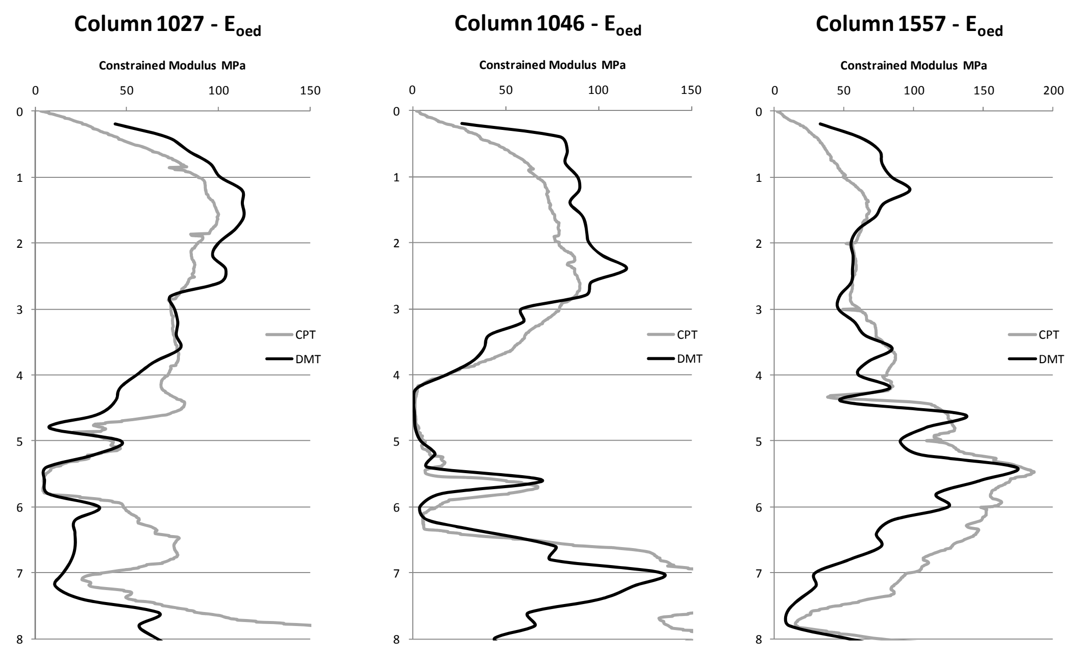


Figure 5 Comparison of CPT and DMT Constrained modulus

Plate load testing (PLT) of a number of sand columns provided estimates of (1-D) modulus based on elastic theory of a rigid loaded circular area. It was anticipated that the lateral constraint provided locally to the sand column by the dense upper sand layer would ensure the validity of this elastic approach. When compared to post CPT testing at the same column location, the PLT estimates compared well to the CPT interpreted modulus at shallow depths(<2m), tending to be conservative for depths greater than 2m. This is highlighted in Figure 6.

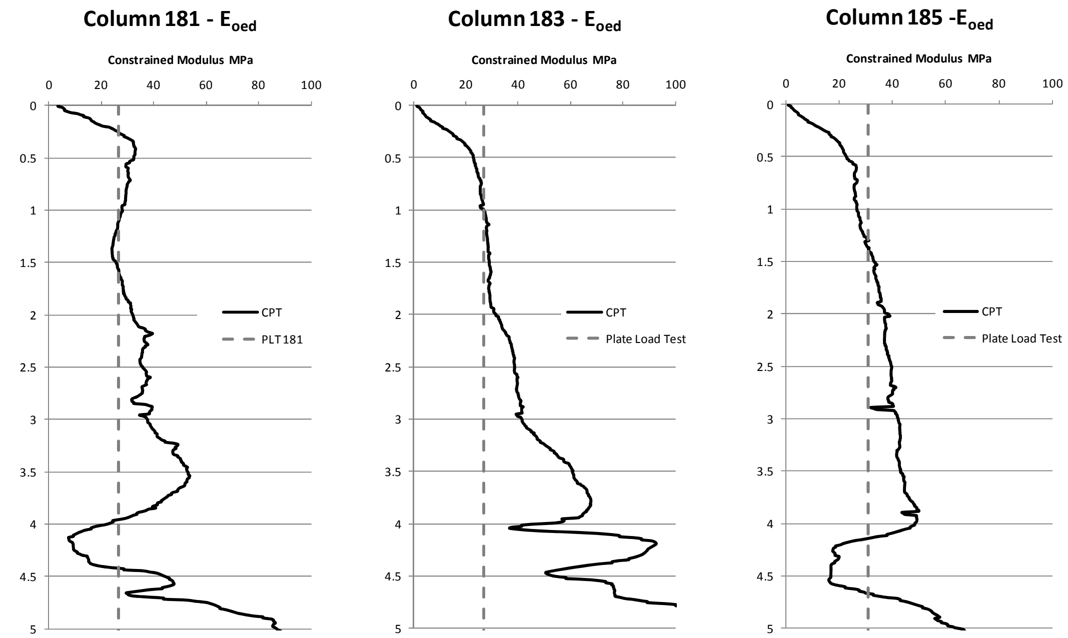


Figure 6 Comparison of modulus estimates from CPT and Plate Load Test through columns

2.3 *Ageing effects*

The effect of "ageing" in sands is a very real phenomenon observed in the results of CPTs undertaken up to 16 days post construction. A comparison of CPTs undertaken directly following column construction and 16 days later is shown in Figure 7, indicating increases in q_c of up to 100%, which compares favorably with other reported results (Mitchell and Soga, 2005). It is noted that the ageing effect was not only shown to present in the constructed sand column but is also noticeable in the natural underlying sands. The mechanism of ageing in sand is not fully understood but is considered to be the result of either chemical or physical changes or both, in the soil over time (Mitchell and Soga, 2005).

3 CONCLUSIONS

The CPT proved to be a valuable tool for calibrating and verifying the effectiveness of the dynamic replacement technique, particularly in regards to the ability of the CPT to indentify very thin clay layers present within the sand columns and to determine the extent of compaction in the sand column. The constrained modulus values for the post construction CPTs compared favorably with the modulus values determined for the DMTs and PLTs results. The CPT was also shown to provide a reliable measurement of aging effects in sand.

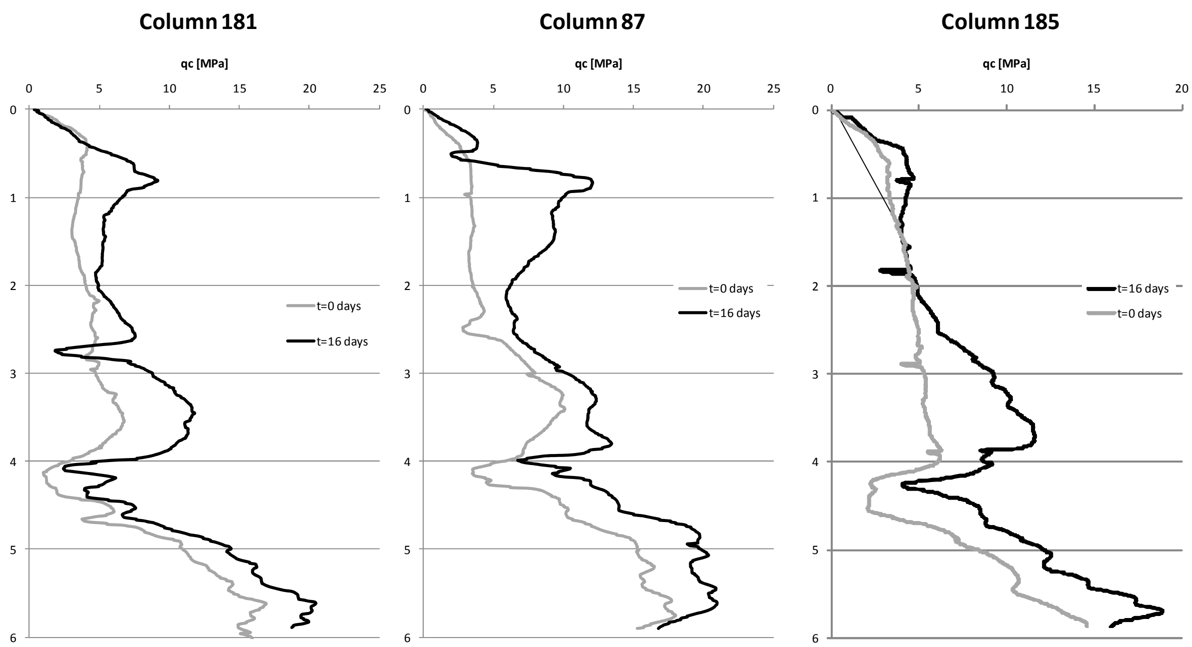


Figure 7 Observed sand ageing effects from CPT

4 ACKNOWLEDGMENTS

The authors would like to thank KGE for the permission to publish and for providing construction information and plate load test results. The authors would like to thank the Centre of Geotechnical and Materials Modeling at the University of Newcastle for their continuing support of the NewSyd Geotechnical Testing Facility.

5 REFERENCES

Jamiolkowski, M., C.C. Ladd, J.T. Germaine, and R. Lancellotta. (1985), “New Developments in Field and Lab Testing of Soils,” Proceedings, 11th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, San Francisco, Calif., pp. 57–154.

Lunne, T., P.K. Robertson, and J.J.M. Powell. (1997), Cone Penetration Testing in Geotechnical Practice, Blackie Academic, EF Spon/Routledge Publishers, New York, N.Y., 312 pp.

Marchetti, S. (1980). "In Situ Tests by Flat Dilatometer". ASCE Journal of Geotechnical Engineering, Vol. 106, No. GT3, 299-321.

Mayne, P.W. (2006), “In-Situ Test Calibrations for Evaluating Soil Parameters,” Overview Paper, Characterization and Engineering Properties of Natural Soils II (Proc. Singapore Workshop), Taylor & Francis Group, London, United Kingdom.

Mitchell, J.K. and Kenichi Soga. (2005), Fundamentals of Soil Behavior (3rd ed), John Wiley & Sons Inc., Hoboken, New Jersey. pp29, 511-515.

Schmertmann, J.H. (1978b), “Use the SPT to Measure Soil Properties?” Dynamic Geotechnical Testing, Special Technical Publication No. 654, American Society for Testing and Materials, West Conshohocken, Pa., pp. 341–355.