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Estimating K_o in sandy soils using the CPT

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ABSTRACT: One of the more challenging geotechnical parameters to estimate using in-situ tests is K_o in sandy soils. Re-search has shown that K_o can have a significant effect on soil behavior and that it can be helpful to estimate a reasonable value using in-situ tests. Marchetti (2015) has shown that ideally this requires two independent measurements and has suggested that a combination of the CPT and DMT can achieve this goal. However, this increases the cost of the site investigation, since two in-situ tests are required at one location and the in-terpretation is not always straight forward since each test collects measurements at different locations and at different depth intervals. The CPT already provides two independent measurements in the cone resistance, q_c and the sleeve resistance, f_s. This paper will present similarities between DMT and CPT data and show that the normalized CPT sleeve resistance (f_s/σ'_{vo}) can be used to estimate both DMT K_D and, when combined with the normalized cone resistance (Q_{tn}), can estimate the in-situ K_o in young, uncemented sandy soils. Background research will be presented to explain the logic and combined CPT and DMT data from several sites around the world will be presented to support the proposed correlation. The paper will also include a short discussion regarding repeatability of the CPT sleeve resistance (f_s) and how this affects the proposed ap-proach.

1 INTRODUCTION

One of the more challenging geotechnical parameters to estimate using in-situ tests is K_o in sandy soils. Research has shown that K_o can have a significant effect on soil behavior and that it can be helpful to estimate a reasonable value using in-situ tests. Marchetti (2015) has shown that ideally this requires two independent measurements and has suggested that a combination of the CPT and DMT can achieve this goal. However, this increases the cost of the site investigation, since two in-situ tests are required at one location and the interpretation is not always straight forward sine each test collects measurements at different locations and at different depth intervals.

This paper presents similarities between DMT and CPT data and show that the normalized CPT sleeve resistance (f_s/σ'_{vo}) can be used to estimate both DMT K_D and, when combined with the normalized cone resistance (Q_{tn}), can estimate the in-situ K_o in young, uncemented sandy soils.

2 CPT-DMT RELATIONSHIPS

Robertson (2009) suggested a preliminary set of average correlations that link the main DMT parameters (I_D, K_D) to normalized CPT parameters (Q_t, F_r). The proposed correlations are approximate and influenced by variations in in-situ stress state, soil density, stress and strain history, age, cementation and soil sensitivity. The correlations are unlikely to be unique for all soils but the suggested relationships form a framework for possible future refinements. The resulting correlations are shown in Figure 1, in the form of contours of I_D, K_D on the CPT normalized SBT chart. Included in Figure 1 are contours (in red) of the normalized sleeve resistance, F = f_s/σ'_{vo}.

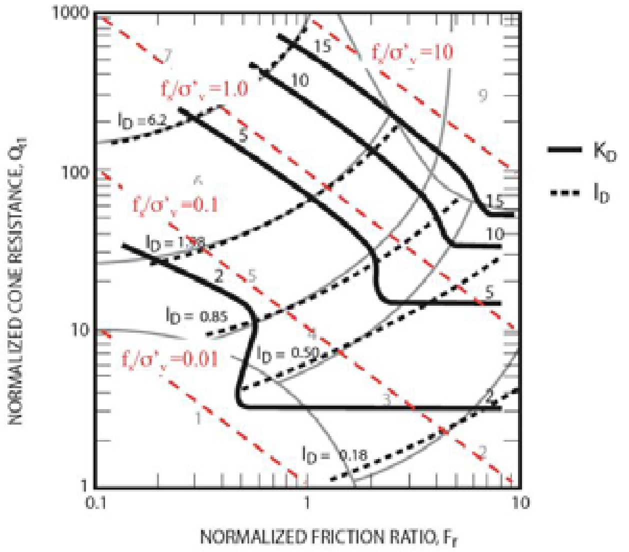

Figure 1. Approximate correlation between DMT K_D and I_D andCPT normalized parameters for soils with little or no microstructure (After Robertson, 2015)

Figure 1 shows that in the region dominated by sandy soils (SBT zones 5, 6 and 7; $I_c < 2.5$; $I_D > 1.0$) there appears to be a clear link between DMT K_D and CPT f_s/σ'_{vo}. Figure 1 shows that f_s/σ'_{vo} ranges over 3 orders of magnitude, with $f_s/\sigma'_{vo} = 0.01$ representing the typical limit of accuracy in the measurement and $f_s/\sigma'_{vo} = 10$ representing the typical limit of capacity of the cone. This matches a similar range for the DMT K_D from a low of about 1.0, based on accuracy, to high of around 50 based on capacity.

To illustrate this link, a comparison is shown in Figure 2 between DMT and CPT data at a sand site in Western Australia (Shenton Park). This site is composed of siliceous wind-blown, dune sand (Amoroso, 2011). Figure 2 shows that K_D and f_s/σ'_{vo} have a very similar variation with depth (note that both K_D and f_s/σ'_{vo} are plotted on a log scale). Figure 3 shows a similar comparison between DMT and CPT data from another sand site (Ledge Point) in Western Australia. This site is composed of slightly cemented calcareous sand, with 90% carbonate (Amoroso, 2011). Figure 3 also shows how both K_D and f_s/σ'_{vo} vary in a similar manner, with larger changes of f_s/σ'_{vo} in fine-grained soils.

Based on companion DMT and CPT data from 10 sites around the world, Figure 4 shows an approximate relationship between K_D and f_s/σ'_{vo} in sandy soils ($I_c < 2.5$; $I_D > 1.0$). The data shown on Figure 4 has been averaged to remove isolated points due to soil variability, since the DMT and CPT were not at the exact same location but within a few meters. Ranges are shown to reflect the variation of each measurement within a given relatively uniform sand zone.

An average relationship can be represented by:

$$\text{Log } F = \log K_D - 0.85$$
for sandy soils where $I_c < 2.5$ or $I_D > 1.0$ (1)

Where $F = f_s/\sigma'_{vo}$

Equation 1 and the data in Figure 3 indicate that the CPT normalized sleeve friction, F, is essentially similar to the DMT K_D in sandy soils, both with similar sensitivity.

3 ESTIMATING K_o IN SANDY SOILS

Hughes and Robertson (1985) discussed the changes in stresses around a cone and showed that there is significant stress relief as soil elements travel pass the shoulder of the cone. However, cavity expansion suggests that although the soil around the friction sleeve has experience a significant stress relief, the final horizontal stress around the sleeve is linked to the original horizontal stress prior to cone penetration and that the measured sleeve friction is strongly influenced by the horizontal effective stress around the sleeve. The data shown in Figures 2, 3 and 4 appear to support that concept. Marchetti (1985) suggested that it was possible to estimate K_o in sandy soils from a combination of both DMT and CPT data, as shown on Figure 5.

Using the link between DMT and CPT in sandy soils, it's possible to estimate K_o directly from CPT data, by combining normalized cone resistance, Q_t and normalized sleeve friction, F. In fine-grained soils ($I_c > 2.6$; $I_D < 0.8$) the in-situ K_o is more closely linked to OCR. Combining these two observations it is possible to represented contours of K_o on the CPT-based normalized soil behavior type chart (Robertson, 2009), as shown in Figure 6. The contours of K_o have been extended into the region of $I_c > 2.5$ based on the link between OCR and K_o in clay-like soils.

In the original SBT chart presented by Robertson (1990) there was a zone shown down the center of the chart that represented approximately normally consolidated soils that is also shown on Figure 6, where $K_o \sim 1 - \sin\phi' \sim 0.5$. This zone matches quite well the proposed contour of $K_o \sim 0.5$. The region to the left of the $K_o = 0.5$ contour can be assumed to be predominately normally consolidated with $K_o \sim 0.5$, as shown on Figure 6.

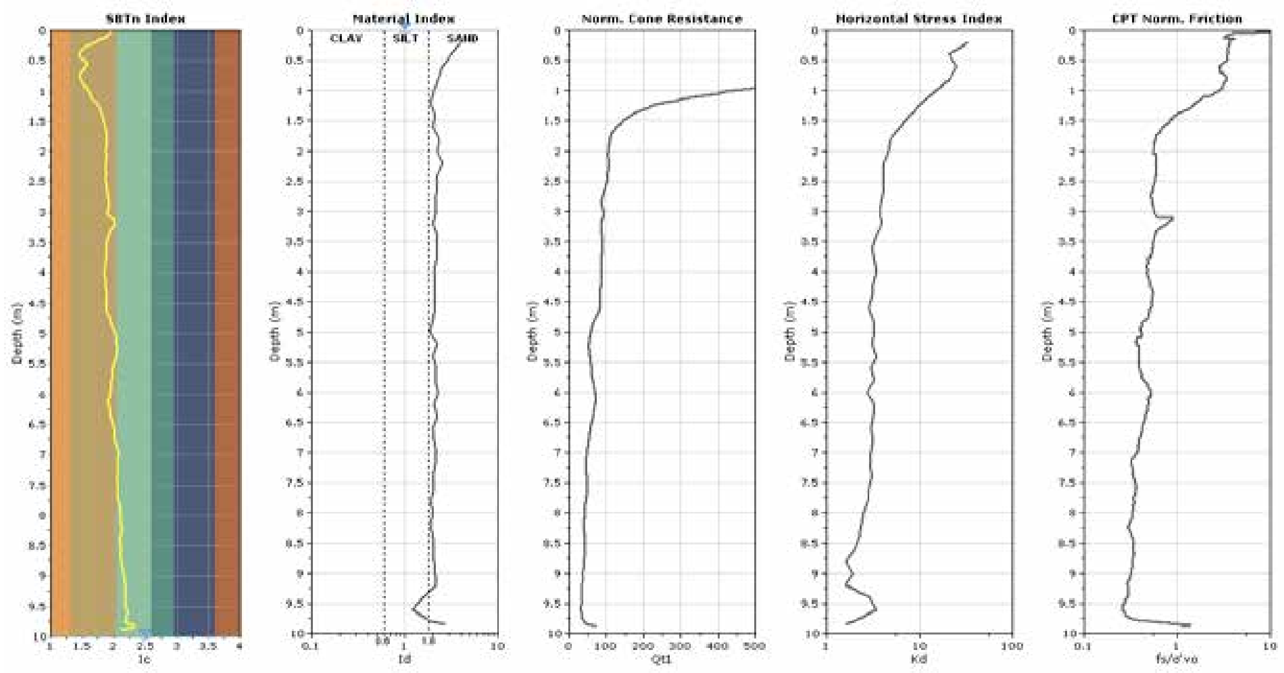

Figure 2. Comparison between CPT and DMT data in a sand site (Shenton Park) in Western Australia (data from Amoroso, 2011)

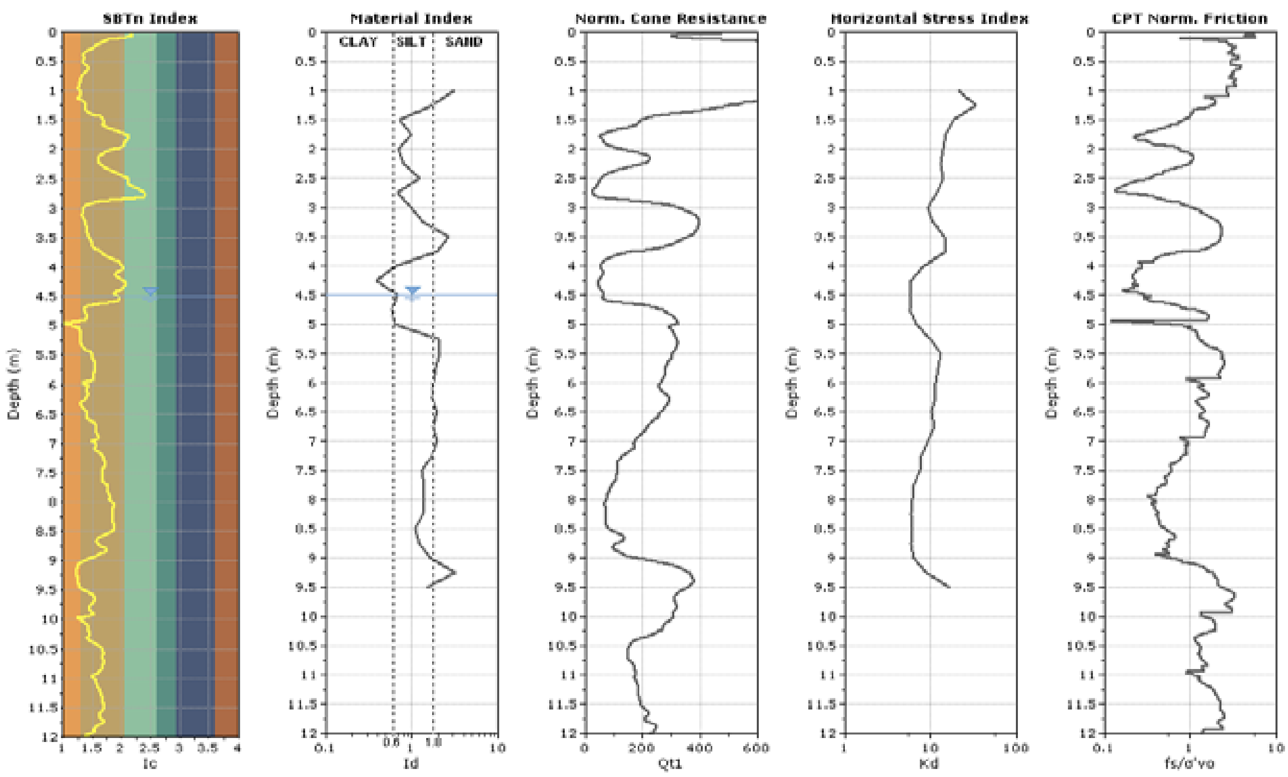

Figure 3. Comparison between CPT and DMT data in a sand site (Ledge Point) in Western Australia (data from Amoroso, 2011)

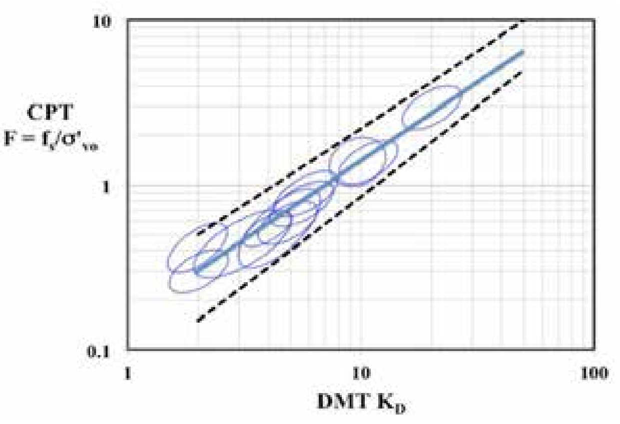

Figure 4. Relationship between DMT K_D and CPT normalized sleeve friction $F = f_s/\sigma'_{vo}$ based on 10 sandy soil ($I_c < 2.5$; $I_D > 1.0$) around the world

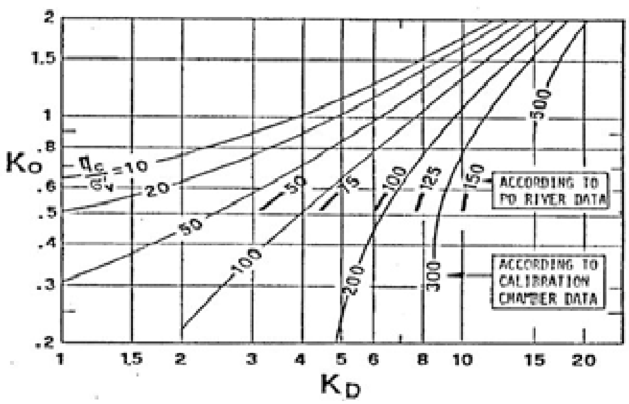

Figure 5. Chart for estimating K_o in sands as a function of DMT K_D and CPT q_c/σ'_{vo} (After Marchetti, 1985)

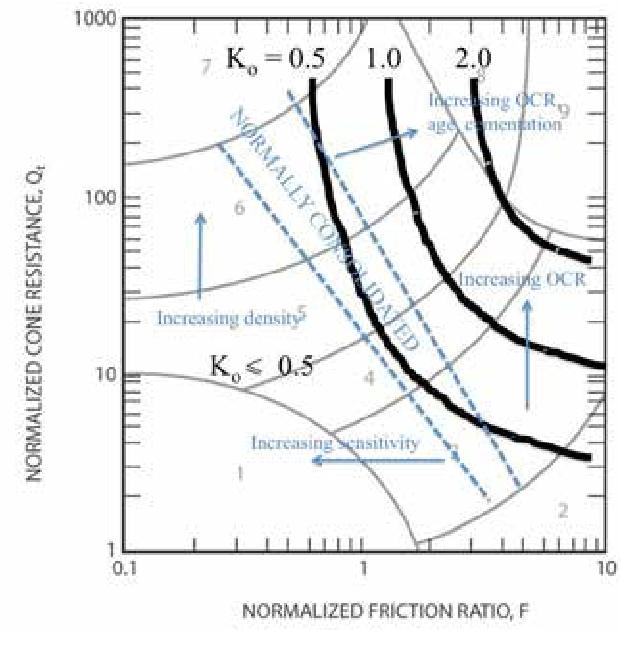

Figure 6. Suggested approximate contours of in-situ K_o on the CPT-based soil behavior type chart by Robertson (2009)

Also shown on Figure 6 are the trends suggested by Robertson (1990) for increasing sensitivity and increasing OCR for fine-grained soils and increasing density and increasing OCR, age and cementation for coarse-grained soils. These trends are consistent with the proposed approximate contours for K_o. In fine-grained soils (SBT zones 1, 2, 3 and 4), the measured sleeve friction tends to become dominated by the remolded shear strength of the soil and hence, can be a less accurate estimate of K_o.

The contours shown on Figure 6 are approximate, since there are many variables that influence K_o in soils. However, the trends are consistent with past experience, where stiff overconsolidated soils tend to plot toward the top right-hand portion of the chart (high Q_t and high F_r) and normally consolidated soils tend to plot in the central and lower left portion of the chart. In fine-grained soil, sensitivity tends to dominate and influence the measured sleeve friction values, since the measured sleeve resistance is often close to the remolded shear strength. Hence, fine-grained soils with high sensitivity tend to plot toward the lower left portion of the chart, regardless of in-situ K_o.

The CPT sleeve friction is often considered an unreliable measurement (e.g. Lunne et al 1986). Most modern electric cones have an accuracy/repeatability of the sleeve friction of between 1 to 5 kPa (e.g. separate load cells and equal-end area friction sleeves). Based on the contours of f_s/σ'_{vo} shown on Figure 1, the sleeve friction is less reliable when $f_s/\sigma'_{vo} < 0.1$, that represents predominately soft sensitive fine-grained soils and some very loose sands close to the ground surface (where σ'_{vo} is small).

4 SUMMARY AND RECOMENDATIONS

One of the more challenging geotechnical parameters to estimate using in-situ tests is K_o in sandy soils. Research has shown that K_o can have a significant effect on soil behavior and that it can be helpful to estimate a reasonable value using in-situ tests. Marchetti (2015) has shown that ideally this requires two independent measurements and has suggested that a combination of the CPT and DMT can achieve this goal. However, this increases the cost of the site investigation, since two in-situ tests are required at one location and the interpretation is not always straight forward since each test collects measurements at different locations and at different depth intervals.

The CPT already provides two independent measurements in the cone resistance, q_c and the sleeve resistance, f_s. Similarities between DMT and CPT data have been presented and show that the normalized

CPT sleeve resistance ($F = f_s/\sigma'_{vo}$) can be used to estimate both DMT K_D and, when combined with the normalized cone resistance (Q_t), can estimate the in-situ K_o in sandy soils.

The CPT and DMT are the most promising in-situ penetration tests currently used in practice. Each test has advantages and limitations. Relationships between the two in-situ tests can be used to expand and improve correlations and applications using experience and databases from one test and extrapolating to the other test. Since the CPT is faster, less expensive and provides a near continuous profile, it is often used more than the DMT, especially for smaller, low risk projects. The correlations presented in this paper provide some insight into how the links between the CPT and DMT can be used to expand our understanding of each test.

5 ACKNOWLEGEMENTS

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REFERENCES

Amoroso, S., 2011. G decay curves by seismic dilatometer (SDMT). PhD thesis, Universita' Degli Studi Dell'Aquila, Departimento di Ingegneria della Strutture, delle Acque e del Terreno, Italy.

Hughes, J.M.O. & Robertson, P.K., 1985. Full displacement pressuremeter testing in sand. Canadian Geotechnical Journal, 22, 3 : 298-307.

Lunne, T., Eidsmoen, T., Gillespie, D., and Howland, J.D., 1986. Laboratory and field evaluation on cone penetrometers. Proceedings of ASCE Specialty Conference In Situ'86: Use of In Situ Tests in Geotechnical Engineering. Blacksburg, ASCE, 714-729

Marchetti, S., 1985. On the Field Determination of K_o in Sand. Proceeding XI ICSMFE, S. Francisco, Vol. 5: 2667-2672.

Marchetti, S., 2015. Some 2015 Updates to the TC 16 DMT Report of 2001. Proceedings of 3rd International Conference on the Flat Dilatometer, DMT'15, Roma, Italy

Robertson, P.K., 2009. Interpretation of Cone Penetration Tests – a unified approach. Canadian Geotechnical Journal, 46: 1337-1355

Robertson, P.K., 2015. Soil Behavior Type using the DMT. Proceedings of 3rd International Conference on the Flat Dilatometer, DMT'15, Roma, Italy