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Laboratory measurement of sensitivity of carbonate soils

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ABSTRACT: Design of geotechnical structures such as piles and offshore pipelines requires knowledge of the soil's sensitivity to account for the effect of remoulding on the soil's strength. This effect of remoulding is particularly significant for soils exhibiting post-depositional structure, such as carbonate fine-grained soils. This paper investigates laboratory measurement of sensitivity using three different methods: fall cone, hand vane and mini T-bar penetrometer. Tests were conducted on two carbonate soils from offshore Western Australia, with different grain size distributions. Additional T-bar tests were performed on two reconstituted specimens of one of the soils that was consolidated from a slurry, to evaluate the influence of the method of reconstitution on the soil structure and sensitivity. The results for the more fine grained soil show that the fall cone and T-bar measurements of sensitivity are similar, whereas the hand vane yields much lower values, in particular for deeper samples; the sensitivity of reconstituted samples of this soil is approximately half that of the intact soil. The hand vane and fall cone data for the sandier soil investigated show a significant amount of scatter, with the average value of sensitivity being similar. The results are analysed in the light of existing frameworks for clays, investigating how soil sensitivity can be related to liquidity index and soil structure.

1 INTRODUCTION

Fine-grained soils are prone to various degrees of loss of strength upon remoulding. For example, some carbonate sediments offshore Australia exhibit sensitivities in the range 2 to 50. Knowledge of the degree of strength reduction due to remoulding is essential for the design of structures such as piles, suction caissons or pipelines, which subject the soil to intense remoulding during installation or in service. The soil's sensitivity can be measured either in situ, using vane shear tests or full-flow penetrometer tests (e.g., Yafrate et al. 2009), or in the laboratory using fall cone tests, vane shear tests, unconfined compression tests or miniature full-flow penetrometer tests (e.g., DeGroot et al. 2012, Tanaka et al. 2012, Hodder et al. 2010).

Previous studies on a variety of clays have shown that significant variation in sensitivity measurements is generally obtained depending on the method used for testing (e.g., DeGroot et al. 2012, Tanaka et al. 2012). These studies have demonstrated that one of the main factors affecting the measurement of remoulded strength (and thus sensitivity) is the mode of remoulding. Specimens remoulded by hand have a much lower strength than those remoulded with the vane, resulting in higher sensitivity. The wide variety of ways in which the undrained strength can be assessed (e.g. empirical correlations with the fall cone or direct strength measurement with the vane) causes variability in the assessed sensitivity- as does variations in the rate of shearing applied in any given test and the soil anisotropy.

This paper extends previous studies on the sensitivity of clays to carbonate soils, which are prevalent offshore Australia. The present study aims at quantifying the difference in sensitivity measurements obtained with three different methods, namely, the fall cone test, hand vane test and miniature T-bar penetrometer test. The two soils tested are a clayey silt (Soil A) and a silty sand (Soil B). Tube samples up to a depth of about 20 m were tested and profiles of intact strength, remoulded strength and sensitivity were determined using the different methods. The sensitivity of two reconstituted specimens of Soil A was also measured using T-bar test. The differences in measurements of intact strength, remoulded strength and sensitivity obtained with the three methods are discussed. The results are analysed in the light of existing frameworks for clays, investigating how soil sensitivity can be related to liquidity index and soil structure.

2 MATERIALS AND PROCEDURES

2.1 *Soils tested*

Soils A and B are from different regions of the Northern Carnavon Basin, on the North West Shelf (NWS) of Australia. Soil A lies in a deep water region, past the continental slope, with water depth of ~1100 m, whereas Soil B is located on the outer continental shelf, in water depth of ~100 m. Their mineral composition is very similar, dominated by carbonate minerals (mainly calcite and aragonite), whereas their particle size distribution differs significantly, as shown by the envelopes in Figure 1. General classification data were summarized by Lehane et al. (2014) and the average values are reproduced in Table 1. Soil A is classified as a well-graded clayey silt (muddy silt), whereas Soil B is a well-graded silty sand.

Table 1. Classification data for Soils A and B

Property	Soil A	Soil B
D_{50} (mm)	0.0065	0.065
Fines content (%)	85	35
Clay fraction (%)	28	10
Clay minerals (%)	1.7	4.5
Organic content (%)	1.6	N/A
Carbonate content (%)	84	89
Water content (%)	84	41
Liquid limit (%)	72	28
Plasticity index (%)	33	18
Liquidity index	1.6	1.7
Specific gravity	2.71	2.75
Estimated void ratio	2.3	1.1
Sensitivity	11.6	10

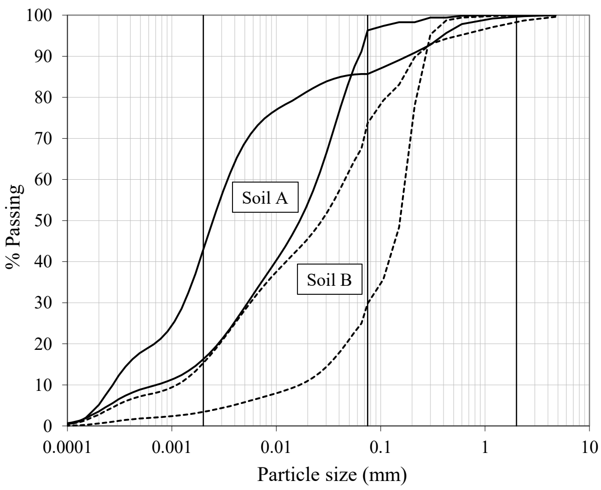

Figure 1. Particle size distribution envelopes for Soils A and B

2.2 *Experimental methods*

2.2.1 *Sample preparation*

Samples were provided in Shelby tubes with inner diameter of 60 mm and wall thickness of 1.6 mm. The tubes were X-rayed and sections showing significant disturbance were disregarded. In particular, samples of Soil B showed a relatively low quality with disturbance along entire tube lengths for multiple tubes. Each sampling tube selected for testing was cut into five sections as follows: two sections of length 45 mm for fall cone tests, two sections of length 110 mm for hand vane tests and one section of length 120 mm for T-bar tests. For some tubes with disturbed zones, only one test for each method could be performed.

Two reconstituted specimens of Soil A were prepared by consolidating a slurry at a water content of ~1.5 times the liquid limit (LL). The specimens were loaded incrementally over 7 days up to their final effective vertical stress, namely 55 kPa and 96 kPa, to represent samples from depths of 11 m and 19.5 m, respectively. The specimens were left to consolidate for a further 7 days, after which the recorded vertical displacement became negligible.

2.2.2 *Fall cone tests*

Fall cone tests were carried out using a cone with an apex angle of 30° and a mass of 80g, which was allowed to fall freely and penetrate into the sample under its own weight for 5 s. Measurement of cone penetration was carried out on the top and bottom side of each specimen. With two specimens tested for each tube (when sample quality permitted), this lead to four measurements, which were averaged to compute the intact undrained shear strength for the tube (using Equation (1) below). After extrusion from the tube and selection of a small fraction for water content measurement, each specimen was remoulded on a glass plate using a spatula and then filled into a cup 56 mm in diameter and 42 mm high. The cone penetration was measured for the remoulded sample. After remoulding the sample again a second measurement was performed. The remoulded undrained shear strength for the tube was determined using the average of four measurements (two for each specimen).

The undrained shear strength was interpreted from the cone penetration using the formulation proposed by Hansbo (1957)

$$s_u = \frac{KQ}{h^2} \tag{1}$$

where Q is the cone weight, h is the penetrated depth and K is a correlation parameter. In this paper, the theoretical value, K = 2.0, determined by Koumoto and Houlsby (2001) for a cone with a smooth surface was adopted. Using Equation (1), the intact (s_{ui}) and remoulded (s_{ur}) undrained shear strength were determined for each tube. The sensitivity was calculated as $S_t = s_{ui}/s_{ur}$ for each specimen and then averaged to obtain a value for each tube. Thus, the choice of the parameter K does not influence the value of sensitivity.

2.2.3 *Hand vane tests*

Hand vane tests were performed using a four-bladed Pilcon Hand vane 19 mm in diameter and 28 mm in height. The vane was initially pushed into the specimen up to a depth of 68 mm (referred to the tip of the vane) and then rotated clockwise at a rate of ~1 revolution per minute until a peak strength value was recorded. Remoulding of the soil was performed by applying 10 clockwise rotations at a faster rate, while maintaining the axis of the vane vertical. After remoulding, a second strength measurement was carried out by again rotating the vane at a rate of ~1 revolution per minute until a maximum value was reached. The soil's undrained shear strength is read directly on the vane dial. The method of calibration of the vane, which uses undrained triaxial tests results, is described by Serota and Jangle (1972). Hand vane tests were performed on two specimens for each tube. The intact strength (s_{ui}), remoulded strength (s_{ur}) and sensitivity for each tube were obtained by averaging the measurements obtained for the two specimens.

2.2.4 *T-bar penetrometer tests*

Miniature T-bar penetrometer tests were carried out using a T-bar of size 20 mm × 5 mm. A penetration rate of 1 mm/s was adopted. The tests consisted of penetrating the T-bar up to a depth of 75 mm, followed by 10 remoulding cycles of 30 mm amplitude (between depths of 75 mm and 45 mm), before extraction of the T-bar. The undrained shear strength s_u was determined by dividing the measured penetration resistance q by the resistance factor N_p = 10.5 (Randolph & Houlsby 1984, Stewart& Randolph 1994). The intact strength was obtained by averaging the penetration resistance between 30 mm and 60 mm depth during the initial penetration. The remoulded strength was determined from the average resistance measured between 65 mm and 50 mm depth, during the extraction phase of the last remoulding cycle. These values were then used to calculate the sensitivity.

2.3 *Testing programme*

The testing programme for Soil A consisted of a series of 15 hand vane tests, 21 fall cone tests and 6 T-bar tests carried out on 9 tubes retrieved from two boreholes between the depths of 8.5 m and 20 m. In addition, 2 T-bar tests were carried out on reconstituted specimens. For Soil B, 9 tubes were also tested, which were obtained from 5 boreholes between the depths of 2 m and 20 m. Due to the sandy nature of Soil B and to the low stress level, the flow around mechanism could not develop around the T-bar and for this reason T-bar tests were not conducted in this soil. A total of 12 hand vane tests and 12 fall cone tests were performed on Soil B.

3 RESULTS AND DISCUSSION

3.1 *Comparison of the different laboratory testing methods*

The intact strength, remoulded strength and sensitivity obtained with the three different methods are shown in Figures 2 to 4 for Soil A, whereas Figures 5 to 6 show the intact strength and sensitivity measured with the fall cone and hand vane for Soil B. Figure 2 indicates some significant variations in intact strength data obtained with the three methods for Soil A. These variations may reflect differences in sample quality as well as the difference in mode of shearing for the three methods. The fall cone and T-bar strength data increase with depth, whereas the hand vane data are approximately uniform.

When compared with the strength profile determined from consolidated undrained simple shear tests, all the measurements yield lower intact strength, with the T-bar giving the best estimate within the 25% range (Figure 2). The lower measured strengths are likely to reflect lower effective stresses in the tube samples which were not reconsolidated to in-situ stress levels (lower effective stresses are a typical consequence of sampling disturbance for lightly overconsolidated soils). It is interesting to note that the hand vane measurements of intact strength at ~20 m depth are almost 4 times less than the estimated in-situ simple shear strengths. The process of inserting the hand vane prior to shearing causes some disturbance and destructuration, which could partly explain the inability of the vane to capture the intact strength reliably.

There is more consistency in the remoulded strength values, which fall approximately within the 1 to 3 kPa range, with lowest values obtained with the fall cone, intermediate values obtained with the T-bar and highest values obtained with the hand vane (Figure 3). This is consistent with the mode of remoulding, which is more intense when using the fall cone method (remoulding by hand), less intense when using the hand vane (remoulding with the vane rotation) and intermediate when using the T-bar. In case of the fall cone, however, the remoulded strength value depends on the choice of cone factor K. On average, the remoulded strength is slightly lower than 2, which is consistent with a water content slightly above the liquid limit.

The sensitivity results plotted in Figure 4 show an increasing trend with depth for the fall cone and T-bar (as observed for the intact strength), with sensitivity values in the range 4 to 33 for the fall cone and 9 to 18 for the T-bar. Lower values of sensitivity are obtained with the hand vane, which are approximately uniform with depth, with an average of $S_t \sim 4$.

As for Soil A, the intact strength measurements for Soil B obtained with the fall cone and the hand vane show significant variations (Figure 5). Both methods fail to capture the increase of strength with depth, which is apparent in the strength profile determined from consolidated undrained simple shear tests, as shown in Figure 5. In general, fall cone and hand vane strength measurements are lower than the simple shear strength. Loss of suction (effective stress) in the samples is the most likely explanation for this trend.

Fall cone and hand vane measurements on Soil B yield similar average remoulded strength, s_{ur} ~ 2.5, and sensitivity, S_t~10 (Figure 6). The fall cone data show significant variability, which may be related to variability in fines content (and hence suction) of the silty sand samples.

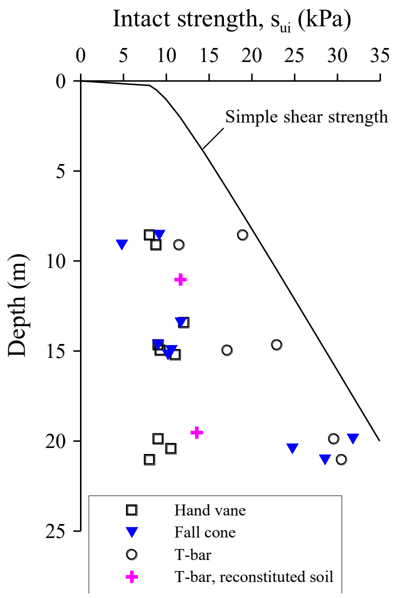

Figure 2. Intact strength measured with different laboratory testing methods for Soil A

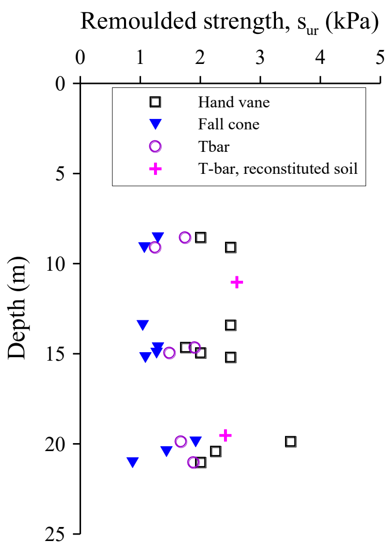

Figure 3. Remoulded strength measured with different laboratory testing methods for Soil A

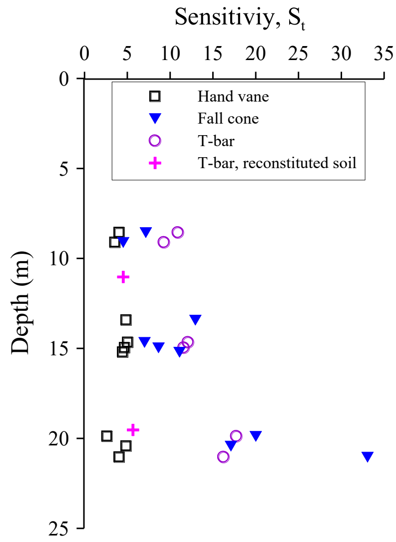

Figure 4. Sensitivity measured with different laboratory testing methods for Soil A

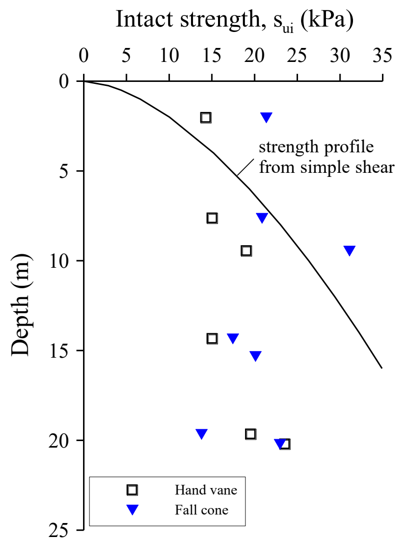

Figure 5. Intact strength measured with different laboratory testing methods for Soil B

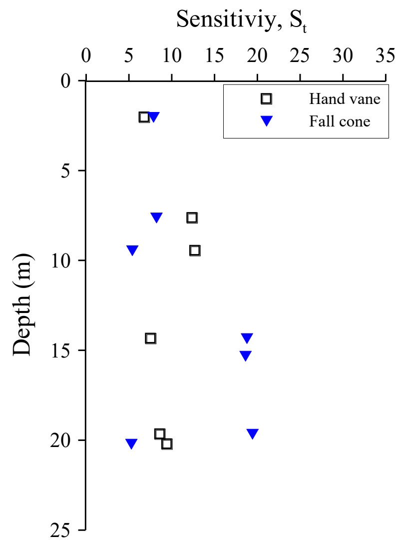

Figure 6. Sensitivity measured with different laboratory testing methods for Soil B

3.2 *Effect of sample reconstitution*

The two reconstituted specimens of Soil A exhibited similar intact (in this case 'intact' means during initial penetration of the T-bar) and remoulded strengths when tested with the T-bar, irrespective of the pre-consolidated stress (55 kPa and 96 kPa). The value s_{ui} ~12.5 kPa is consistent with the intact strength measured for specimens at ~10 m depth, but is much lower than the strength measured at ~20 m depth (Figure 2). When compared with the remoulded strength measured with the T-bar on the original specimens, the value of s_{ur} for the reconstituted specimens is slightly higher (Figure 3). The sensitivity of the reconstituted specimens is S_t~5, which is 2.0 times less than the sensitivity of the undisturbed samples at ~10 m depth measured with the T-bar. Evidently, the intact soil can exist at a higher void ratio and has a more sensitive structure than that created by the reconstitution process.

3.3 *Comparison with sensitivity of marine clays*

The sensitivity measurements for Soil A obtained with the three different methods are plotted as a function of the liquidity index (LI) in Figure 7. LI was determined from the water content measured on each specimen tested and using average values of liquid limit (LL) and plastic limit (PL) obtained from a previous study on the same soil (see Table 1). The data in Figure 7 are compared with the following relationship

$$S_t = \exp(kI_L) \quad (2)$$

which was used by Muir Wood (1990), with k in the range 1 to 3, to fit data obtained for various natural clays. For example, data from Bjerrum (1954) were reasonably well fitted with k = 2. The data for Soil A shown in Figure 7 also fall within the k range of 1 and 3. However, for the narrow range of liquidity indices of the specimens tested (1<LI<1.6), a wide range of sensitivity values were measured (from fall cone data, $4<S_t<33$ and from T-bar data $9<S_t<18$). As discussed earlier, soil structure is a key variable influencing soil sensitivity and the LI may not be adequate to capture this influence.

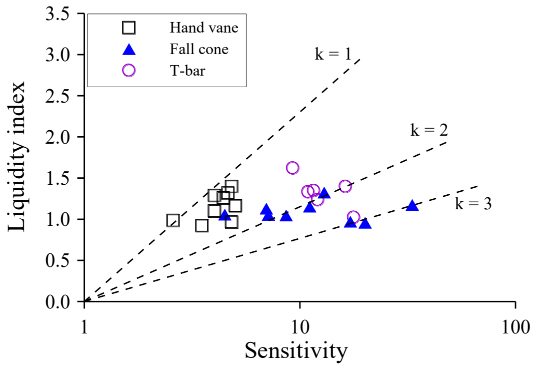

Figure 7. Liquidity index vs sensitivity for Soil A

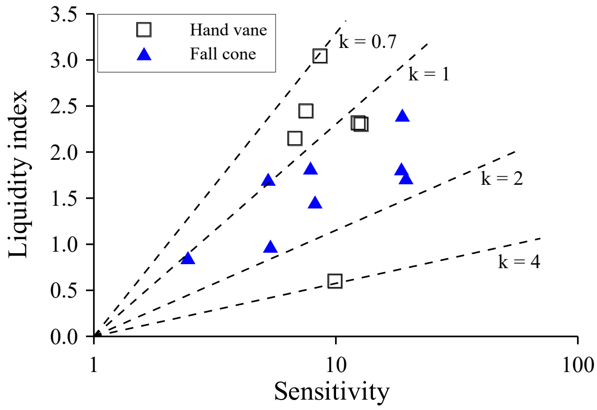

Figure 8. Liquidity index vs sensitivity for Soil B

Figure 8 shows the data of sensitivity versus LI for Soil B. The data exhibit a greater variability in LI and the fall cone data indicate an increasing trend of sensitivity with LI. However, the data should be regarded with caution as average values of LL and PL were used to compute LI, whereas a previous study indicated significant variations in these parameters, correlating with variations in fines content.

3.4 *Comparison with prediction using the idealized sensitivity framework*

Cotecchia & Chandler (2000) have proposed a sensitivity framework based on the observation that clays with similar sensitivity follow similar curves during one-dimensional compression. These curves can be plotted in terms of the void index, $I_v = (e - e^*_{100})/(e^*_{100} - e^*_{1000})$, where e^*_{100} and e^*_{1000} are the void ratios of the clay reconstituted and compressed one-dimensionally to 100 kPa and 1000 kPa respectively (Burland, 1990). The compression curves of the reconstituted clays are intrinsic compression curves (ICL) and can be approximated by a unique line in the normalized space $I_v - \log \sigma'_v$. The compression curves for the natural clays with their natural structure plot above the ICL, with the horizontal distance between the yield point (σ'_{vy}) and the ICL (σ'_{ey}) being related to the sensitivity, $S_t = \sigma'_{vy} / \sigma'_{ey}$.

Figure 9 shows the ICL for soil A obtained from an oedometer test conducted on a reconstituted specimen (from a slurry with water content w ~ 1.5 LL pre-consolidated to 50 kPa), together with the ICL predicted using Burland's correlations for e^*_{100} and $C_c^* = e^*_{100} - e^*_{1000}$. The correlations, which were derived for clays, give a reasonable estimate of C_c^* (C_c^* = 0.46 from correlations and C_c^* = 0.39 from compression of reconstituted sample), but underestimate the void ratio in the intrinsic state. However, void ratio was derived from water content measurements and this may not be adequate for calcareous soils having hollow particles which can trap water.

Figure 10 shows three compression curves obtained from oedometer tests conducted on tube specimens of Soil A plotted in terms of I_v, together with the ICL. Tests T1, T2 and T3 were conducted on specimens from depth 11.5 m, 5.5 m and 5.9 m, respectively. Using the relation, $S_t = \sigma'_{vy} / \sigma'_{ey}$, sensitivity values of 11.5, 5.5 and 5.0 are estimated for T1, T2 and T3 specimens, respectively. These values are slightly lower than sensitivities measured on specimens of similar depth of 15.5, 10.5 and 7.5, respectively. The lower sensitivity prediction may be attributed partly to disturbance caused by tube sampling, which results in a decrease in yield stress σ'_{vy}.

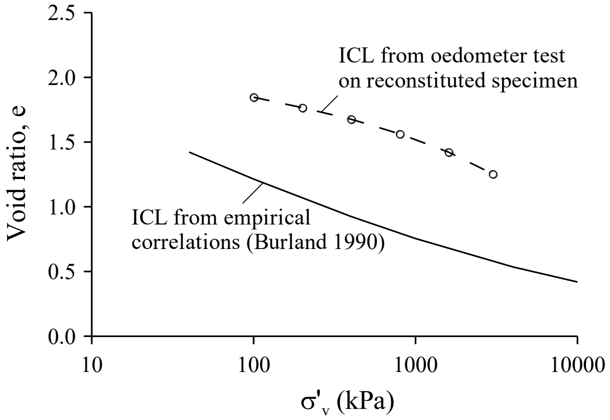

Figure 9. ICL for Soil A

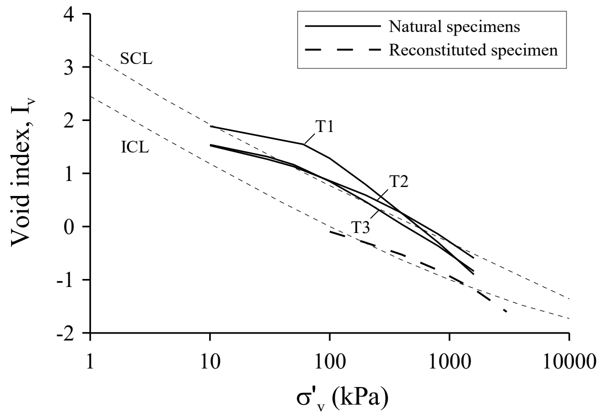

Figure 10. Oedometer results for Soil A in terms of I_v

4 CONCLUDING REMARKS

Three laboratory methods have been used to measure the sensitivity of two calcareous soils from offshore Australia, namely the fall cone, vane shear and T-bar penetrometer. For Soil A, the fall cone and T-bar lead to similar values of intact and remouled undrained strength (s_{ui} and s_{ur}), whereas the hand vane yields lower s_{ui} and slightly higher s_{ur}, resulting in lower sensitivity. The sensitivity of reconstituted specimens is approximately half that of the intact specimens. For Soil B, the hand vane and fall cone yield similar sensitivity on average. Large variation in sensitivity is observed in specimens having similar liquidity indices (LI), indicating that LI is not an adequate parameter to predict sensitivity. This may be related to the fact that water content measurement in calcareous soil is not indicative of the particle packing due to the presence of trapped water in hollow particles. Applying the idealized sensitivity framework (Cotecchia & Chandler, 2000), which predicts sensitivity based on the distance of the yield point in compression to the ICL, yielded slightly lower sensitivity compared with measured values. This preliminary finding needs to be investigated further with additional testing.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Bjerrum, L. 1954. Geotechnical properties of Norwegian marine clays. *Géotechnique* 4(2): 49-69.
Burland, J.B. 1990. On the compressibility and shear strength of natural clays. *Géotechnique* 40(3): 49-69.
Cotecchia, F. & Chandler, R.J. 2000. A general framework for the mechanical behaviour of clays. *Géotechnique* 50(4): 431-447.
DeGroot, D.J.., Lunne, T., Andersen, K.H. & Boscardin, A.G. 2012. Laboratory measurement of the remoulded shear strength of clays with application to design of offshore infrastructure. In, , *Offshore Site Investigation and Geotechnics, London, 12-14 September 2012*. Society of Underwater Technology.
Hansbo, S. 1957. A new approach to the determination of the shear strength of clay by the fall cone test. *Proc. R. Swedish Geotechnol. Inst.* 14: 1-49.
Hodder, M.S., White, D.J. & Cassidy, M.J. 2010. Analysis of soil strength degradation during episodes of cyclic loading, illustrated by the T-bar penetration test. *Int. J. Geomech* 10(3): 117-123.
Koumoto, T. & Houlsby, G.T. 2001. Theory and practice of the fall cone test. *Géotechnique* 51(8): 701-712.
Lehane, B., Carraro, A., Boukpeti, N. & Elkhatib, S. 2014. Mechanical response of two carbonate sediments from Australia's north west shelf. *Proc. Int. conf. Ocean Offshore Arctic Engnr. (OMAE), San Francicsco, USA*.
Muir Wood, D. 1990. *Soil behaviour and critical state soil mechanics*. Cambridge: Cambridge University Press.
Randolph, M.F. & Houlsby, G.T. 1984. The limiting pressure on a circular pile loaded laterally in cohesive soil. *Géotechnique* 34(4): 613-623.
Serota, S. & Jangle, A. 1972. A direct reading pocket shear vane. *Civil Engineering – American Society of Civil Engineers*.
Stewart, D.P. & Randolph, M. F. 1994. T-bar penetration testing in soft clay. *J. Geotech. Engng* ASCE 120(12): 2230-2235.
Tanaka, H., Hirabayshi, H., Matsuoka, T. & Kaneko H. 2012. Use of fall cone test as measurement of shear strength for soft clay materials. *Soils and Foundations* 52(4): 590-599.
Yafrate, N., DeJong, J. DeGroot, D. & Randolph, M. 2009. Evaluation of remolded shear strength and sensitiveity of soft clay using full-flow penetrometers. *Journal of Geotechnical and Geoenvironmental Engineering.* 135: 1179-1189.