EVALUATION OF OCR IN SAND FROM DMT & CPT

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ABSTRACT

This paper is focused on the in situ evaluation of *OCR* in sands. In particular the correlation for estimating *OCR* in sand from the ratio M_{DMT}/q_c ("proxy" of stress history), involving the combined use of DMT and CPT/CPTU, is discussed. The available experience which forms the basis of the correlation OCR-M_{DMT}/q_c is briefly overviewed.

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Key Words: sand, stress history, overconsolidation ratio, flat dilatometer test, cone penetration test

INTRODUCTION

The flat dilatometer test (DMT), introduced by Marchetti (1980), is increasingly used in the last years, also stimulated by the diffusion of its efficient "All-in-One" seismic version (SDMT). The DMT, like the pressuremeter (PMT), is an in situ deformation test rather than a penetration test. Deformation tests can provide very detailed information about the soil behaviour in terms of stiffness, hence more accurate predictions of settlements/displacements, often governing geotechnical design. They seem to be complementary to penetration tests that can provide strength parameters.

Major distinctive contributions that the DMT can provide in a *routine* site investigation are: (1) information on stress history, which has a dominant influence on soil behaviour; (2) being an in situ pressure-displacement test, DMT results are more closely related to "working strain" soil stiffness than penetration tests. As to the SDMT, the add-on seismic module has supplemented the parameters measurable by DMT with the shear wave velocity V_S, hence information on small strain stiffness.

As emphasized by Marchetti (2015), research carried out over the years has pointed out the centrality of the horizontal stress index K_D, a key parameter obtained from DMT and one of the few in situ parameters able to provide information on stress history, especially in sand. K_D reflects cumulatively various stress history effects, such as aging (Monaco & Schmertmann 2007, Monaco & Marchetti 2007, Jamiolkowski & Lo Presti 1998, Marchetti 2010) and in situ horizontal earth pressure (K_0). Knowledge of stress history is fundamental for obtaining realistic predictions, e.g. of settlements and liquefaction behaviour. If the site investigation does not provide adequate information on stress history, the benefits of stress history are ignored, leading to less economical design.

Current trends and ongoing developments of DMT research and practice have been addressed in recent papers (Marchetti 2015, Burlon et al. 2016). One notable emerging trend is the increasing diffusion of a "multi-parameter/multi-test approach" in site investigation practice, based on the combination/comparison of results of DMT/SDMT and other in situ tests, mostly cone/piezocone penetration test (CPT/CPTU).

Most in situ tests are only able to measure "mixed" soil responses that depend at the same time on strength, stiffness, stress history, etc. Hence "pure" soil properties are determined by solving an inverse problem, based on multiple independent in situ responses. Mayne et al. (2009) emphasized the use of direct-push in situ tests providing multi-measurements, in particular "hybrid" tests that combine the advantages of full-displacement penetrometer probes with downhole geophysics (such as seismic piezocone SCPTU and SDMT), as a more efficient approach to geotechnical site characterization. While in simple problems one in situ technique could be sufficient, in general an adequate number of responses from different in situ tests should be available to define a soil model. Moving towards an in-situ multi-parameter/multi-test approach appears a logical trend. In this respect, the availability of the DMT stress history parameter K_D is important not only "per se", but also in combination with parameters obtained from other in situ tests less sensitive to stress history (e.g. CPT).

The estimation of the overconsolidation ratio *OCR* in sand based on the combined use of DMT and CPT, discussed in this paper, is a significant example of in-situ multi-parameter/multi-test approach. Other examples are the methods for estimating K_0 in sand (described by Marchetti 2015) and the method for estimating liquefaction resistance proposed by Marchetti (2016).

SENSITIVITY OF DMT AND CPT TO STRESS HISTORY

Numerous researchers have observed that the horizontal stress index K_D from DMT is considerably more sensitive to stress history than the cone penetration resistance q_c from CPT, either in monitoring compaction in the field and in calibration chamber. Relevant experience is described in detail by Marchetti (2015) and is briefly summarized hereinafter.

Monitoring compaction

The higher sensitivity of the DMT to stress history is indicated by comparisons of pre-post CPTs and DMTs executed for monitoring compaction – which is a way of imposing stress history.

Schmertmann (1984) found that the modulus increase due to overconsolidation predicted by DMT was four times than predicted by CPT, noting that *"the cone during its insertion movement appears to destroy a large portion of the modifications in soil structure that result from the overconsolidation and it therefore measures very little of the related increase in modulus. In contrast, the lower strain penetration of the DMT preserves more of the effects of overconsolidation and it subsequently can measure a greater portion of the modulus increase"*.

Schmertmann et al. (1986) compared the pre-post variations in the constrained modulus M_{DMT} obtained from DMT interpretation (Marchetti 1980) and in q_c from CPT in a ground improvement quality control job. They found that M_{DMT} increased relatively much more than q_c and the compaction produced an average ratio (percent increase in M_{DMT}) / (percent increase in q_c) of about 2.3.

A similar trend was observed by Jendeby (1992), who compared DMT and CPT results before and after the compaction of a loose sand fill and found an increase of the ratio M_{DMT}/q_c from a pre-compaction $M_{DMT}/q_c \approx 7$-9 to a post-compaction $M_{DMT}/q_c \approx 12$-22 (Fig. 1a). More recently Balachowski & Kurek (2015), in monitoring vibroflotation of a sand deposit, found the mean increase in M_{DMT} after compaction about 2.3 times higher than the corresponding increase in q_c (Fig. 1b). Additional comparisons of pre-post-ground improvement values of M_{DMT}/q_c are reported by Sharif (2015) and by Amoroso et al. (2015).

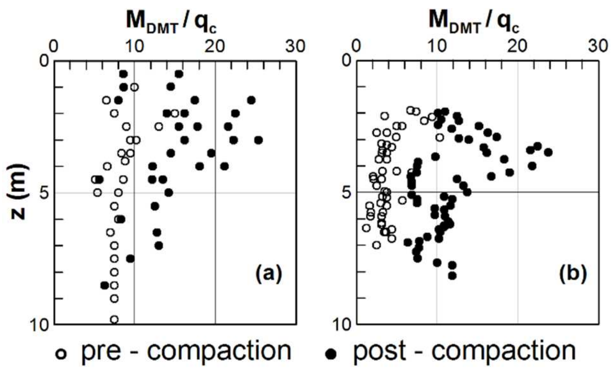


Figure 1 – Ratio M_{DMT}/q_c before/after compaction: (a) Jendeby (1992), (b) Balachowski & Kurek (2015).

In summary, several studies have found M_{DMT} approximately twice more sensitive than q_c to compaction. (Note that the increase in M_{DMT} is primarily due to the increase in K_D, incorporated in the Marchetti 1980 correlation for obtaining the constrained modulus from DMT). The finding that compaction – a sort of "imparted overconsolidation" – increases both M_{DMT} and q_c, but M_{DMT} at a faster rate, suggests that the ratio M_{DMT}/q_c should increase with *OCR*. In order to accumulate additional experience and to reduce the dispersion in the observed M_{DMT}/q_c values, it would be helpful to promote the practice of performing pre- and post- DMTs and CPTs in ground improvement works.

Calibration Chamber (CC) testing

Jamiolkowski & Lo Presti (1998), in CC tests in Ticino sand, observed that K_D from DMT is considerably more sensitive to stress history (including aging) than q_c from CPT.

Lee et al. (2011) presented results from CC research carried out in Korea, aimed at comparing the effects of stress history on CPT and DMT. Forty large specimens of Busan silica sand, having different values of relative density D_r, were preconsolidated to *OCR* in the range 1 to 8. Then half of the specimens were tested by CPT, the other half by DMT. As shown in Fig. 2, *OCR* produced a substantial increase in K_D (≈ 1.30 to 2.50, Fig. 2b), but an almost negligible increase in the normalized cone resistance $q_c/(\sigma'_v)^{0.5}$ (≈ 1.10 to 1.15, Fig. 2a).

It is noted that, while the normalized q_c (Fig. 2a) reflects essentially the relative density D_r (presumably because stress history and structure have been largely obliterated by penetration), K_D (Fig. 2b) reflects not only D_r, but also stress history. The coefficient of determination r^2 close to 1 in Fig. 2a, for data points of all *OCR* values, indicates poor ability of the normalized q_c to distinguish overconsolidated (OC) from normally consolidated (NC) sands. Hence estimating *OCR* from CPT alone appears problematic.

The comparison in Fig. 2 confirms that K_D is considerably more reactive to *OCR* than the normalized q_c. This implies that to the same normalized q_c may correspond different values of K_D, as shown in the schematic example in Fig. 3 (Marchetti 2016). However Fig. 2b shows that a given value of K_D may be due to a low D_r and a high *OCR* or to a high D_r and a low *OCR*. In order to separate the D_r effect from the *OCR* effect, i.e. to pinpoint the right (*OCR*, D_r) pair and therefore to estimate *OCR*, the normalized q_c is also necessary to provide an indication of D_r on the horizontal axis. Hence in order to estimate *OCR* in sand both the normalized q_c and K_D are needed, i.e. CPT alone or DMT alone are insufficient.

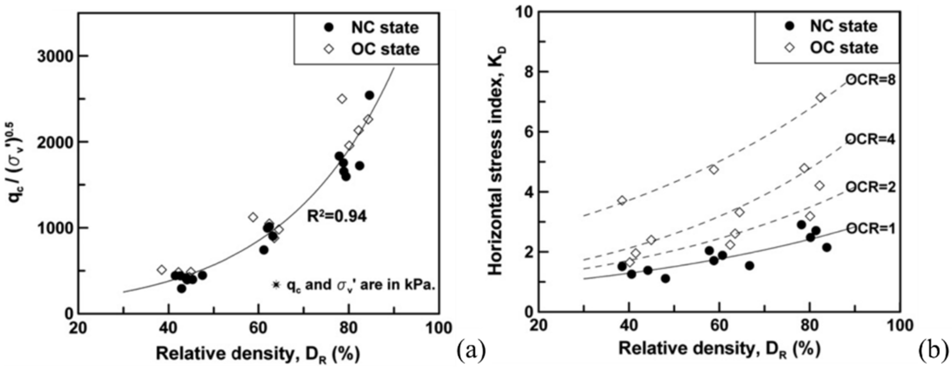


Figure 2 – Effect of stress history on (a) normalized q_c from CPT, and (b) K_D from DMT (Lee et al. 2011).

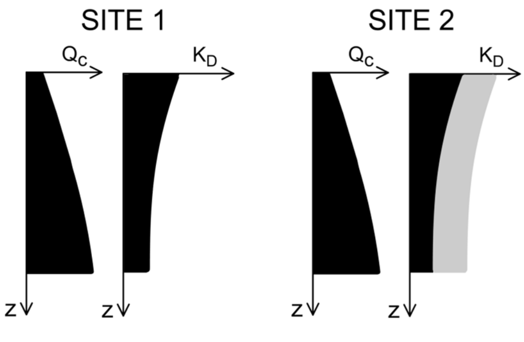


Figure 3 – Schematic profiles of two sites having the same q_c but different K_D (Marchetti 2016).

CORRELATIONS FOR ESTIMATING OCR IN SAND FROM DMT & CPT

Preliminary guidelines

In clays the correlation $OCR = f\,(K_D)$ proposed by Marchetti (1980), confirmed both experimentally and theoretically by subsequent studies, provides generally reasonable estimates of *OCR*. In contrast, in sands K_D alone is insufficient for estimating *OCR* and some additional information is necessary. Correlations for estimating *OCR* from DMT in sands have been attempted by Schmertmann (1983), Marchetti (1985), Mayne et al. (2009). Correlations OCR-K_D in sand have also been established for some sites, but with local applicability.

A way of getting some information on *OCR* in sand is to use the ratio between the constrained modulus M_{DMT} from DMT and the cone penetration resistance q_c from CPT. The basis of the potential use of the ratio M_{DMT}/q_c as a broad indicator of *OCR* in sands descends from the previously recalled experience of field observations before/after compaction of sand fills, where M_{DMT}/q_c was found to increase with the overconsolidation achieved by compaction.

Based on field data before/after compaction reported by Jendeby (1992) (Fig. 1a), similar to data found in many subsequent compaction works, combined with data from calibration chamber testing research (Baldi et al. 1988, 1989) and additional data from instrumented embankments and screw plate tests in sands (Jamiolkowski 1995), the 2001 TC16 DMT Report (Marchetti et al. 2001) proposed the following indicative reference values of the ratio M_{DMT}/q_c:

M_{DMT}/q_c = 5-10 in NC sands (1)
M_{DMT}/q_c = 12-24 in OC sands (2)

The above semi-quantitative guidelines imply that estimating *OCR* in sands requires a multi-parameter/multi-test approach, in that both K_D from DMT and q_c from CPT are needed, i.e. DMT alone or CPT alone are not sufficient.

Correlations *OCR*-M_{DMT}/q_t and *OCR*-K_D in sand (Treporti Test Site)

The possibility to estimate *OCR* in sand by the combined use of DMT and CPTU was investigated by Monaco et al. (2014) as part of an extensive experimental study carried out at the Treporti Test Site (TTS), Venice (Italy). At this site a full-scale cylindrical trial embankment was built and monitored from the beginning of its construction until complete removal, four years later, permitting to calculate *OCR* at each depth (by its simple definition). SDMT and CPTU soundings performed before embankment application and post-removal permitted to analyze how the *OCR* caused by the embankment was reflected by the before-after SDMT and CPTU results.

The Treporti trial embankment, constructed between September 2002 and March 2003, had a cylindrical shape of 40 m diameter, 6.7 m height and applied a uniform pressure of 106 kPa to the ground surface. It was continuously monitored towards pore water pressures, surface settlements, horizontal and vertical displacements with depth (Simonini 2004). Monitoring went on for almost four years after the construction as well as throughout the gradual removal of the embankment (June 2007 to March 2008).

The bank area was extensively investigated by paired CPTU and DMT soundings, also in seismic configuration (SCPTU, SDMT), continuous coring boreholes and high quality laboratory tests. DMT-SDMT and CPTU-SCPTU soundings were executed before starting the construction of the embankment (SI-1), at the end of construction from the top of the embankment (SI-2), and after completing the gradual removal of the embankment (SI-3).

The Venice lagoon soil deposits are highly heterogeneous and characterized by a predominant silt fraction, combined with sand and/or clay, forming a chaotic interbedding of different sediments of similar mineralogy. The upper portion of the TTS deposit consists of a medium-fine silty sand layer (2-8 m of depth), located below a thin soft silty clay layer and followed by a clayey-sandy silt layer (8-20 m). Below 20 m of depth, the soil is mostly composed of alternating layers of clayey and sandy silt. Based on field compression curves inferred from accurate measurements of local vertical strains in the soil at 1-m depth intervals under the bank provided by sliding deformeters (Monaco et al. 2014), the deposit appears nearly NC or slightly OC in the upper ≈ 8 m.

Profiles of *OCR* under the center of the embankment were known (based directly on the definition $OCR = \sigma'_{v\,max} / \sigma'_{v0}$) at two times: (1) at full load, when it was considered $OCR \approx 1$, assuming that at each depth the vertical stress had exceeded the maximum past pressure; (2) after load removal, when the *OCR* was evaluated assuming as $\sigma'_{v\,max}$ the geostatic stress plus the vertical stress increment induced by the uniformly loaded circular area, according to the theory of elasticity.

Monaco et al. (2014) combined parallel DMT and CPTU data to derive a correlation for estimating OCR in the TTS sands from the ratio M_{DMT}/q_t (Fig. 4a):

$$OCR = 0.0344\,(M_{DMT}/q_t)^2 - 0.4174\,(M_{DMT}/q_t) + 2.2914 \qquad (3)$$

Eq. (3) was constructed using same-depth values of M_{DMT} and q_t obtained in sand layers (having material index $I_D > 1.8$) between 2 and 35 m depth. The DMT/CPTU data were those obtained at the times when the reference "imparted OCR" profiles were available, i.e. at end-of-construction (SI-2) and post-removal (SI-3). The data pairs M_{DMT}-q_t were carefully selected to avoid any possible mismatching of data, by retaining only pairs from uniform soil layer of significant thickness. The OCR-M_{DMT}/q_t data points in Fig. 4a are in reasonable agreement either with the TC16 guidelines (Marchetti et al. 2001, Eqns 1 and 2) and the existing experimental base relative to other sands. These trends appear to support each other and may possibly provide broad OCR estimates at different sand sites.

As indicated by previous CC research (Jamiolkowski et al. 1988), the OCR-M_{DMT}/q_t relationship is also dependent, at least moderately, on the relative density D_r and on the stress level, and is possibly influenced by sand type and cementation. The experimental data obtained at the TTS, mostly in medium dense sands ($D_r \approx$ 50 to 80%) and in a

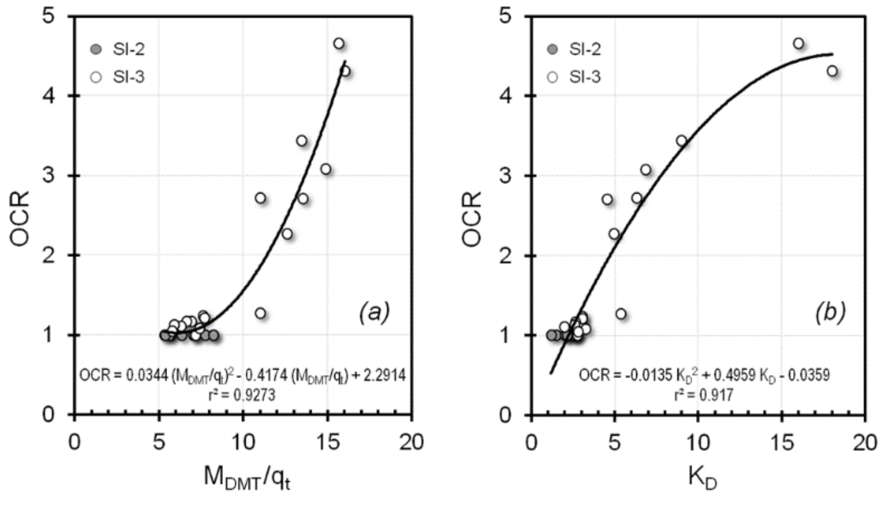


Figure 4 – Correlations OCR-M_{DMT}/q_t (a) and OCR-K_D (b) for sands obtained from DMT-CPTU data at the Treporti trial embakment test site (Monaco et al. 2014)

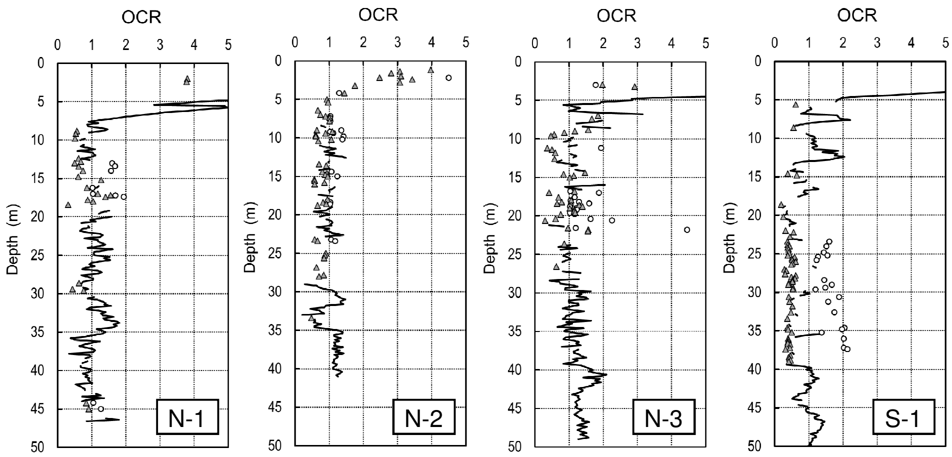
limited range of vertical stress, do not permit to assess definitely the dependency of the OCR-M_{DMT}/q_t relationship on the above parameters. However a relationship based on full-scale testing in situ should represent real-life experimental evidence unsubjected to possible calibration chamber artifacts.

Using the same TTS data set, Monaco et al. (2014) also constructed a correlation OCR-K_D (Fig. 4b), based only on DMT (K_D) and not requiring CPTU data:

$$OCR = -0.0135\,K_D^2 + 0.4959\,K_D - 0.0359 \tag{4}$$

The correlation OCR-K_D (Fig. 4b) turned out to have a coefficient of determination ($r^2 = 0.917$) similar to the OCR-M_{DMT}/q_t correlation in Fig. 4a ($r^2 = 0.927$). However, as observed by Marchetti (2015), the OCR-K_D correlation is not unique, but it depends also on the relative density D_r, as demonstrated by CC research (Lee et al. 2011, Choo et al. 2015). In fact, by examining Fig. 2b, it can be deduced that for a given D_r there is a one-to-one correspondence between K_D and OCR values (i.e. a vertical line having constant D_r in the diagram intersects each OCR curve for a unique K_D value), but if D_r is not constant the same OCR may result from a different combination of K_D and D_r values. Hence the OCR-K_D correlation (Eq. 4) may show a high r^2 value at the site of Treporti, where it was calibrated, because in the Treporti sands D_r is almost uniform, but it could not work at sites where D_r is variable. Therefore the OCR-K_D correlation (Eq. 4) probably only has local validity for the Treporti sand.

Bosco & Monaco (2017) presented an application of the correlations OCR-M_{DMT}/q_t and OCR-K_D derived at the TTS in silty-sandy alluvial deposits along the Tevere river in the outskirts of Rome (Italy). Fig. 5 shows the profiles of OCR estimated using Eqns (3) and (4) in sand layers, identified by $I_D > 1.8$, at four sites (N-1, N-2, N-3, S-1). The ratio M_{DMT}/q_t (Eq. 3) was calculated using same-depth SDMT and SCPTU data from nearby soundings. Since M_{DMT} values are calculated every 0.20 m of depth (spacing of DMT readings), while q_t values are measured every cm of advancing of the piezocone, average values of q_t were calculated over a depth interval of 0.20 m centered on the DMT test data depth. For a proper matching of SDMT and SCPTU data in the sand layers, complicated by the thin interbedding of the deposits, Eq. (3) was applied only where the material index from DMT was $I_D > 1.8$ and at the same time the Soil Behavior Type Index from CPTU (average over 0.20 m) was $I_c < 2.6$. Fig. 5 also shows, for comparison, the OCR profile estimated from DMT in fine-grained layers ($I_D < 1.2$) according to the correlation OCR-K_D proposed by Marchetti (1980), considered generally reliable. Fig. 5 shows that *OCR* estimated from M_{DMT}/q_t (Eq. 3) is generally close to 1 and nearly constant with depth, indicating the NC condition of the deposits, in agreement with the geological history. Higher isolated values of *OCR* sporadically observed (e.g. at ≈ 22 m at site N-3) could derive from a non perfect coupling between sand layers detected by nearby SDMT and SCPTU soundings. The values of *OCR* estimated from K_D (Eq. 4) are generally slightly lower than those estimated from M_{DMT}/q_t (Eq. 2), with a more marked difference at site S-1, even though showing a similar trend. This seems to confirm that the OCR-K_D correlation (Eq. 4), established for the Treporti sand, is not valid for all sands.



○ Eq. (3) OCR = f (M_{DMT}/q_t) △ Eq. (4) OCR = f (K_D) — OCR = f (K_D) silt-clay (Marchetti 1980)

Figure 5 – Estimates of *OCR* in sand layers using the correlations *OCR*-M_{DMT}/q_t (Eq. 3) and *OCR*-K_D (Eq. 4) in alluvial deposits along the Tevere river, Rome (Bosco & Monaco 2017)

Correlations *OCR*-K_D in sand from CC testing

Choo et al. (2015) performed a series of large calibration chamber tests on Busan sand specimens having different D_r and *OCR*. DMT measurements were taken both during loading and unloading. The results indicated that K_D strongly reflects the overconsolidation effect. Given the dependency of K_D on both D_r and *OCR*, also observed by Baldi et al. (1986) in CC testing in Ticino sand, the estimation of D_r is a prerequisite for the evaluation of stress history using K_D.

Based on CC results, Choo et al. (2015) proposed a new correlation to estimate *OCR* in sand as a function of K_D and D_r, with D_r also estimated from DMT, hence using only

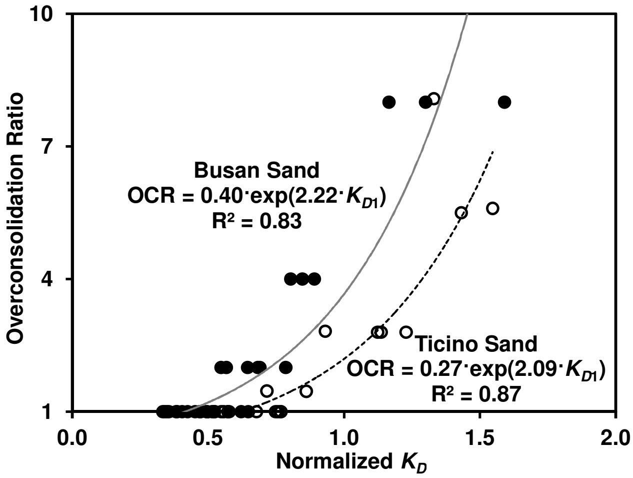


Figure 6 – Relation between normalized K_D and *OCR* for Busan sand and Ticino sand (data from Baldi et al. 1986), with normalized $K_D = K_{D1} = K_D / \exp(2.2 \cdot D_r)$ for both sands (Choo et al. 2015)

DMT results. In order to isolate the effect of D_r on K_D in the OCR-K_D correlation, the relation K_D -D_r is expressed in the form:

$$K_D = A \cdot \exp(B \cdot D_r) \tag{5}$$

where A, B are fitting parameters. The relative density D_r can be estimated from the relation:

$$D_r = C \cdot \ln(E_{D1}) - D \tag{6}$$

where E_{D1} is the normalized dilatometer modulus, defined as $E_{D1} = E_D / (\sigma'_v \cdot \sigma_{atm})^{0.5}$, with σ'_v = effective vertical stress, σ_{atm} = atmospheric pressure (100 kPa), and C, D are fitting parameters. The OCR-K_D correlation was then formulated as:

$$OCR = E \cdot \exp(F \cdot K_{D1}) \tag{7}$$

where $K_{D1} = K_D / \exp(B \cdot D_r)$ is the normalized horizontal stress index and E, F are fitting parameters. Choo et al. (2015) suggest to estimate *OCR* from DMT in sand in two steps: (1) estimate D_r using Eq. (6), (2) estimate *OCR* using Eq. (7).

Fig. 6 (Choo et al. 2015) shows the application of Eq. (7) in two different sands tested in CC, Busan sand and Ticino sand (data from Baldi et al. 1986). Fig. 6 indicates that

Eq. (7) depicts reasonably well the increase in *OCR* with increasing normalized K_D for both sands, however the two sands have different fitting parameters. This suggests that the *OCR*-K_D correlation expressed by Eq. (7) has not general validity and needs to be calibrated for each specific sand.

CONCLUSIONS

Based on the available experience, briefly overviewed in this paper, the currently preferred correlation for estimating *OCR* in sand is the *OCR*-M_{DMT}/q_t correlation (Eq. 3), constructed by Monaco et al. (2014) using end-of-construction and post-removal DMT-CPTU and *OCR* data at the Treporti trial embankment test site. This 2-parameter *OCR*-M_{DMT}/q_t correlation (Eq. 3), based on the combined use of DMT and CPTU, is along the lines of a "multi-parameter/multi-test approach" and appears to have more general validity than the 1-parameter *OCR*-K_D correlation (Eq. 4) derived from the same data set based on DMT only. Similarly, the *OCR*-K_D correlation established by Choo et al. (2015) based on CC testing on Busan sand (Eq. 7) appears not to have general validity and requires specific calibration for different sands. Additional research is encouraged to investigate the dependency of the correlation *OCR*-M_{DMT}/q_t (Eq. 3) on relative density and stress level, and possibly on sand type.

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