Perception of Overconsolidated States of Coarse-Grained Soils using DMT Results

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ABSTRACT: The present investigation characterizes soil properties in overconsolidated state using the results of dilatometer tests, with the ultimate goal of estimating OCR and K_0 of sands. A series of large calibration chamber tests were performed, and P_0 and P_1 pressures were measured during loading and unloading steps. The results demonstrate that, among DMT indices, the horizontal stress index (K_D) strongly reflects the overconsolidation effect of coarse grains; therefore, OCR of sands is expressed as a function of relative density and K_D. Additionally, a relation between K_D / K_0 and E_D / σ'_m is established to estimate K_0 because both parameters have a common factor, which is the state parameter.

1 INTRODUCTION

Since the introduction of the DMT (flat dilatometer test) by Marchetti (1980), it has been widely used by a number of geotechnical engineers due to its simplicity, repeatability, and operator insensitivity (Campanella and Robertson 1991). Being different from other penetration-type in-situ soil testing methods such as CPT (cone penetration test) and SPT (standard penetration test), DMT measures the pressures at specific horizontal displacements, including: P_0 (lift-off at $\delta = 0$) and P_1 ($\delta = 1.1$ mm deflection). This led to the opinion that DMT results are quite suitable for the evaluation of compressibility or modulus of soils (Konrad 1988).

Soils in the overconsolidated state are very common in nature due to a number of overconsolidation-inducing mechanisms, including change in vertical stress, fluctuation of groundwater levels, desiccation, freeze-thaw, and chemical effects (Chen and Mayne 1994; Choo and Burns 2014; Jamiolkowski et al. 1985; Mitchell and Soga 2005). Overconsolidated soils show distinctive behavior (i.e., reduced compressibility and increased strength) when compared to those of normally consolidated soils. Most notably, previous studies (Clayton et al. 1985; Yoshimi et al. 1975) showed that the compressibility is the most sensitive to the stress history. Consequently, the DMT may be the ideal test to evaluate the stress history of soils because its results highly reflect the compressibility of soils. Soils in the overconsolidated state have a memory of the maximum past stress (preconsolidation stress, σ'_p), which can be considered as a yield point in the mechanical behavior of soils. Therefore, the estimation of overconsolidation ratio (OCR = σ'_p / σ'_v where σ'_v = vertical effective stress) is an important task in many geotechnical projects.

The permanent fabric change and the lateral stress locking during unloading cause the distinctive behavior of soils in overconsolidated state (Choo et al. 2015; Choo and Burns 2014; Fam and Santamarina 1997). However, as the penetration of in-situ testing devices into the soil deposits induces a considerable disturbance of soil fabric, the effect of

permanent fabric change becomes less significant when evaluating the stress history by using in-situ soil testing methods (Clayton et al. 1985; Lee et al. 2011). Therefore, the increase in horizontal stress due to the lateral stress locking is considered as the main cause of preloading effect of soils when evaluating soil properties with in-situ testing methods. Additionally, the horizontal stress is an important input parameter for the design of geo-structures. However, a direct estimation of horizontal stress is not easy because it needs special testing equipment. Consequently, the coefficient of lateral earth pressure at rest (K_0), which is the ratio of horizontal to vertical effective stresses (σ'_h / σ'_v), can be an alternative for the evaluation of horizontal effective stress (Ku and Mayne 2013). This resulted in the development of many empirical and theoretical K_0 estimating formulas.

This study aims at investigating the possibility of perceiving the stress history of coarse-grained soil by using DMT results. A series of large calibration chamber specimens were fabricated to have different relative densities and states of stress, and DMTs (dilatometer tests) were conducted under loading and unloading steps of specimens. The sensitivity of dilatometer indices to OCR is observed, and the relations between the stress history and dilatometer indices are developed. In addition, new methods are suggested to quantify OCR and K_0 by employing only DMT results.

Table 1. K_0 and OCR Formulas for Sand from DMT

Type	Equations
1. K_0 Baldi et al. (1986)	$K_0 = C_0 + C_1 \cdot K_D - C_2 \cdot \dfrac{q_c}{\sigma'_v}$
2. K_0 Jamiolkowski and Robertson (1988)	$\dfrac{K_D}{K_0} = C_3 \cdot \left(\dfrac{q_c - \sigma_m}{\sigma'_m} \right)^{C_4}$
3. K_0 Jamiolkowski et al. (1988)	$\dfrac{K_D}{K_0} = C_5 \cdot \exp(-C_6 \cdot \psi)$
4. OCR Marchetti et al. (2001)	$M_{DMT} / q_c = 5 \sim 10$ (NC) $M_{DMT} / q_c = 12 \sim 24$ (OC)
5. OCR Monaco et al. (2014)	$OCR = C_7 \cdot \left(\dfrac{M_{DMT}}{q_t} \right)^2 + C_8 \cdot \left(\dfrac{M_{DMT}}{q_t} \right) + C_9$
6. OCR Monaco et al. (2014)	$OCR = C_{10} \cdot K_D^{\ 2} + C_{11} \cdot K_D + C_{12}$

Notes: K_0 = coefficient of lateral stress at rest; OCR = overconsolidation ratio; C_x = fitting parameter; K_D = horizontal stress index; q_c = cone tip resistance; ψ = state parameter; M_{DMT} = dilatometer constrained modulus.

2 ESTIMATION OF K_0 AND OCR IN SAND USING DMT

While many theoretical and empirical formulas for estimating K_0 or OCR in clays have been developed by numerous researchers using DMT results, studies on sands based on DMT are very limited. Table 1 summarizes the existing K_0 and OCR estimating formulas for sands based on DMT indices. It is notable that most previous equations (Cases 1 ~ 5 in Table 1) need not only DMT results but also the results of other tests such as CPT or triaxial test. Therefore, without performing multiple tests, equations in Table 1 may not be applicable in practice. Though Case 6 in Table 1 expresses OCR as a sole function of K_D, it lacks in the consideration of the effect of relative density on K_D because K_D of sands is significantly affected by relative density (Jamiolkowski et al. 2003; Reyna and Chameau 1991).

3 EXPERIMENTAL PROGRAMS

3.1 Materials

Busan sand, which is a natural sand obtained from the South Sea of Korea, was used in this study. The basic material properties are shown in Table 2. The specific gravity of the soils was determined according to ASTM D854; extreme void ratios were determined according to ASTM D4253 and ASTM D4254; and grain size distribution was determined according to ASTM D422. In addition, the shape of particles is sub-angular to angular according to the method of Wadell (1935). The sand particles are mainly composed of silicon dioxide (76.1%) and aluminum oxide (8.3%) with other trace materials such as potassium oxide and calcium oxide (15.6%).

3.2 Calibration chamber tests

DMTs in this study were performed in large sand specimens that were fabricated in a calibration chamber by using a raining method. A schematic drawing of calibration chamber system at Korea University, which has a dimension of 100 cm in height and 120 cm in diameter, is shown in Fig. 1.

Table 2. Material Properties of Busan Sand

G_s	D_{50}	C_u	C_c	e_{max}	e_{min}
2.62	0.32	2.35	0.71	1.06	0.66

Notes: G_s = specific gravity; D_{50} = median grain size (mm); C_u = uniformity coefficient; C_c = coefficient of curvature; e_{max} = maximum void ratio; e_{min} = minimum void ratio.
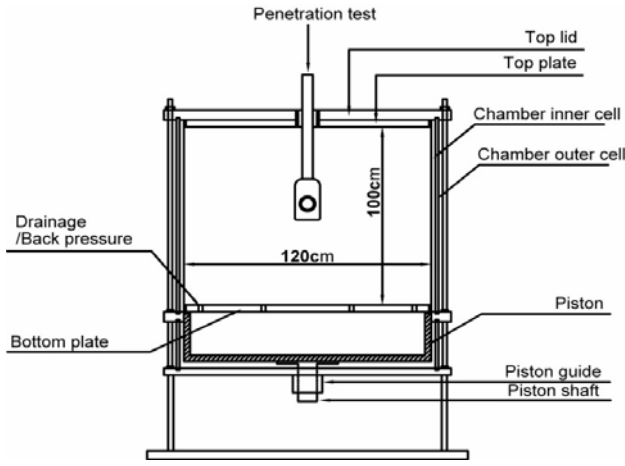
Fig. 1. Test setup for dilatometer tests in the calibration chamber.

Due to the difficulty in sampling of undisturbed sand specimens, correlations between geotechnical properties and in-situ testing indices have been generally developed based on results of calibration chamber tests. Homogeneous sand specimens with initial relative densities of 30, 50, and 70% were prepared in a chamber by employing a modified rainer system (Choi et al. 2010).

A standard dilatometer was penetrated into the prepared sand specimens at the recommended rate of 2 cm/s. To minimize the boundary effects, DMTs were conducted every 10 cm at depths of 30 ~ 70 cm and test results from upper and lower 30 cm were discarded. The confinement of specimens was controlled to maintain K_0 condition (boundary condition BC1: constant vertical and horizontal stresses) at vertical stresses ranging from 50 to 400 kPa. Consequently, prepared samples have a maximum OCR of 8.

4 TEST RESULTS

The measured P_0 and P_1 values increase with increases in both relative density and applied stress (Fig. 2). With an increase in vertical stress and the corresponding increase in horizontal stress (K_0 stress state), the pressure required for the lift-off (P_0) or 1.1 mm deflection (P_1) of thin stainless steel membrane is expected to increase due to the increased frictional resistance at interparticle contacts. Additionally, with an increase in relative density, deformability of soil specimen would be decreased due to the increased coordination number, which in turn leads to the increased P_0 and P_1 pressures. Most notably, it can be observed that P_0 and P_1 pressures during unloading stage are larger than those during loading stage due to the locked-in horizontal stress induced by the preloading.
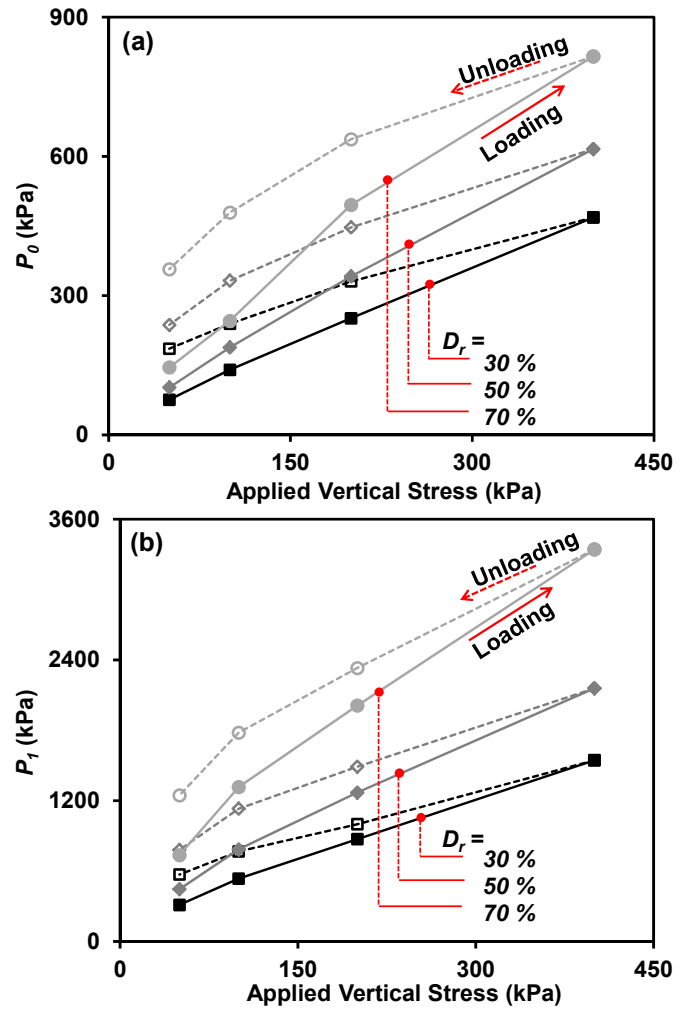

Fig. 2. Variation of P_0 and P_1 as a function of applied vertical stress and relative density: (a) P_0 pressure; (b) P_1 pressure.

Fig. 2 also demonstrates that the results of DMT are affected by OCR. Therefore, to quantify the effect of OCR on DMT indices, their ratios are defined as follows:

$$\frac{K_D}{K_{D(NC)}} = \frac{(P_{0(OC)} - u_0)/\sigma'_v}{(P_{0(NC)} - u_0)/\sigma'_v} = \frac{P_{0(OC)} - u_0}{P_{0(NC)} - u_0} \quad (1)$$

$$\frac{E_D}{E_{D(NC)}} = \frac{34.7(P_{1(OC)} - P_{0(OC)})}{34.7(P_{1(NC)} - P_{0(NC)})} = \frac{P_{1(OC)} - P_{0(OC)}}{P_{1(NC)} - P_{0(NC)}} \quad (2)$$

$$\frac{I_D}{I_{D(NC)}} = \frac{P_{1(OC)} - P_{0(OC)}}{P_{1(NC)} - P_{0(NC)}} \cdot \frac{P_{0(NC)} - u_0}{P_{0(OC)} - u_0} = \frac{E_D}{E_{D(NC)}} \cdot \frac{K_{D(NC)}}{K_D} \quad (3)$$

where, K_D = horizontal stress index; E_D = dilatometer modulus; I_D = material index; OC = overconsolidated state; NC = normally consolidated state. It is indicated in Fig. 3 that, among DMT indices, the K_D is most significantly affected by OCR. It is also observed that both K_D ratio and E_D ratio increase with an increase in OCR while I_D ratio decreases with OCR because I_D ratio is equivalent to E_D ratio / K_D ratio (Eq. (3)).
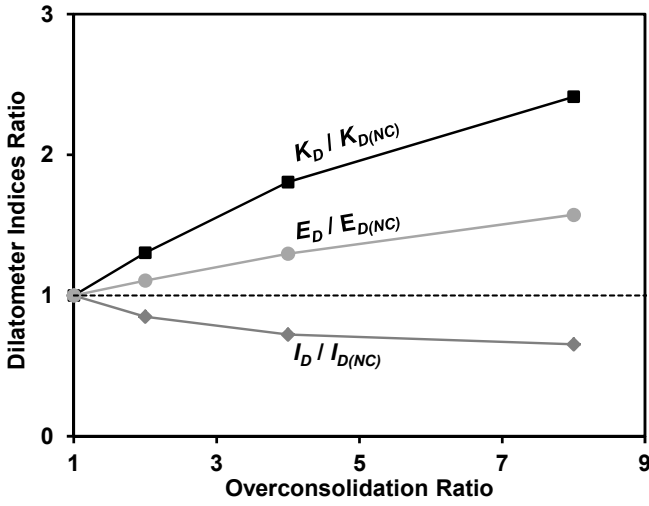
Fig. 3. The variation of dilatometer indices ratios according to OCR. Note, dilatometer indices ratio = index during unloading / index during loading.
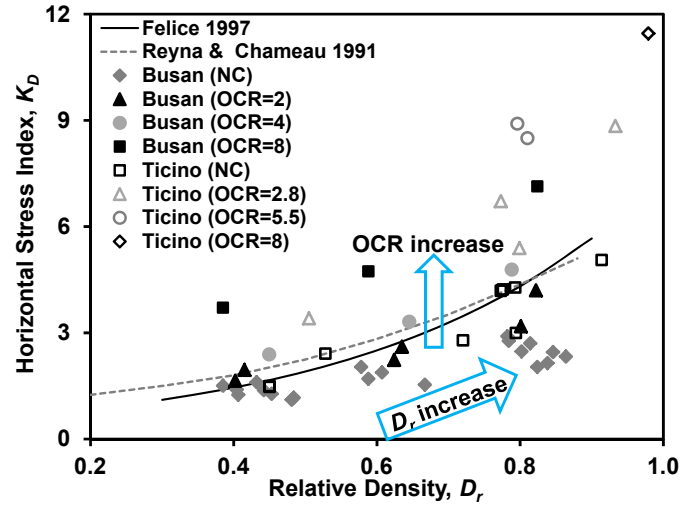

Fig. 4. Variation of horizontal stress index as a function of relative density (D_r) and overconsolidation ratio (OCR): data of Ticino sand = Baldi et al. (1986). Note that two trendlines from previous studies are included above to show the dependency of K_D on D_r.

5 ANALYSIS AND DISCUSSION

5.1 *Estimation of OCR in sand*

Comparing with other DMT indices (Fig. 3), K_D increases remarkably with an increase in overconsolidation ratio due to the increased horizontal stress (lateral stress locking). Additionally, previous studies (Jamiolkowski et al. 2003; Reyna and Chameau 1991) showed that K_D is exponentially proportional to the relative density (D_r) as:

$$K_D = A \cdot \exp(B \cdot D_r) \qquad (4)$$

where, A and B = fitting parameters. Fig. 4 shows the dependency of K_D on relative density and OCR for various coarse-grained soils. It can be observed that K_D exponentially increases with an increase in relative density. Additionally, at a given relative density, K_D increases with an increase in OCR. Consequently, the estimation of relative density is a prerequisite for the evaluation of stress history using K_D because both OCR and D_r affect K_D.

Recalling Fig. 2, both P_0 and P_1 pressures may be expressed as a power function of applied stress; thus, dilatometer modulus ($E_D = 34.7(P_1 - P_0)$) is expected to be the power function of applied stress as well. Additionally, E_D increases with an increase in relative density due to the increased resistance to volume change. Consequently, the following empirical formula for the estimation of D_r can be suggested:

$$D_r = C \cdot \ln(E_{D1}) - D \qquad (5)$$

where, C and D = fitting parameters; E_{D1} = normalized dilatometer modulus, which is defined as $E_{D1} = E_D / (\sigma'_v \cdot \sigma_{atm})^{0.5}$, where σ'_v = vertical effective stress; σ_{atm} = atmospheric pressure (100 kPa).
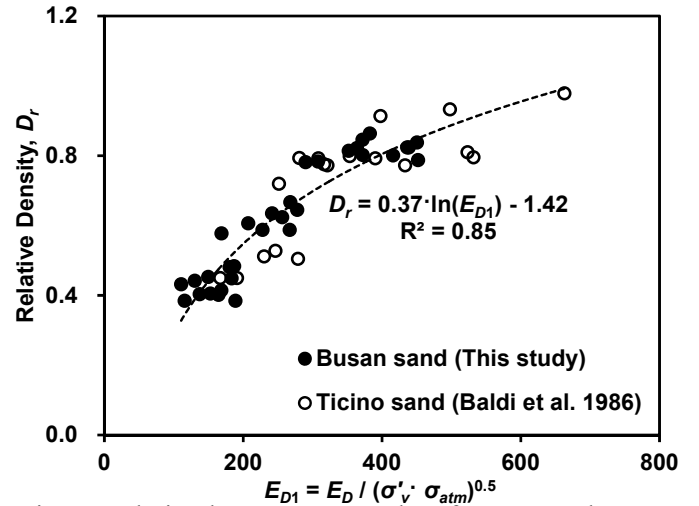

Fig. 5. Relation between E_{D1} and D_r for two sands. Note data points include both NC and OC results; trendline is based on data of two sands.

It is notable that Eq. (5) is similar to the previous D_r estimating formulas based on the cone tip resistance (Baldi et al. 1986; Jamiolkowski et al. 2003). With an increase in normalized dilatometer modulus, the estimated relative density increases (Fig. 5 and Eq. 5). Most notably, it can be observed in Fig. 5 that the plot between relative density and normalized dilatometer modulus is quite similar for two different sands (Busan sand and Ticino sand), therefore, their relations can be expressed as an identical function. In addition, it is expected that Eq. (5) may yield a reliable estimation of D_r regardless of stress states because Fig. 5 is for both NC and OC data and E_D is normalized with vertical effective stress.

Because K_D is affected by both OCR and D_r as mentioned earlier, the effect of D_r on K_D should be isolated in order to estimate OCR with K_D.

Therefore, for the inclusion of the effect of overconsolidation ratio on the K_D estimating formula with the exclusion of the effect of relative density on K_D, the following empirical relation is made under the assumption that K_D is exponentially proportional to OCR:

$$OCR = E \cdot \exp(F \cdot K_{D1}) \qquad (6)$$

where, E and F = fitting parameters; K_{D1} = normalized horizontal stress index, which is defined as $K_{D1} = K_D / \exp(B \cdot D_r)$ (Eq. 4).

Fig. 6 clearly demonstrates that OCR increases with an increase in normalized K_D for Busan and Ticino sands. Therefore, a reasonable estimation of OCR in sands can be made with Eq. (6) though two different sands have different fitting parameters in Eq. (6). Summing up, OCR of sands can be estimated in the following two steps: 1) relative density of sands can be estimated by employing normalized dilatometer modulus (Eq. 5); 2) over-consolidation ratio of sands can be appraised by using normalized horizontal stress index (Eq. 6).

5.2 Estimation of K_0 in sand

Recalling Case 3 in Table 1, the ratio of K_D to K_0 can be a function of state parameter (ψ). Note the state parameter was defined as a difference in void ratio between current and steady states at the same mean effective stress (Been and Jefferies 1985). As shown in Fig. 7a, the $K_D/K_0 - \psi$ relation is unique regardless of the stress history. Therefore, K_0 of sands can be estimated with the information of state parameter; however, this method may not be practically preferred since it needs a series of triaxial test results.
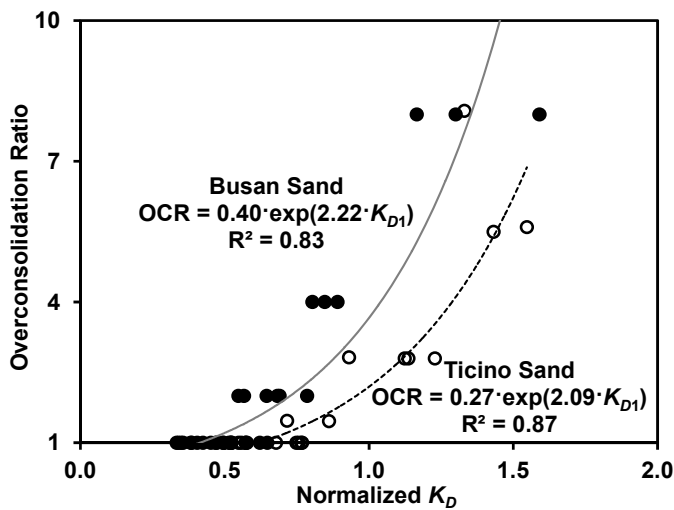
Konrad (1988) showed that the difference in P_I and P_0 pressures normalized by mean effective stress, $(P_I - P_0)/\sigma'_m$, is a function of state parameter. It is, therefore, expected that E_D/σ'_m is the function of state parameter as well (Fig. 7b). Consequently, it can be postulated that the state parameter may act as a medium for connecting between K_D/K_0 and E_D/σ'_m because both K_D/K_0 and E_D/σ'_m are functions of state parameter:

$$\frac{K_D}{K_0} = G \cdot \left(\frac{E_D}{\sigma'_m} \right)^H \qquad (7)$$

where G and H = fitting parameters; σ'_m = mean effective stress ($\sigma'_m = (\sigma'_v + 2K_0 \cdot \sigma'_v)/3$). To check the validity of Eq. (7), the relationships between K_D/K_0 and E_D/σ'_m of two sands (Busan and Ticino) are investigated. Fig. 8 reveals good correlations between those two although fitting parameters (G and H) in Eq. (7) of two sands are different.

Fig. 6. Relation between normalized K_D and OCR for two sands. Note normalized parameter $\bar{K}_D = K_{D1} = K_D / \exp(2.2 \cdot D_r)$ for both sands.
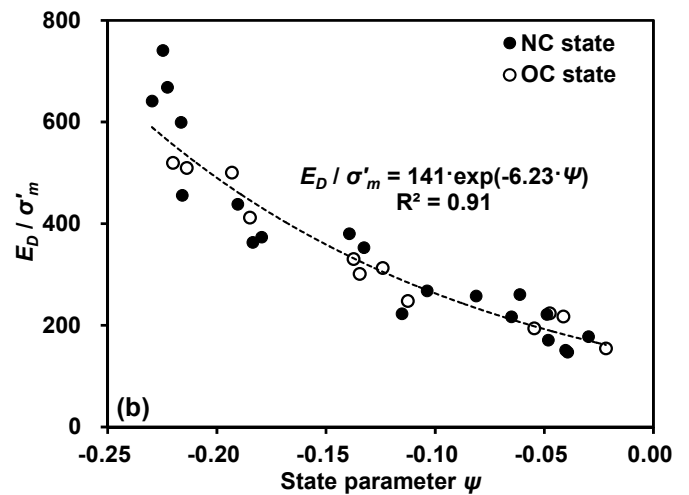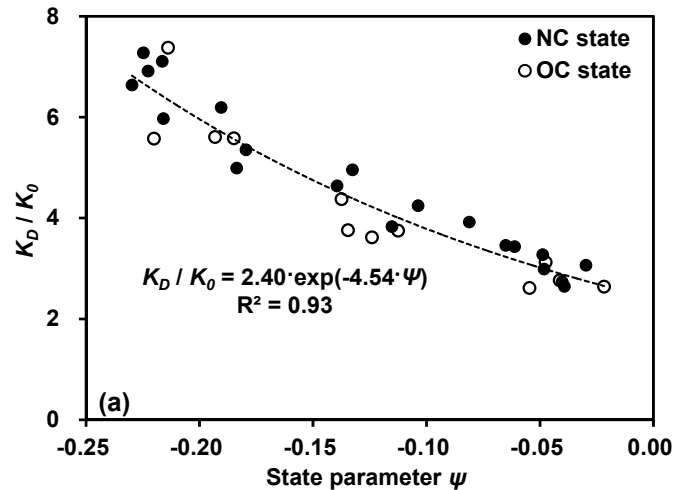

Fig. 7. Relation between dilatometer indices and state parameter for Busan Sand: (a) relation of K_D / K_0 with state parameter; (b) relation of E_D / σ'_m with state parameter. Note trendline includes both NC and OC results.
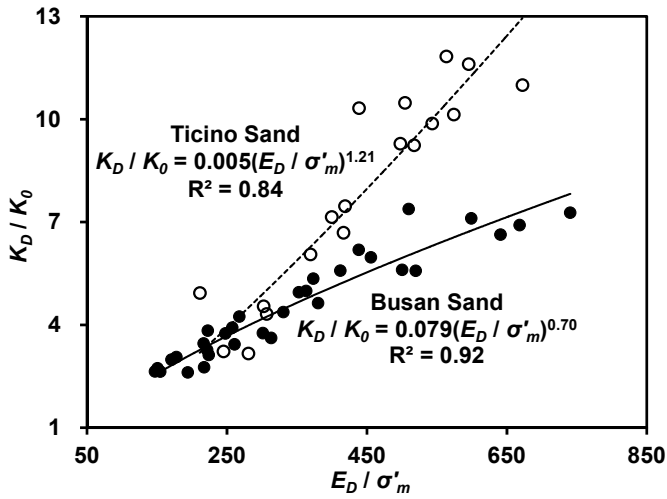
Fig. 8. Relation between K_D / K_0 and E_D / σ'_m. Note equation of trendline indicates Eq. (7), and data points include both NC and OC results.

The use of Eq. (7) needs an iteration process because mean effective stress (σ'_m) is a function of K_0. Therefore, additional effort is directed to replacing σ'_m in Eq. (7) with σ'_v (vertical effective stress). Because K_0 is closely related to OCR, the following approximation may be possible based on Eq. (7):

$$\frac{K_D}{K_0} = G \cdot \left(\frac{3E_D}{(1 + 2K_0) \cdot \sigma'_v} \right)^H \approx G' \cdot \left(\frac{E_D}{\sigma'_v} \right)^{H'} \cdot OCR^I \quad (8)$$

Note that the iteration process is not required in Eq. (8). Because OCR of sands can be estimated from Eq. (6), Eq. (8) may be more practically applicable than Eq. (7). Regression analysis reveals that OCR exponents I in Eq. (8) for two different sands show similar number as -0.25; therefore, the relation between $K_D/K_0/OCR^{-0.25}$ and E_D/σ'_v is plotted (Fig. 9).
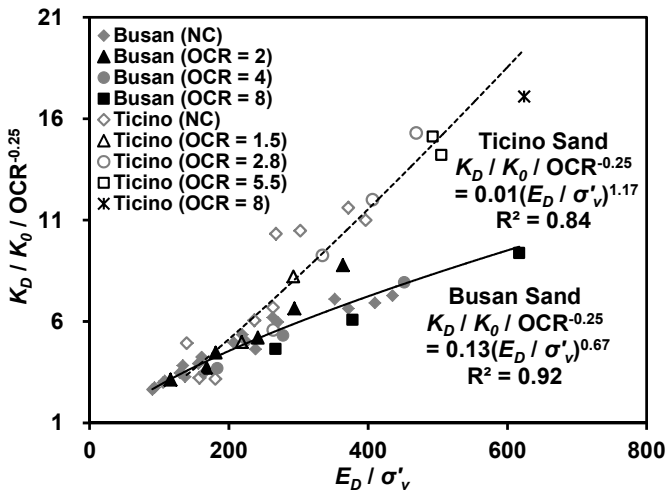

Fig. 9. Relation between K_D / K_0 and E_D / σ'_v. Note equations of trendline indicate Eq. (8) with I = -0.25 for both Ticino and Busan sands.

As shown in Fig. 9, good correlations between two parameters can be obtained, regardless of stress state or overconsolidation ratio. Summing up, the value of K_0 for sands can be estimated by either of two methods: 1) a relation between K_D / K_0 and E_D / σ'_m can be established using Eq. (7); 2) OCR value can be estimated with Eq. (5), and the K_0 of sands can be directly appraised by Eq. (8).

5.3 *Suggestion of simple design charts*

The estimation of OCR and K_0 of sands using the suggested equations in this study may not be easy to follow in practice because of many unknown fitting parameters in Eqs. (6) and (8). Therefore, based on Fig. 6 and 10, the simple design charts to evaluate OCR and K_0 of Busan sand are developed as shown in Fig. 10. Note that the suggested charts in Fig. 10 are only for Busan sand because Busan and Ticino sands show different fitting parameters in Eqs. (6) and (8). Additionally, it is notable that Fig. 10a, the chart for estimating OCR of sands with the information of K_D and E_{D1}, is very similar to Fig. 4 because E_{D1} captures D_r of sands (Fig. 5).
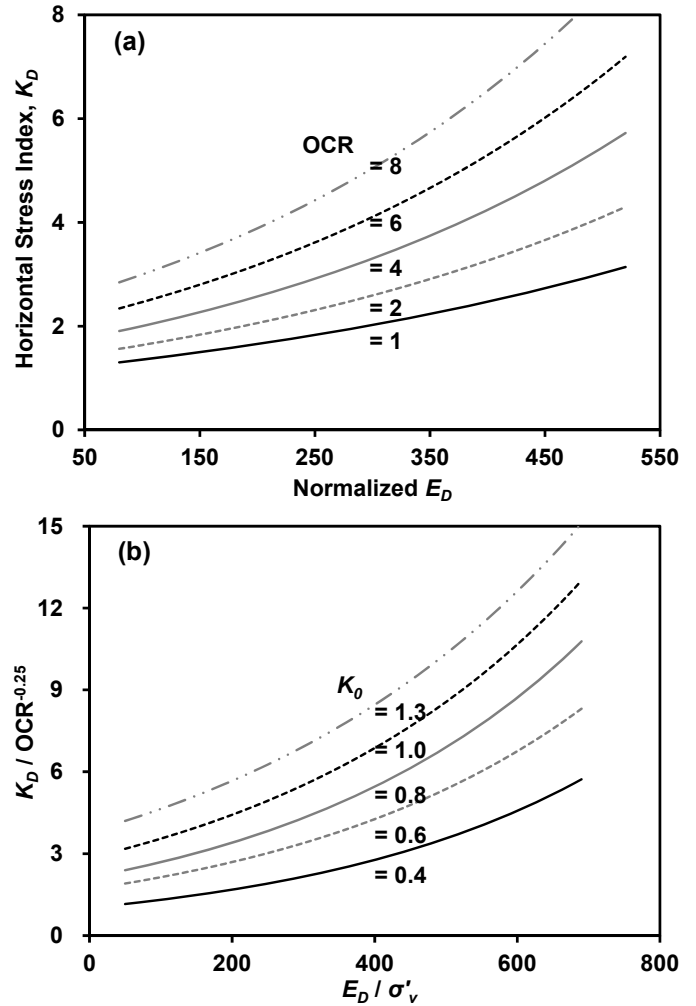

Fig. 10. Chart for estimating OCR and K_0 of sands using DMT results: (a) OCR estimation; (b) K_0 estimation.

Fig. 10b is the chart for estimating K_0 of sands with the information of K_D, OCR, E_D, and σ'_v. Because OCR of sands can be predicted using Fig. 10a, Fig. 10 clearly demonstrates that OCR or K_0 of sands can be quantified by employing only DMT results.

6 CONCLUSIONS

A series of dilatometer tests were performed in a large calibration chamber in order to investigate the soil properties in an overconsolidated state. Specifically, this study focuses on the estimation of OCR and K_0 of sands using the results of dilatometer tests alone. The following key observations are made through this study:

1. The measured P_0 and P_1 pressures increase with an increase in both relative density and applied stress level, reflecting a decreased deformability of soils with an increase in relative density and applied stress. Additionally, the measured P_0 and P_1 pressures during unloading are greater than those during loading due to the locked-in horizontal stress reflecting an effect of overconsolidation.

2. The ratios of dilatometer indices (index during unloading / index during loading) are plotted as a function of OCR. The results indicate that K_D ratio is the most sensitive to the variations of OCR; therefore, K_D is employed as a primary factor estimating OCR of sands.

3. The empirical OCR estimating formula (OCR = $C \cdot \exp(D \cdot K_{D1})$) is expressed as the function of relative density-normalized K_D ($K_{D1} = K_D / \exp(B \cdot D_r)$) to minimize the effect of D_r on K_D. In addition, because the estimation of relative density is a prerequisite for calculating normalized K_D, the D_r estimating formula ($D_r = E \cdot \ln(E_D / (\sigma'_v \cdot \sigma_{atm})^{0.5}) - F$) is empirically suggested.

4. Because both K_D / K_0 and E_D / σ'_m are functions of state parameter, it is assumed that state parameter acts as a medium for connecting between K_D / K_0 and E_D / σ'_m leading to the development of the empirical formula ($K_D / K_0 = G \cdot (E_D / \sigma'_m)^H$) for the estimation of K_0. Additionally, another K_0 estimating empirical formula ($K_D / K_0 = G' \cdot (E_D / \sigma'_v)^{H'} \cdot OCR^I$) is suggested in this study.

7 ACKNOWLEDGEMENT

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