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

Hyunwook Choo
*Korea University, Seoul, South Korea. E-mail:choohw@gmail.com*

Woojin Lee
*Korea University, Seoul, South Korea. E-mail:woojin@korea.ac.kr*

Changho Lee
*Chonnam National University, Yeosu, South Korea. E-mail:changho@jnu.ac.kr*

Young-Sang Kim
*Chonnam National University, Yeosu, South Korea. E-mail:geoyskim@chonnam.ac.kr*

Moon-Joo Lee
*Hanwha Engineering and Construction, Seoul, South Korea. E-mail: moonjoo@hanwha.com*

*Keywords:* overconsolidation ratio, coefficient of lateral stress, relative density, DMT indices

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 $E_D$ / $\sigma'_m$ 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, $\sigma'_p$), which can be considered as a yield point in the mechanical behavior of soils. Therefore, the estimation of overconsolidation ratio (OCR = $\sigma'_p$ / $\sigma'_v$ where $\sigma'_v$ = 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 ($\sigma'_h$ / $\sigma'_v$), 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) | $K_0 = C_0 + C_1 \cdot K_D - C_2 \cdot \frac{q_c}{\sigma'_v}$ |
| 2. $K_0$ Jamiolkowski and Robertson (1988) | $\frac{K_D}{K_0} = C_3 \cdot \left(\frac{q_c - \sigma_m}{\sigma'_m}\right)^{C_4}$ |
| 3. $K_0$ Jamiolkowski et al. (1988) | $\frac{K_D}{K_0} = C_5 \cdot \exp(-C_6 \cdot \psi)$ |
| 4. OCR Marchetti et al. (2001) | $M_{DMT} / q_c = 5 \sim 10$ (NC)<br>$M_{DMT} / q_c = 12 \sim 24$ (OC) |
| 5. OCR Monaco et al. (2014) | $OCR = C_7 \cdot \left(\frac{M_{DMT}}{q_t}\right)^2 + C_8 \cdot \left(\frac{M_{DMT}}{q_t}\right) + C_9$ |
| 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; $\psi$ = 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.

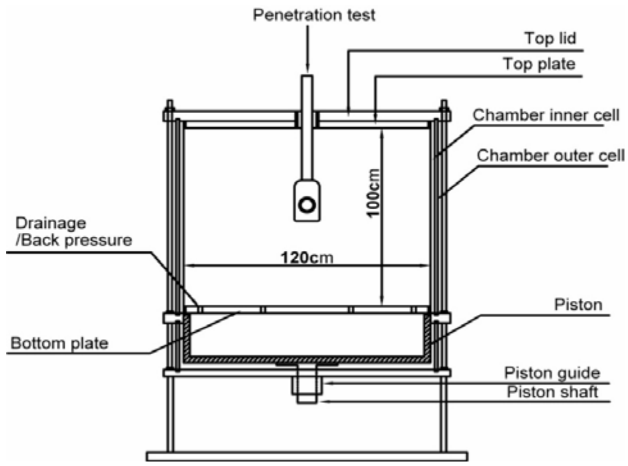


Fig. 1. Test setup for dilatometer tests in the calibration chamber.

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.

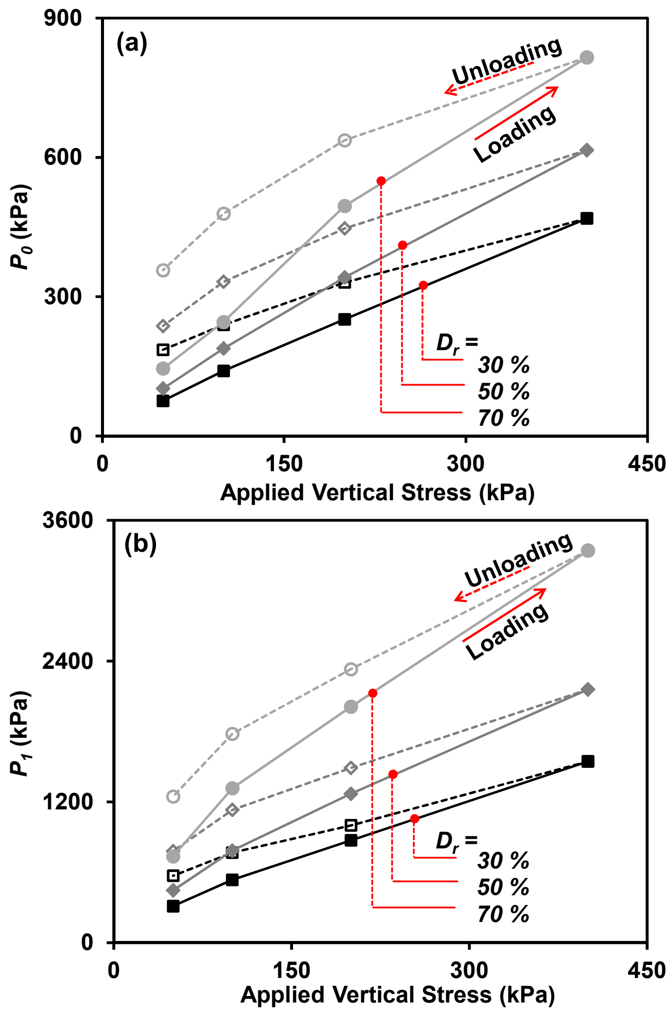


Fig. 2. Variation of $P_0$ and $P_1$ as a function of applied vertical stress and relative density: (a) $P_0$ pressure; (b) $P_1$ pressure.

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:

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

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

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

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)).

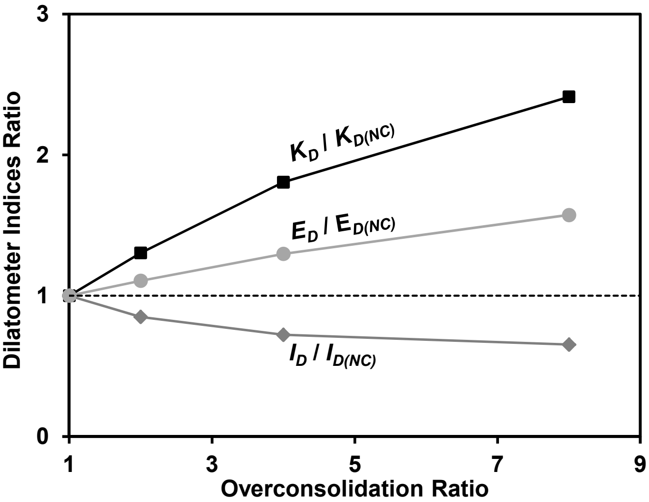


Fig. 3. The variation of dilatometer indices ratios according to OCR. Note, dilatometer indices ratio = index during unloading / index during loading.

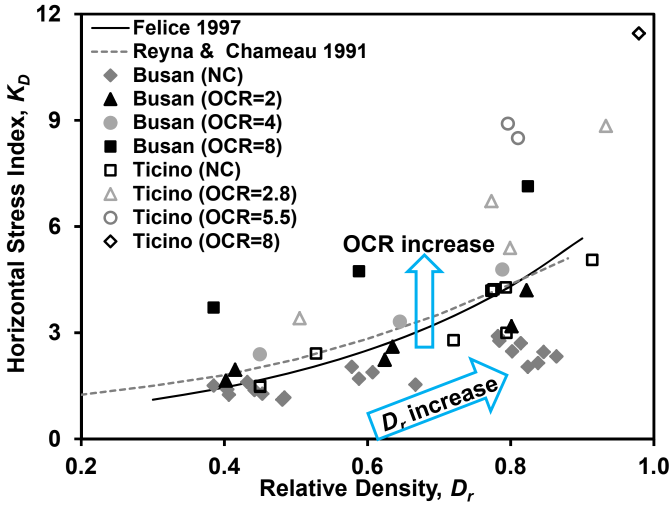


Fig. 4. Variation of horizontal stress index as a function of relative density ($D_r$) and overconsolidation ratio (OCR): data of Ticino sand = Baldi et al. (1986). Note that two trendlines from previous studies are included above to show the dependency of $K_D$ on $D_r$.

# 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:

$$K_D = A \cdot \exp(B \cdot D_r) \tag{4}$$

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:

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

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 $\sigma'_v$ = vertical effective stress; $\sigma_{atm}$ = atmospheric pressure (100 kPa).

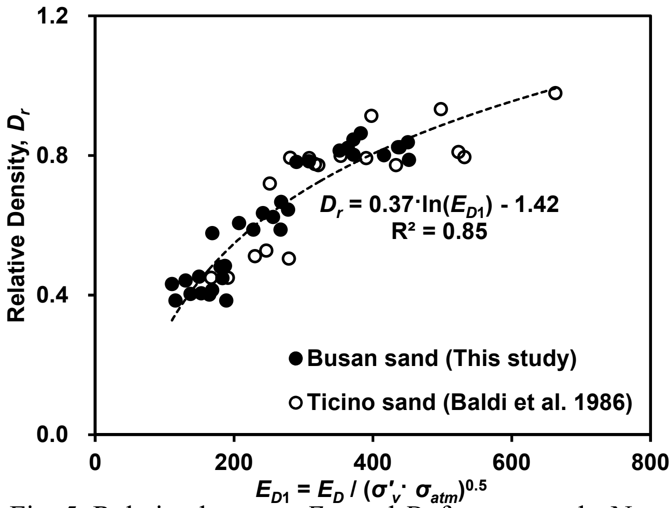


Fig. 5. Relation between $E_{D1}$ and $D_r$ for two sands. Note data points include both NC and OC results; trendline is based on data of two sands.

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:

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

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 ($\psi$). 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.

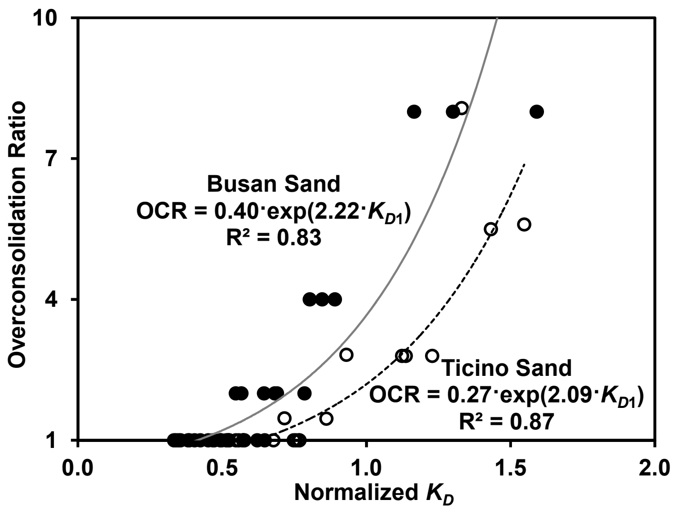


Fig. 6. Relation between normalized $K_D$ and OCR for two sands. Note normalized parameter $K_D = K_{D1} = K_D / \exp(2.2 \cdot D_r)$ for both sands.

Konrad (1988) showed that the difference in $P_1$ and $P_0$ pressures normalized by mean effective stress, $(P_1 - P_0)/\sigma'_m$, is a function of state parameter. It is, therefore, expected that $E_D/\sigma'_m$ 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 $E_D/\sigma'_m$ because both $K_D/K_0$ and $E_D/\sigma'_m$ are functions of state parameter:

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

where $G$ and $H$ = fitting parameters; $\sigma'_m$ = 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 $E_D/\sigma'_m$ 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.

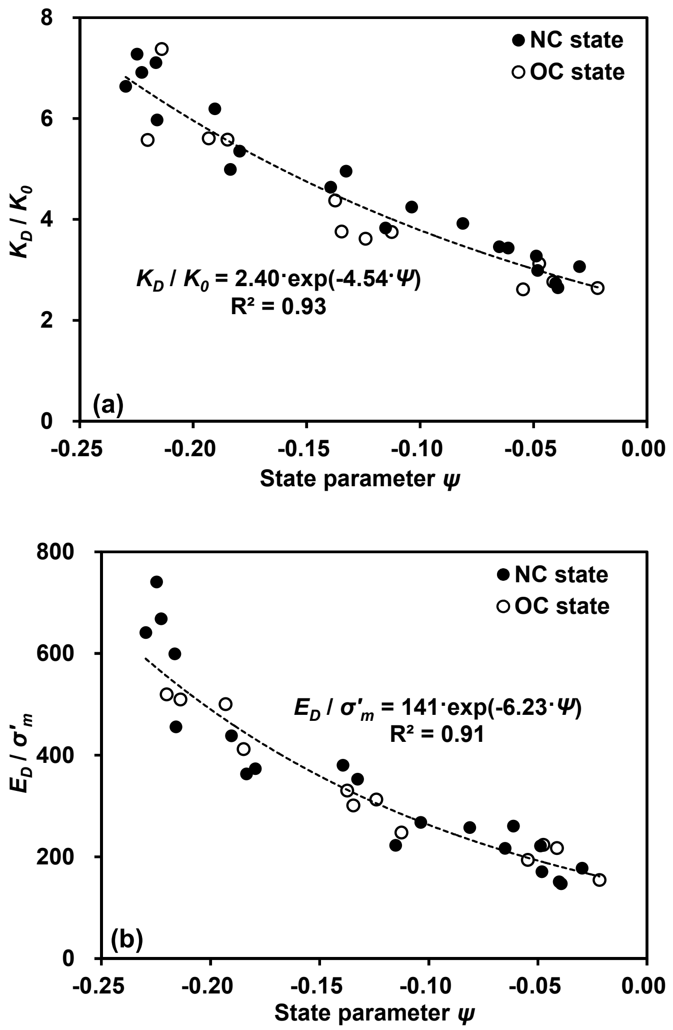


Fig. 7. Relation between dilatometer indices and state parameter for Busan Sand: (a) relation of $K_D / K_0$ with state parameter; (b) relation of $E_D / \sigma'_m$ with state parameter. Note trendline includes both NC and OC results.

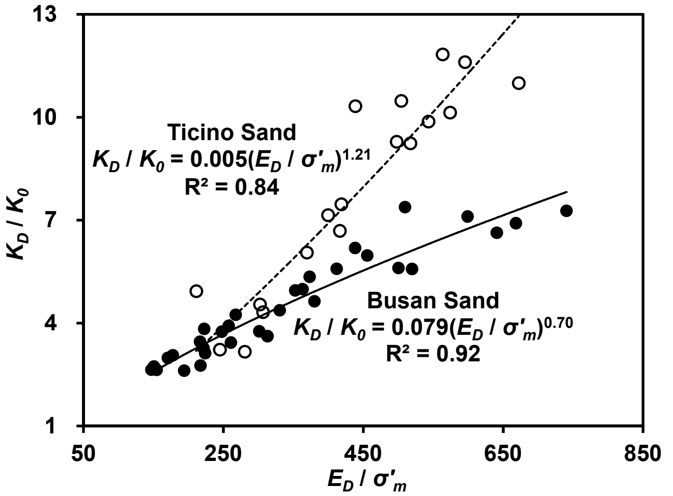


Fig. 8. Relation between $K_D$ / $K_0$ and $E_D$ / $\sigma'_m$. Note equation of trendline indicates Eq. (7), and data points include both NC and OC results.

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

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

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 $K_D/K_0/\mathrm{OCR}^{-0.25}$ and $E_D/\sigma'_v$ is plotted (Fig. 9).

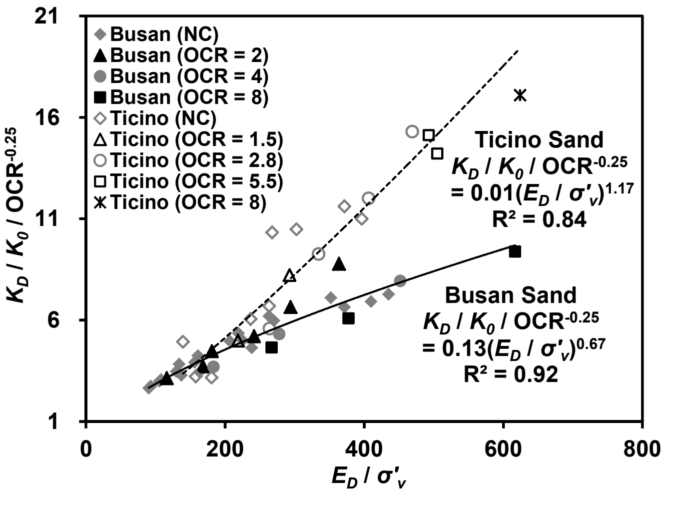


Fig. 9. Relation between $K_D$ / $K_0$ and $E_D$ / $\sigma'_v$. Note equations of trendline indicate Eq. (8) with $I$ = -0.25 for both Ticino and Busan sands.

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 $E_D$ / $\sigma'_m$ 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).

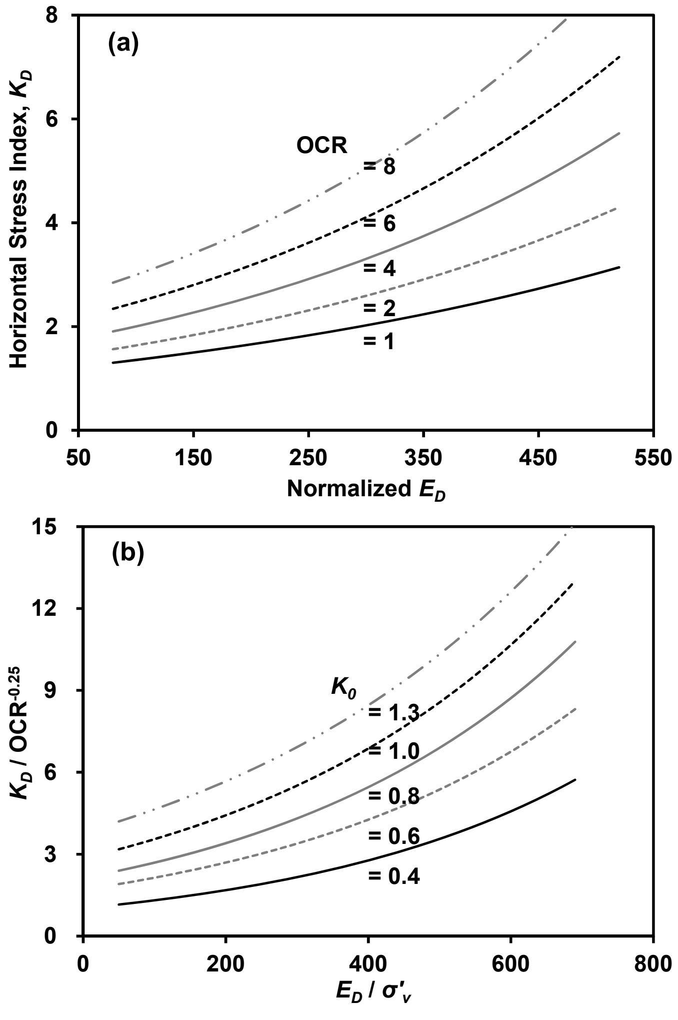


Fig. 10. Chart for estimating OCR and $K_0$ of sands using DMT results: (a) OCR estimation; (b) $K_0$ estimation.

Fig. 10b is the chart for estimating $K_0$ of sands with the information of $K_D$, OCR, $E_D$, and $\sigma'_v$. 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 $E_D / \sigma'_m$ are functions of state parameter, it is assumed that state parameter acts as a medium for connecting between $K_D / K_0$ and $E_D / \sigma'_m$ 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 ($K_D / K_0 = G' \cdot (E_D / \sigma'_v)^{H'} \cdot \mathrm{OCR}^I$) is suggested in this study.

## 7 ACKNOWLEDGEMENT

This research was supported by a grant (14-RDRP-B076564-01) from Regional Development Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

## 8 REFERENCES


Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., Marchetti, S., and Pasqualini, E. "Flat dilatometer tests in calibration chambers." *Proc., Use of In Situ Tests in Geotechnical Engineering (GSP 6)*, ASCE, 431-446.

Been, K., and Jefferies, M. G. (1985). "A State Parameter for Sands." *Geotechnique*, 35(2), 99-112.

Campanella, R. G., and Robertson, P. K. (1991). "Use and Interpretation of a Research Dilatometer." *Canadian Geotechnical Journal*, 28(1), 113-126.

Chen, B. S., and Mayne, P. W. (1994). "Profiling the Overconsolidation Ratio of Clay by Piezocone Tests." *Georgia Tech Research Corporation and Georgia Institute of Technology*.

Choi, S. K., Lee, M. J., Choo, H., Tumay, M. T., and Lee, W. (2010). "Preparation of a Large Size Granular Specimen Using a Rainer System with a Porous Plate." *Geotechnical Testing Journal*, 33(1), 45-54.

Choo, H., Bate, B., and Burns, S. E. (2015). "Effects of organic matter on stiffness of overconsolidated state and anisotropy of engineered organoclays at small strain." *Engineering Geology*, 184, 19-28.

Choo, H., and Burns, S. E. (2014). "Effect of overconsolidation ratio on dynamic properties of binary mixtures of silica particles." *Soil Dynamics and Earthquake Engineering*, 60, 44-50.

Clayton, C. R. I., Hababa, M. B., and Simons, N. E. (1985). "Dynamic Penetration Resistance and the Prediction of the Compressibility of a Fine-Grained Sand - a Laboratory Study." *Geotechnique*, 35(1), 19-31.

Fam, M., and Santamarina, J. C. (1997). "A study of consolidation using mechanical and electromagnetic waves." *Geotechnique*, 47(2), 203-219.

Jamiolkowski, M., Ghionna, V. N., and Lancellotta, R. "New Correlations of Penetration Tests for Design Practice." *Penetration Testing 1988*, Vol. 1 (ISOPT), Balkema, Rotterdam, 263-296.

Jamiolkowski, M., Ladd, C. C., Germaine, J. T., and Lancellotta, R. "New Developments in Filed and Laboratory Testing of Soils." *11th International Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, San Francisco, 57-153.

Jamiolkowski, M., Lo Presti, D., and Manassero, M. "Evaluation of Relative Density and Shear Strength of Sands from CPT and DMT." *Proc., Soil Behavior and Soft Ground Construction (GSP 11)*, ASCE, 201-238.

Jamiolkowski, M., and Robertson, P. K. "Future trends for penetration testing (Closing address)." *Proc., Penetration testing in the UK*, Institution of Civil Engineers, London, 321-342.

Konrad, J. M. (1988). "Interpretation of Flat-Plate Dilatometer Tests in Sands in Terms of the State Parameter." *Geotechnique*, 38(2), 263-277.

Ku, T., and Mayne, P. W. (2013). "Evaluating the In Situ Lateral Stress Coefficient (K-0) of Soils via Paired Shear Wave Velocity Modes." *Journal of Geotechnical and Geoenvironmental Engineering*, 139(5), 775-787.

Lee, M. J., Choi, S. K., Kim, M. T., and Lee, W. (2011). "Effect of stress history on CPT and DMT results in sand." *Engineering Geology*, 117(3-4), 259-265.

Marchetti, S. (1980). "Insitu Tests by Flat Dilatometer." *Journal of the Geotechnical Engineering Division*, ASCE, 106(3), 299-321.

Marchetti, S., Monaco, P., Totani, G., and Calabrese, M. (2001). "The flat dilatometer test (DMT) in soil investigations." *ISSMGE Committee TC16*.

Mitchell, J. K., and Soga, K. (2005). Fundamentals of Soil Behavior, *John Wiley & Sons*, New York.

Monaco, P., Amoroso, S., Marchetti, S., Marchetti, D., Totani, G., Cola, S., and Simonini, P. (2014). "Overconsolidation and Stiffness of Venice Lagoon Sands and Silts from SDMT and CPTU." *Journal of Geotechnical and Geoenvironmental Engineering*, 140(1), 215-227.

Reyna, F., and Chameau, J. L. "Dilatometer based liquefaction potential of sites in the Imperial Valley." *Proc., 2nd Int. Conf. on Recent Advances in Geot. Earthquake Engrg. and Soil Dyn.*, Vol. 1, St. Louis, 385-392.

Wadell, H. (1935). "Volume, shape, and roundness of quartz particles." *Journal of Geology*, 43(3), 250-280.

Yoshimi, Y., Kuwabara, F., and Tokimatsu, K. (1975). "One-dimensional volume change characteristics of sands under very low confining stresses." *Soils and Foundations*, 15(3), 51-60.