Effect of stress history on CPT and DMT results in sand

Moon-Joo Lee, Sung-Kun Choi, Min-Tae Kim, Woojin Lee

Abstract

In order to investigate the effect of stress history on in-situ test results in granular sediments, a series of CPTs and DMTs are performed on Busan sand prepared in the calibration chamber. $K_0$ is found to be the most sensitive to the stress history among CPT and DMT measurements. $E_d$ and $q_c$ are observed to be similarly affected by the stress history and, therefore, the $E_d$–$q_c$ relation appears to be almost independent of the stress history. The $K_0$–$q_c$ relation established without considering the stress history is likely to overestimate the relative density of OC sand. It is shown that the existence of the pre-stress of the granular sediment can be indirectly recognized by an estimation of the relative density larger than 100% when using the $K_0$–$q_c$ relation suggested for NC sand. Although $q_c$/$q_{c}^{'prime}$–$K_0$/0 and $E_d$/$v_0$–$K_0$/0 relations are heavily influenced by the stress history, $q_c$/$q_{c}^{'prime}$–$K_0$/0 and $E_d$/$v_0$–$K_0$/0 relations are observed to be independent of the stress history. Based on these relations, charts to evaluate the $K_0$ value from $q_c$ and/or DMT indices are developed for both NC and OC sands. The design chart based on $E_d$/$v_0$–$K_0$/0 and $E_d$/$v_0$–$K_0$/0 relations is expected to be practically useful as the usage of this chart requires only DMT indices. The developed design charts are applicable to Busan sand but different sets of equations and charts may be developed for other sands.

Keywords: Stress history Horizontal stress index Dilatometer modulus Cone resistance $K_0$ estimation

1. Introduction

In-situ sediments inevitably experience the change of stress by natural or sometimes artificial process; this is called stress history effect. If the present effective overburden pressure of soil is equal to the past maximum pressure, this soil is considered to be in the normally consolidated (NC) state. If the soil has experienced the larger overburden pressure than the present one, this soil is considered over-consolidated (OC). The ratio of the maximum overburden pressure in the past ($\sigma_{0m}$) and the present vertical effective pressure ($\sigma_{v0}^{'prime}$) is the over-consolidation ratio (OCR), which characterizes the stress history effect. The in-situ test is a practical method for the indirect prediction of soil properties and is an essential site exploration tool for granular sediments due to the difficulty of sampling of undisturbed granular soils. Although the relative density and current stress level are the most influential factors on in-situ test results, the stress history also plays an important, albeit secondary, role because the deformation modulus of the granular deposit is considerably affected by the stress history (Lambrechts and Leonards, 1978; Clayton et al., 1985).

The influence of stress history on the behavior of a cohesionless soil is issued due to the plastic strain hardening and the increase in horizontal stress (Jamiolkowski et al., 1988). As the former effect disappears due to a large strain within the surrounding soil during the penetration of in-situ probes, the major effect of the stress history on in-situ test results is due to the increase in the horizontal stress level (Clayton et al., 1985; Jamiolkowski et al., 1988). Yoshimi et al. (1975), Lambrechts and Leonards (1978) and Clayton et al. (1985) observed that the modulus of the pre-stressed sand is significantly larger than that of the normally consolidated sand while the penetration resistance of the pre-stress sand is only 10–15% larger than that of NC sand. Marchetti (1980) and Jamiolkowski et al. (1988) found that the profile of the horizontal stress index ($K_0$) is similar in trend to the profile of OCR. Marchetti (1982) and Jamiolkowski and Lo Presti (1988) showed that $K_0$ is more sensitive to the stress history than the penetration resistance. The $K_0$ value of granular soil that is an indicative property of the stress history has been evaluated from the cone resistance and/or $K_0$ (Marchetti, 1985; Baldi et al., 1986a; Jamiolkowski et al., 1988; Mayne, 1995). Nevertheless, the effect of the pre-stress on penetration test results has not been fully understood.

The purpose of this study is to investigate the effect of the stress history on the in-situ test results and their relations to geotechnical properties. A series of cone penetration tests (CPTs) and dilatometer tests (DMTs) are performed on NC and OC granular specimens prepared in the calibration chamber using an improved rainer system. Also, charts are developed to evaluate the $K_0$ value for both NC and OC granular soils from CPT and/or DMT results.
2. Experimental program

2.1. Material

Busan sand, which is a natural sand obtained in the South Sea of Korea, was used in this study. The particle size distribution and basic properties of Busan sand are presented in Fig. 1 and Table 1. This sand is poorly graded and is classified as SP by the Unified Soil Classification System, and SiO₂ is identified as a dominant particle mineral of this sand. The mean particle size (D₅₀) of sand is 0.32 mm and the roundness is angular to sub-angular. Also, the maximum and minimum void ratios are determined as 1.063 and 0.658, respectively.

2.2. Penetration tests in calibration chamber

Many empirical correlations between soil properties and in-situ test indices have been developed from the test results in the calibration chamber. The calibration chamber system used in this study consists of a 1.0 m high chamber cell with a diameter of 1.2 m, as illustrated in Fig. 2. The hydraulic pressures in the inner and outer chamber cells control the horizontal boundary or stress condition of the specimen. The vertical stress is applied by a piston assembly located below the specimen.

Homogeneous sand specimens were fabricated in the chamber using a rainer system, which consists of a 1.0 m high split mold, a sand storage, and a diffuser system. During pluviation, a constant drop height was maintained using four strings connecting the diffuser system to a cover plate on sands in the sand storage. Details of the specimen preparation are given in Choi et al. (2010). After pluviating the sands, the chamber system was assembled and then de-aired water was filled into the inner and outer cell spaces of the calibration chamber. Chionna and Jamiolkowski (1992) suggested four boundary conditions of the calibration chamber, as shown in Table 2. In this study, the vertical stress and corresponding Kᵥ horizontal stress were applied to the specimen under the boundary condition 1. At each relative density, four levels of vertical stress (50, 100, 200, and 400 kPa) were applied for NC specimens. By unloading the vertical stress to 50–200 kPa after loading it up to 200–400 kPa, specimens were prepared to have OCRs of 2, 4 and 8. Table 3 shows the conditions of specimens prepared.

Cone penetrometer is an electronic steel probe which is penetrated into the ground for collecting continuous data such as cone tip resistance (qₜ), sleeve friction (fₛ), and pore-water pressure (u) of in-situ sediment. Acquired data can be used to evaluate the sub-surface stratigraphy, soil types, water table, and geotechnical properties of the ground. Cone penetration tests (CPTs) were carried out on granular specimens in the calibration chamber through one of the adaptors located on the top plate. A reference cone, which has a 10 cm² cross-sectional area and a 150 cm² sleeve area, was penetrated up to 80 cm depth with a penetration rate of 2 cm/s. As the cone resistance became almost constant at a depth greater than 30 cm depth, an average qₜ value at 30–70 cm depth was regarded as a representative value. Because the cone resistance difference between the chamber and in-situ was affected by the ratio of chamber to cone diameter (diameter ratio). Among four boundary conditions, BC 1 and BC 3 are the most frequently used in the calibration chamber. BC 1 causes a lower cone resistance of the chamber specimen than the in-situ value, whereas BC 3 induces the higher cone resistance than the field. The measured cone resistance was corrected using chamber size standardization factors suggested by Been et al. (1986).

The dilatometer introduced by Marchetti (1980) is a 14 mm thick, 95 mm wide and 230 mm long flat plate with a 20° apex. A flexible stainless steel membrane of 60 mm diameter is located on one face of the blade. In this study, a DMT blade was penetrated with a penetration rate of 2 cm/s and DMTs were performed every 10 cm at 30–70 cm depth. The A and B pressures were measured at 0.05 and 1 mm membrane expansions, respectively, and were corrected for the membrane stiffness and gauge offset. Then, P₀ and P₁ pressures, which are a lift-off pressure and a 1.1 mm expansion pressure, respectively, were obtained from the corrected A and B pressures. For the specimens of various relative densities and OCRs, the horizontal stress index, Kᵥ = (P₀ – u₀)/αᵥ₀, and the dilatometer modulus, E₀ = 34.7(P₁ – P₀), were determined. Here, u₀ is the hydrostatic water pressure and αᵥ₀ is the in-situ vertical effective stress. The constrained modulus, Mᵥ₀, was also evaluated by applying the correction factor Rᵥ to E₀ as suggested by Marchetti (1980). Since DMT induces a smaller disturbance than CPT,

Table 1

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<th>Dₙ₀</th>
<th>Cu</th>
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<th>εₘₐₓ</th>
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Table 2

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<td>4</td>
<td>–</td>
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Fig. 1. Particle size distribution of Busan sand.

Fig. 2. Schematic view of the calibration chamber system for penetration tests.
the size effect of DMT in the 1.2 m diameter calibration chamber can be negligible (Balachowski, 2006).

3. Analysis and discussion

3.1. Sensitivity of in-situ measurements to stress history

Fig. 3 shows the variation of dilatometer indices (ED and KD), constrained modulus (MD), and cone resistance (qc) with vertical effective stresses for three relative densities of Busan sand. As shown in Fig. 3(a), the KD value of NC sand remains essentially constant regardless of the vertical effective stress while the KD value of OC sand increases significantly as OCR increases. This is due to the residual horizontal stress remaining in OC specimens after unloading from the pre-stress of 400 kPa to the current vertical effective stress level. It is noted that the pre-stress of the granular specimen (OCR = 2–8) causes about 1.3–2.5 times larger KD value, compared with that of NC soil, at the same vertical stress and relative density. Fig. 3(b) shows that the ED value of NC sand increases as the vertical effective stress increases. Although the ED value of OC sand decreases as the vertical effective stress decreases, its value is observed to be 1.1–1.6 times larger than that of NC sand at the same vertical stress and relative density. The pre-stress appears to be more influential to KD than ED because the P₀ pressure is more sensitive to the stress level and pre-stress than the P₁ pressure.

It is known that the stress history significantly affects the deformation modulus of granular soil (Yoshimi et al., 1975; Lambrechts and Leonards, 1978; Clayton et al., 1985). In Fig. 3(c), the MD of NC Busan sand increases as the vertical effective stress increases. As OCR increases, the MD of OC sand increases slightly at low relative density while it decreases slightly at higher density. It is also shown that the pre-stress of sand causes about 1.3–3.0 times increase in the MD value at the same vertical stress and relative density. Fig. 3(d) presents the variation of the cone resistance of Busan sand with the vertical effective stress level. It can be observed that the trends of ED and qc variations with respect to the effective stress and OCR are quite similar. It is therefore concluded that KD is considerably more sensitive to the stress history than ED and qc, both of which show a similar sensitivity to the stress history. Consequently, the interpretation of KD is helpful for understanding the stress history of granular soil (Marchetti, 1980; Jamiolkowski et al., 1988).

3.2. Effect of stress history on qc and ED

Since the penetration resistance mainly depends on the density and stress level, previous studies of Schmertmann (1976), Baldi et al.
focused on the development of the \( q_c - D_R - \sigma'_v \) relation for granular soils. It is shown in Fig. 4(a) that the normalized cone resistance with respect to the current effective stress level increases exponentially as the relative density increases and the stress history has an insignificant effect on the \( q_c - D_R - \sigma'_v \) relation. It is suggested by Baldi et al. (1986a) that the magnitude of horizontal stress increment caused by the insertion of an in-situ device is dependent on the relative density of granular soils. Therefore, for a given soil, the difference in the horizontal stress before and after the DMT penetration depends on the density and current confining stress (Jamiolkowski and Robertson, 1988). Konrad (1988) suggested that the additional pressure \( \Delta P = P_1 - P_0 \) in DMT depends on both the state parameter, which is the difference between the void ratio of the current state and that of a steady (or critical) state at the same mean effective stress (Been and Jefferies, 1985), and the average stress state. Therefore, it is possible to express the \( E_D - D_R - \sigma'_v \) relation in Fig. 4(a), the normalized \( E_D \) of Busan sand also increases exponentially with the increase in \( D_R \), and the stress history shows only a slight influence on the \( E_D - D_R - \sigma'_v \) relation.

As shown in Fig. 4, the values of normalized \( q_c \) and \( E_D \) of OC sand are slightly larger than those of NC sand at the same relative density. This is due to the residual horizontal stress caused by the pre-stress. Jeffries et al. (1987) and Houlsby and Hitchman (1988) also showed that the cone resistance of sand is significantly influenced by the horizontal stress as well as the vertical stress. It is also shown in Fig. 5 that a linear \( E_D - q_c \) relation is adoptable for Busan sand, regardless of stress history. This means that not only state variables, such as relative density or current stress, but also the pre-stress has a similar effect on \( q_c \) and \( E_D \). It is also observed that the \( E_D - q_c \) relation of Busan sand is slightly deviated from that suggested by Campanella and Robertson (1991).

### 3.3. Effect of stress history on \( K_D \)

For cohesive soils, the OCR value is related to \( K_D \) as a form of OCR = \( \alpha (K_D)^{\beta} \) (Marchetti, 1980; Finno, 1993; Kamei and Iwasaki, 1995; Yu, 2004). Because the previously suggested \( K_D - OCR \) relations remarkably resemble each other, the OCR values of clay soils can be predicted successfully using only \( K_D \). However, the direct correlation between \( K_D \) and OCR for sands has not been proposed.

Marchetti (1982) and Reyna and Chameau (1991) suggested the relationships between \( K_D \) and \( D_R \) for NC sands from several sources. Fig. 6 presents the \( K_D - D_R \) relations for NC and OC Busan sands. It is observed that the \( K_D \) of sand increases as the relative density increases and the pre-stress induces a larger \( K_D \) value at the same relative density. Although the \( K_D - D_R \) relation of NC Busan sand locates slightly below the relations suggested by Marchetti (1982) and Reyna and Chameau (1991), the trend of the \( K_D - D_R \) relation is found to be similar for all three. However, even at the NC state, the \( K_D - D_R \) relation is very crude due to the lack of consideration to the current stress level. It is noted from Fig. 6 that the \( K_D \) value of granular soil is significantly affected by the pre-stress as well as the relative density. Therefore, the \( K_D - D_R \) relation established without considering the pre-stress effect is likely to overestimate the relative density of OC sand. This is because the pre-stress causes little change in the relative density of sand although the increase in the horizontal stress level due to the pre-stress induces the significant increase in the horizontal stress index.
Fig. 7 shows the effect of the pre-stress on the \(q_c/\sigma_v'–K_D\) relation. As distinct from Campanella and Robertson (1991) and Robertson (2009), who suggested a linear \(q_c/\sigma_v'–K_D\) relation, the \(q_c/\sigma_v'\) value of Busan sand is observed to increase exponentially with the increase in \(K_D\) at the same OCR. It is also shown that the \(q_c/\sigma_v'–K_D\) relation moves to the right side as OCR increases. This may be due to \(K_D\) being more sensitive than \(q_c\) to the pre-stress. Baldi et al. (1986a) established a \(K_D–q_c\) relation for evaluating \(K_0\), based on the DMT and CPT results on Ticino and Hokksund sands in a calibration chamber. Bellotti et al. (1994) suggested that the relation of Baldi et al. (1986a) offers an acceptable agreement between the measured and estimated \(K_0\) values of NC Toyoura sand while it provides \(42–52\%\) smaller values than the measured \(K_0\) of OC Toyoura sand with OCR = 7.0–7.3. It can therefore be concluded that the \(K_0–q_c\) relation of granular soil is heavily dependent on the stress history since \(K_0\) and \(q_c\) are affected differently by the stress history.

For NC sand, both \(q_c\) and \(K_D\) can be expressed as a function of the relative density and vertical effective stress (Jamiolkowski et al., 2003). In Fig. 8, the CPT and DMT results for OC Busan sand are plotted in the charts of \(q_c–\sigma_v'–D_R\) and \(K_D–\sigma_v'–D_R\) relations suggested for NC Busan sand. As shown in Fig. 8(a), the relative density of OC Busan sand is overestimated by about 5–10% points and the existence of pre-stress is not easily noticed. It is, however, observed in Fig. 8(b) that, when using the \(K_D–\sigma_v'–D_R\) relation suggested for NC sand, the relative density of OC Busan sand is significantly overestimated by about 15–55% points and some of the estimated relative densities of OC sand exceed 100%. The estimation of a relative density larger than 100% using the \(K_D–\sigma_v'–D_R\) relation of NC sand is believed to indirectly indicate the existence of pre-stress. Therefore, it seems to be possible to recognize the existence of the pre-stress of granular sediment by using the \(K_D–\sigma_v'–D_R\) relation.

3.4. Estimation of \(K_0\) of cohesionless soils using in-situ tests

As the unloading from the pre-stress results in a larger horizontal stress than that under the NC state, the pre-stress effect is reflected in the at-rest coefficient of earth pressure, \(K_0\), which is the ratio of horizontal and vertical effective stresses (\(\sigma_h' / \sigma_v'\)). Jamiolkowski et al. (1988) observed that the relation between \(K_0/K_D\) and the state parameter (\(\psi\)) is not affected by the stress history. This is because \(K_0/K_D\) is less sensitive to the stress history than \(K_0\). Since the state parameter describes well the behavior of granular soil at critical state, which is not influenced by the stress history, the state parameter is
less affected by the stress history. However, as the determination of the state parameter for the given sand is not easy, it is useful to correlate $K_0$ with some other measurements of in-situ tests.

Fig. 9(a) is the $q_c/\sigma_{v}'-K_0/K_0$ relation of Busan sand. It can be observed that the $q_c/\sigma_{v}'$ of NC Busan sand is quite well correlated with $K_0/K_0$, but the $q_c/\sigma_{v}'-K_0/K_0$ relation is significantly affected by the pre-stress. At the same $K_0/K_0$ value, the $q_c/\sigma_{v}'$ value is observed to increase as OCR increases. To minimize the effect of pre-stress on the $q_c/\sigma_{v}'-K_0/K_0$ relation in Fig. 9(a), $q_c$ is normalized by mean effective stress, instead of vertical effective stress. As shown in Fig. 9(b), the $q_c/\sigma_{m}'-K_0/K_0$ relation of Busan sand is independent of the stress history and it is similar to the relation suggested by Jamiolkowski and Robertson (1988). Since both $E_D$ and $q_c$ are observed to be affected similarly by the stress history, relative density and vertical effective stress, $K_0/K_0$ is expected to be well related to the normalized dilatometer modulus ($E_D/\sigma_{v}'$ or $E_D/\sigma_{m}'$). As shown in Fig. 10, the $E_D/\sigma_{v}'-K_0/K_0$ relation of Busan sand is heavily dependent on the stress history while the $E_D/\sigma_{m}'-K_0/K_0$ relation is independent of the stress history.

Based on Figs. 9 and 10, the design charts to evaluate the $K_0$ value of Busan sand from CPT and DMT are developed as shown in Fig. 11. The $K_0-K_0-q_c/\sigma_{v}'$ chart proposed in this study is similar to the $K_0-K_0-q_c/\sigma_{v}'$ relation by Marchetti (1985), which was developed by combining the $K_0-K_0-\phi'$ relation of Schmertmann (1983) with the $q_c-K_0-\phi'$ relation of Durgunoglu and Mitchell (1975). Baldi et al. (1986a) also proposed the following equation.

$$K_0 = C_0 + C_1 K_0 - C_2 \frac{q_c}{\sigma_{v0}}$$

(1)

where, $C_0$, $C_1$, and $C_2$ are regression constants. Jamiolkowski and Robertson (1988) suggested the following equation based on the calibration chamber test results for Ticino sand.

$$\frac{K_0}{\sigma_0} = C_3 \left( \frac{q_c}{\sigma_{m}} \right)^{C_4}$$

(2)

It should be noted that the relations by Marchetti (1985), Baldi et al. (1986a) and Jamiolkowski and Robertson (1988) require both CPT and DMT results and the relations by Marchetti (1985) and Baldi et al. (1986a) are applicable only to NC sands. The $K_0-K_0-q_c/\sigma_{v}'$ and $K_0-E_D/\sigma_{v}'$ charts in Fig. 11 are applicable only to NC Busan sand while the $K_0-K_0-q_c/\sigma_{m}'$ and $K_0-E_D/\sigma_{m}'$ charts in Fig. 11 are relevant to both NC and OC sands. It should be noted that the plots in Fig. 11(b) require only DMT results to evaluate the $K_0$ values of granular soils.

4. Summary and conclusions

Stress history is an important factor affecting the behavior of granular soil. This study investigates the effect of the stress history on the CPT and DMT results and the probable method used to perceive the existence of the pre-stress. Conclusions drawn from the study are summarized as follows.

It is shown that $K_0$ is considerably more sensitive to the stress history than $E_D$ and $q_c$ because the increase in the horizontal stress level due to the pre-stress induces the significant increase in $K_0$. It is also found that a linear $E_D-q_c$ relation is adoptable for Busan sand, regardless of the stress history, since $E_D$ and $q_c$ vary quite similarly...
with respect to the effective stress and stress history. The $q_c/\phi$ and $E_D/(\phi v)^{0.5}$ of Busan sand are observed to increase exponentially with the increase in $D_R$ and the stress history shows only a slight influence on the $q_c/\phi^{0.5}$ and $E_D/(\phi v)^{0.5}$ relations.

As the $K_0$ value of granular soil is significantly affected by the pre-stress as well as the relative density, the $K_0-D_R$ relation established without considering the pre-stress effect is likely to overestimate the relative density of OC sand. However, when using the $q_c-\phi$ relation, the relative density of OC Busan sand is slightly overestimated by about 5–10% points and the existence of pre-stress is not easily perceived.

Although $q_c/\phi-\sigma_m$ and $E_D/\phi-\sigma_m$ relations appear to be acceptable for Busan sand, these relations are heavily influenced by the stress history, whereas $q_c/\phi-\sigma_m$ and $E_D/\phi-\sigma_m$ relations are found to be independent of the stress history. Based on these relations, the design charts used to evaluate the $K_0$ value using CPT and/or DMT measurements are suggested for both NC and OC Busan sands. Design charts based on $E_D/\phi-\sigma_m-K_0$ and $E_D/\phi-\sigma_m-K_0$ relations are expected to be practically useful as the usage of these charts requires only DMT indices.

The empirical relations developed in this study can be used to interpret state variables of Busan sand from in-situ measurements. However, the empirical relations for Busan sand cannot be applied to different sands unless their intrinsic variables are similar. In order to obtain the empirical relation for sands that have quite different intrinsic variables, a series of calibration chamber tests are required to be performed. In general, the same empirical relation for different sands shows a similar tendency but different regression constants.

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