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Effect of stress history on CPT and DMT results in sand

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A B S T R A C T

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_D 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_D–D_R 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_D–σ_v'–D_R relation suggested for NC sand. Although q_c/σ_v'–K_D/K_0 and E_D/σ_v'–K_D/K_0 relations are heavily influenced by the stress history, q_c/σ_m'–K_D/K_0 and E_D/σ_m'–K_D/K_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/σ_m'–K_D/K_0 and E_D/σ_v'–K_D/K_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.

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 (σ_p') and the present vertical effective pressure (σ_{v0}') 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_D) is similar in trend to the profile of OCR. Marchetti (1982) and Jamiolkowski and Lo Presti (1998) showed that K_D 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_D (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.

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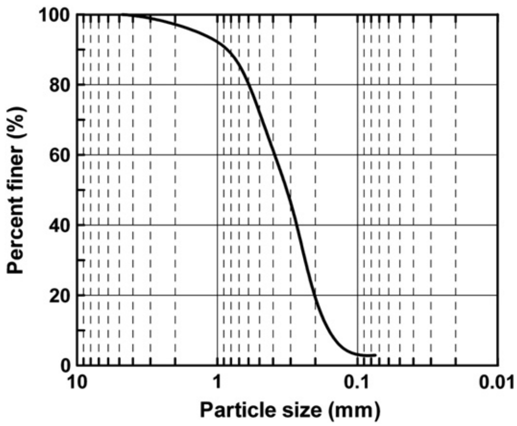

Fig. 1. Particle size distribution of Busan sand.

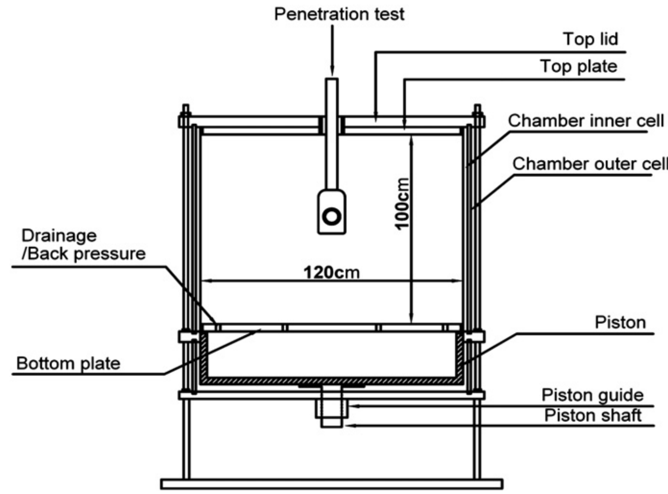

Fig. 2. Schematic view of the calibration chamber system for penetration tests.

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 SiO_2 is identified as a dominant particle mineral of this sand. The mean particle size (D_{50}) 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 1.0 m high extension tube, a 1.2 m high 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. Ghionna and Jamiolkowski (1992) suggested four boundary conditions of the calibration chamber, as shown in Table 2. In this study, the vertical stress and corresponding K_0 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.

Table 1
Engineering properties of Busan sand.

Gs	D_{10} (mm)	D_{50} (mm)	Cu	Cc	e_{max}	e_{min}	USCS
2.62	0.162	0.315	2.35	0.71	1.063	0.658	SP

Cone penetrometer is an electronic steel probe which is penetrated into the ground for collecting continuous data such as cone tip resistance (q_c), sleeve friction (f_s), 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 cm^2 cross-sectional area and a 150 cm^2 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 q_c 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 1.1 mm membrane expansions, respectively, and were corrected for the membrane stiffness and gauge offset. Then, P_0 and P_1 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, $K_D = (P_0 - u_0)/\sigma_{v0}'$, and the dilatometer modulus, $E_D = 34.7(P_1 - P_0)$, were determined. Here, u_0 is the hydrostatic water pressure and σ_{v0}' is the in-situ vertical effective stress. The constrained modulus, M_D, was also evaluated by applying the correction factor R_M to E_D as suggested by Marchetti (1980). Since DMT induces a smaller disturbance than CPT,

Table 2
Boundary conditions (BC) in the calibration chamber.

BC	Vertical		Lateral	
	Stress	Strain	Stress	Strain
1	Constant	–	Constant	–
2	–	0	–	0
3	Constant	–	–	0
4	–	0	Constant	–

Table 3
Condition of specimen preparation in the chamber.

Target relative density, D_R (%)	Vertical effective stress during penetration, $\sigma_{v(pt)}'$ (kPa)	Maximum pre-stress before penetration, $\sigma_{v(max)}'$ (kPa)	OCR ($\sigma_{v(max)}'/\sigma_{v(pt)}'$)
40, 60, 80	50	50	1
	100	100	1
	200	200	1
	400	400	1
	200	400	2
	100	400	4
	50	400	8
	100	200	2

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 (E_D and K_D), constrained modulus (M_D), and cone resistance (q_c) with vertical effective stresses for three relative densities of Busan sand. As shown in Fig. 3(a), the K_D value of NC sand remains essentially constant regardless of the vertical effective stress while the K_D 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 K_D value, compared with that of NC soil, at the same vertical stress and relative density. Fig. 3(b) shows that the E_D value of NC sand increases as the vertical effective stress increases. Although the E_D 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 K_D than E_D because the P_0 pressure is more sensitive to the stress level and pre-stress than the P_1 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 M_D of NC Busan sand increases as the vertical effective stress increases. As OCR increases, the M_D 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 M_D 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 E_D and q_c variations with respect to the effective stress and OCR are quite similar. It is therefore concluded that K_D is considerably more sensitive to the stress history than E_D and q_c, both of which show a similar sensitivity to the stress history. Consequently, the interpretation of K_D is helpful for understanding the stress history of granular soil (Marchetti, 1980; Jamiolkowski et al., 1988).

3.2. Effect of stress history on q_c and E_D

Since the penetration resistance mainly depends on the density and stress level, previous studies of Schmertmann (1976), Baldi et al.

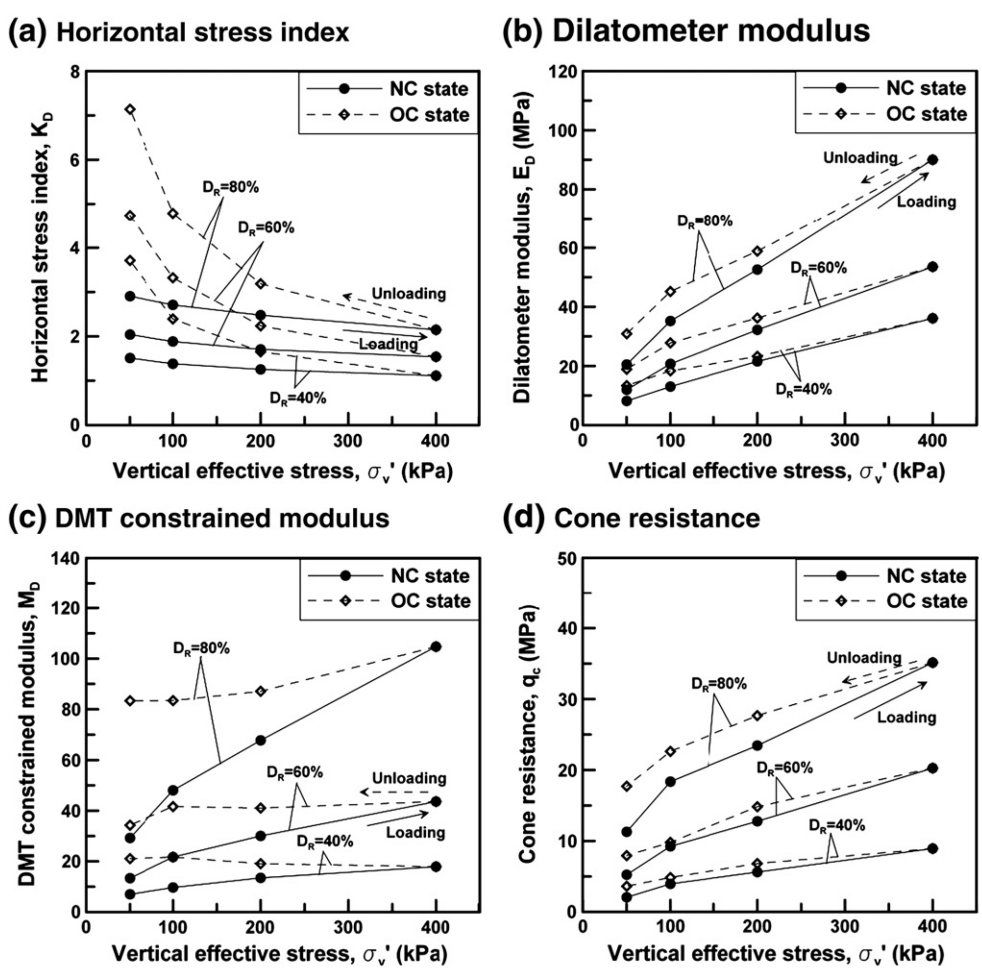

Fig. 3. Effect of stress history on dilatometer indices, cone resistance and the DMT constrained modulus.

(1986b) and Jamiolkowski et al. (2003) focused on the development of the q_c–D_R–σ' 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–σ_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 ΔP $(= P_1 - P_0)$ 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–σ_v' relation as shown in Fig. 4(b). Similar to the q_c–D_R–σ_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–σ_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. Jefferies 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).

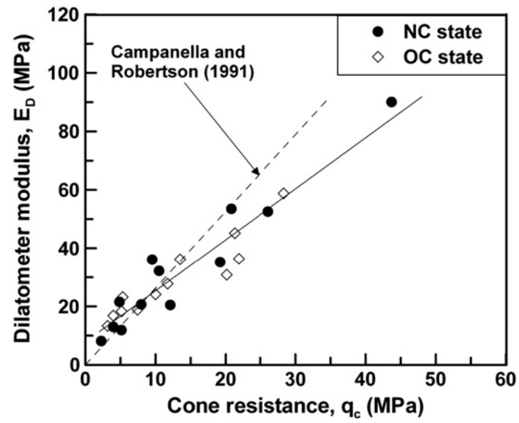

Fig. 5. Effect of stress history on the relation of E_D and q_c.

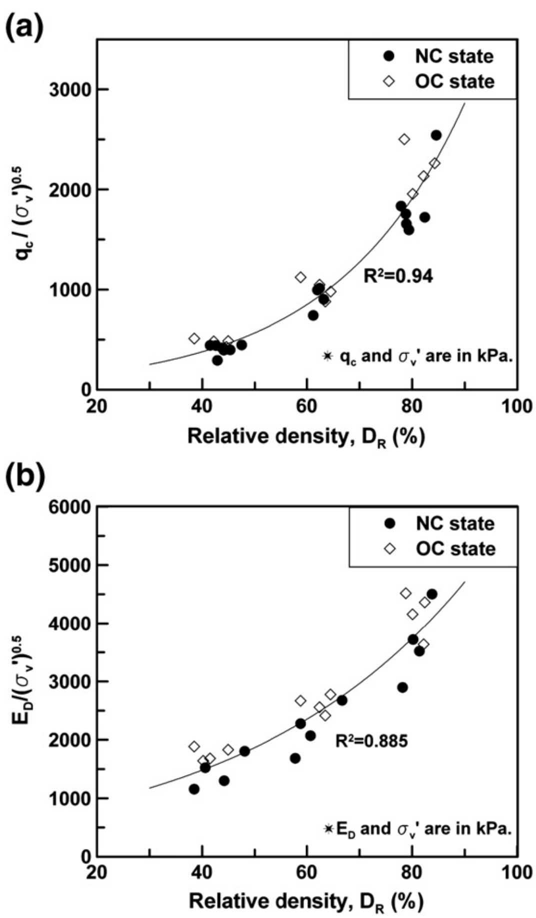

Fig. 4. Effect of stress history on normalized q_c and E_D; (a) q_c–D_R–σ_v' relation, and (b) E_D–D_R–σ_v' relation.

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.

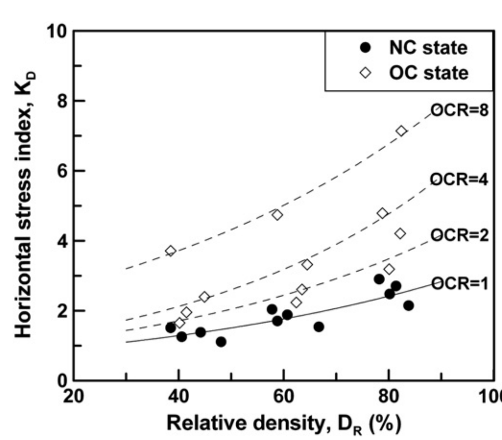

Fig. 6. Effect of stress history on the horizontal stress index.

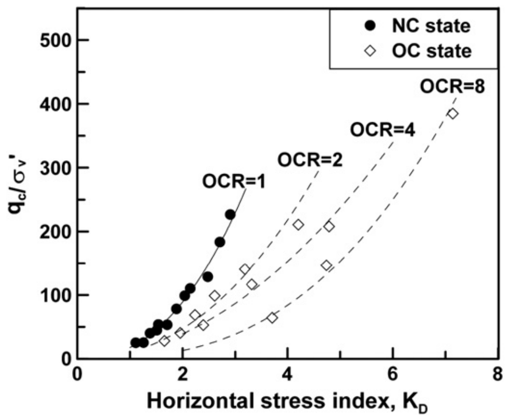

Fig. 7. Effect of stress history on the K_D–q_c relation.

Fig. 7 shows the effect of the pre-stress on the q_c/σ_v'–K_D relation. As distinct from Campanella and Robertson (1991) and Robertson (2009), who suggested a linear q_c/σ_v'–K_D relation, the q_c/σ_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/σ_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_D–q_c relation of granular soil is heavily dependent on the stress history since K_D 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–σ_v'–D_R and K_D–σ_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–σ_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–σ_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–σ_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 (σ_h'/σ_v'). Jamiolkowski et al. (1988) observed that the relation between K_D/K_0 and the state parameter (ψ) is not affected by the stress history. This is because K_D/K_0 is less sensitive to the stress history than K_D. 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

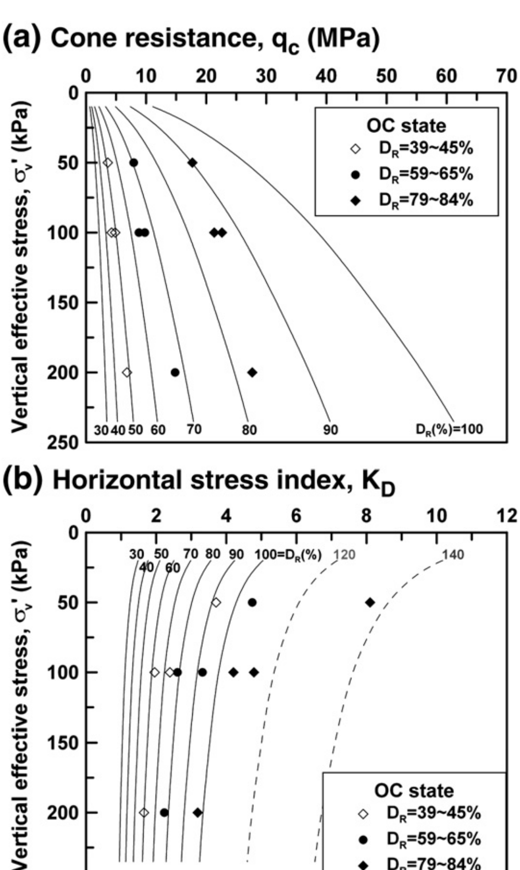

Fig. 8. q_c and K_D of OC Busan sand plotted in the charts for NC Busan sand; (a) q_c–σ_v'–D_R relation, and (b) K_D–σ_v'–D_R relation.

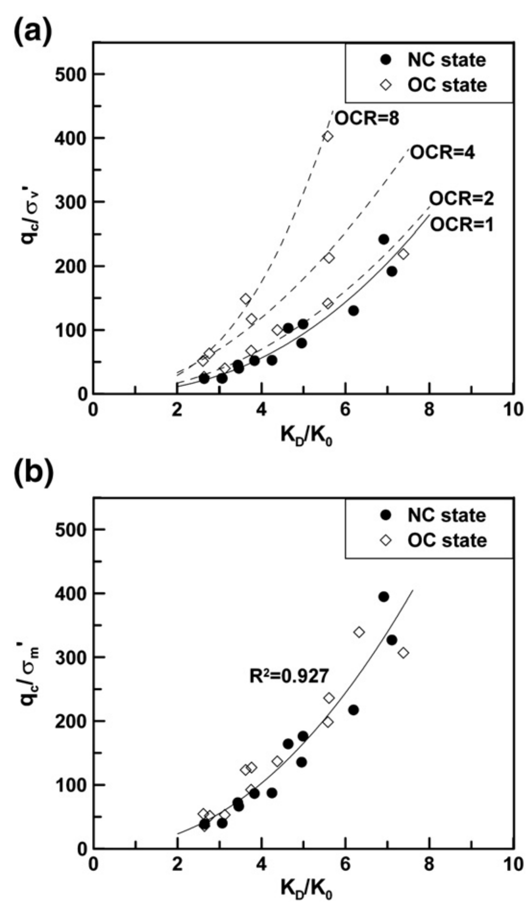

Fig. 9. Effect of stress history on the relation of K_D/K_0 and normalized q_c; (a) normalization of q_c using σ_v', and (b) normalization of q_c using σ_m'.

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_D/K_0 with some other measurements of in-situ tests.

Fig. 9(a) is the q_c/σ_v'–K_D/K_0 relation of Busan sand. It can be observed that the q_c/σ_v' of NC Busan sand is quite well correlated with K_D/K_0, but the q_c/σ_v'–K_D/K_0 relation is significantly affected by the pre-stress. At the same K_D/K_0 value, the q_c/σ_v' value is observed to increase as OCR increases. To minimize the effect of pre-stress on the q_c/σ_v'–K_D/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/σ_m'–K_D/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_D/K_0 is expected to be well related to the normalized dilatometer modulus (E_D/σ_v' or E_D/σ_m'). As shown in Fig. 10, the E_D/σ_v'–K_D/K_0 relation of Busan sand is heavily dependent on the stress history while the E_D/σ_m'–K_D/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_D–q_c/σ_v' chart proposed in this study is similar to the K_0–K_D–q_c/σ_v' relation by Marchetti (1985), which was developed by combining the K_D–K_0–φ' relation of Schmertmann (1983) with the q_c–K_0–φ' relation of Durgunoglu and Mitchell (1975). Baldi et al. (1986a) also proposed the following equation.

$$K_0 = C_0 + C_1 K_D - C_2 \frac{q_c}{\sigma_{v0}'} \tag{1}$$

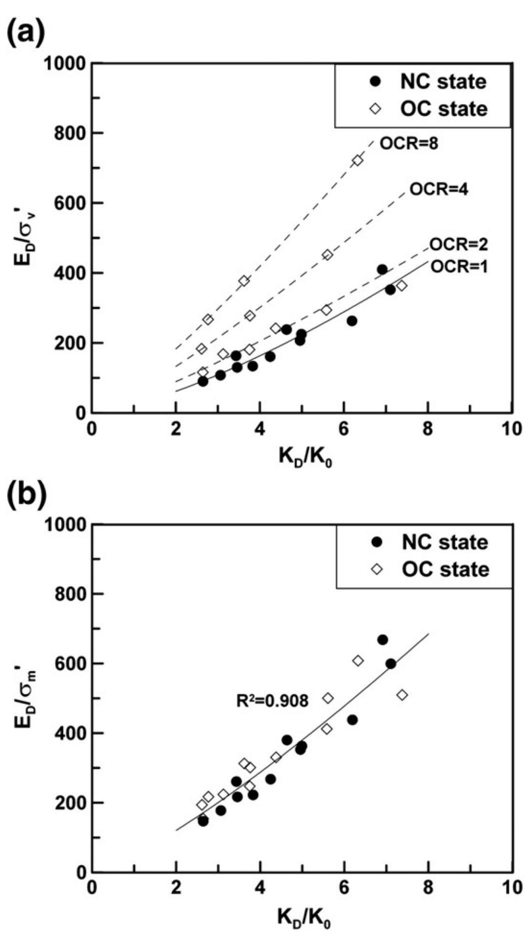

Fig. 10. Effect of stress history on the relation of K_D/K_0 and normalized E_D; (a) normalization of E_D using σ_v', and (b) normalization of E_D using σ_m'.

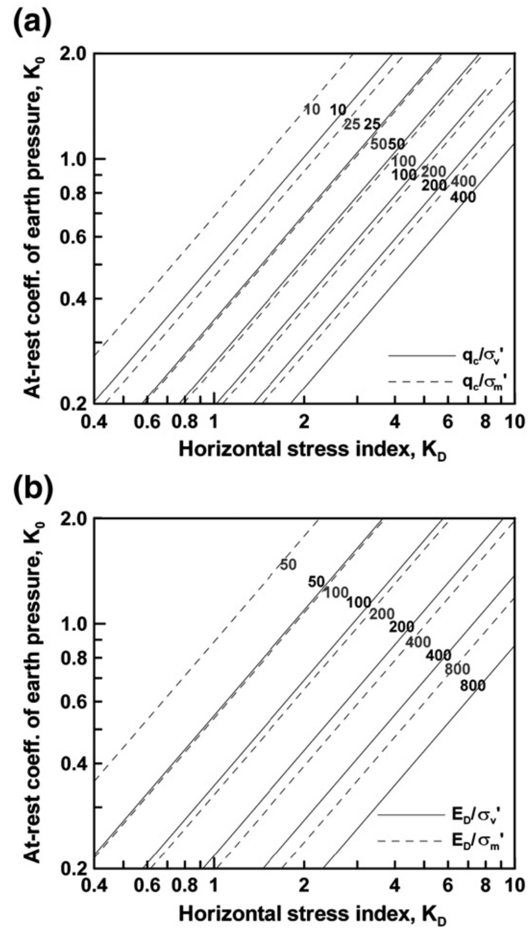

Fig. 11. Chart for predicting K_0 from CPT and DMT in Busan sand; (a) using cone resistance, and (b) using dilatometer modulus.

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.

$$\frac{K_D}{K_0} = C_3 \left(\frac{q_c - \sigma_m}{\sigma_{m'}} \right)^{C_4}. \tag{2}$$

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_D–q_c/σ_v' and K_0–K_D–E_D/σ_v' charts in Fig. 11 are applicable only to NC Busan sand while the K_0–K_D–q_c/σ_m' and K_0–K_D–E_D/σ_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_D 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_D. 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 $q_c/(\sigma_v')^{0.5}$ and $E_D/(\sigma_v')^{0.5}$ 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 $q_c/(\sigma_v')^{0.5}$–D_R and $E_D/(\sigma_v')^{0.5}$–D_R relations.

As the K_D value of granular soil is significantly affected by the pre-stress as well as the relative density, the K_D–D_R relation established without considering the pre-stress effect is likely to overestimate the relative density of OC sand. The existence of pre-stress of granular sediment may be indirectly recognized by the evaluation of the relative density larger than 100% when using the K_D–σ_v'–D_R relation of NC sand. However, when using the q_c–σ_v'–D_R 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/σ_v'–K_D/K_0 and E_D/σ_v'–K_D/K_0 relations appear to be acceptable for Busan sand, these relations are heavily influenced by the stress history, whereas q_c/σ_m'–K_D/K_0 and E_D/σ_m'–K_D/K_0 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/σ_m'–K_D/K_0 and E_D/σ_v'–K_D/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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