Effect of cementation on cone tip resistance and DMT indices
L'effet de cémentation sur le cône incline la résistance et DMT indices

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ABSTRACT
In this study, a series of piezocone and dilatometer tests are performed on a cemented specimen prepared in a large calibration chamber in order to investigate how the cementation effect is reflected in the cone tip resistance (q_c) and the DMT indices (M_D, K_D). Although the q_c value and DMT indices increase with the cementation level, E_D is found to be more sensitive to the cementation than K_D and q_c. It is observed that the cementation of sand appears to have a more significant effect on the behavior of cemented sand at a lower stress level and its effect diminishes with an increasing stress level. It is also shown that the E_D/q_c ratio of cemented sand is always higher than that of uncemented sand at the same q_c, while the difference in the E_D/q_c ratio between cemented and uncemented sands decreases with an increase in q_c. The E_D/q_c-q_c relation suggested in this study can be used to verify that the soil sediment is cemented.

RÉSUMÉ
Dans cette etude, une série de piezocone et les épreuves de dilatometer est execute sur un exemplaire cimenté préparé dans une grande chambre d'étalonnage pour enquêter comment l'effet de cémentation est reflété dans la résistance de bout de cône (q_c) et la DMT indices (M_D, K_D). Bien que la valeur de q_c et DMT indices l'augementation avec le niveau de cementation, l'E_D soit trouvé pour être plus sensible à la cémentation que K_D et q_c. Il est remarqué que la cémentation de sable a l'air d'avoir un effet plus significatif sur la conduite de sable cimenté à un niveau de tension plus bas et son effect diminue avec un niveau de tension augmentant. Il est aussi montré que le rapport E_D/q_c de sable cimenté est toujours plus haut que ce de sable non cimenté à même q_c, tandis que la différence dans le rapport E_D/q_c entre les sables cimentés et non cimentés diminue avec une augmentation dasn q_c. La relation E_D/q_c-q_c suggérée dans cette etude peut être utilisée pour vérifier que le sédiment de sol est cimenté.

Keywords : cementation, cone tip resistance, dilatometer modulus, horizontal stress index, relative density, confining stress

1 INTRODUCTION

The cementation of granular soil is either induced naturally by the deposition of the cementing agent at particle contacts or is achieved artificially by the injection of chemical grouts into the soil. It is known that the behavior of cemented sand is affected by the cement agent type, the cementation level, the relative density, the stress state, and the particle characteristics, etc. Since it is difficult and uneconomical to obtain a cemented specimen without damaging the cementation bonds, it is necessary to estimate the cemented sediment using in-situ tests. Several cone penetration tests have been conducted on natural cemented sediments (Beringen et al., 1982; Schnaid et al., 1998; Puppala et al., 1998), and on artificially cemented specimens prepared in a laboratory calibration chamber (Akili and Torrance, 1981; Akili and Al-Joulani, 1988; Joshi et al., 1995; Puppala et al., 1995; Rad and Tumay, 1986). In general, it is known that the cone tip resistance and sleeve friction increase with an increase in the content of the cementing agent. Puppala et al. (1995) concluded that cementation has a more significant effect on cone tip resistance at a lower confining stress.

A limited number of dilatometer tests have been performed on cemented sands. Cruz and Fonseca (2006) showed that the horizontal stress index (K_D) of residual soil increases with an increasing cohesion intercept. Kaggwa et al. (1996) combined CPT and DMT results obtained from cemented or structured residual sediments and showed that the cone tip resistance provides a smaller constrained modulus of cemented calcareous sediments than that of the dilatometer modulus.

In most of the previous research, the various factors that influence cementation have not been considered. Furthermore, the estimation of the cementation effect from in-situ tests is difficult due to the non-homogeneity and unknown cementation level of natural sediments. Therefore, it is necessary to prepare an artificially cemented specimen in a large calibration chamber under strictly controlled laboratory conditions. In this study, an investigation is carried out on how the cementation effect is reflected in the cone tip resistance (q_c) and the DMT indices (M_D, K_D). For this, a series of piezocone and dilatometer tests are performed on cemented specimens prepared in a large calibration chamber. The cemented specimens were prepared using air-pluviation in a calibration chamber with various combinations of relative density and gypsum content.

2 EXPERIMENTAL PROGRAM

2.1 *Sand and Cementing Agent*

In this study, K-7 sand, which is an artificially crushed sand obtained from a parent rock, is used. The particle size distribution and basic properties of this sand are presented in Figure 1 and Table 1. This sand is classified as SP in the unified soil classification system (USCS) and the mean particle size (D_{50}) is 0.17mm. From X-ray fluorescence analyses, SiO_2 was identified as the dominant particle mineral. The roundness of the particle was identified as sub-angular by scanning electron microscopy analysis. Gypsum, generally used for manufacturing ceramics, was used as the cementing agent in this study because the behavior of gypsum-cemented sand is similar to that of naturally cemented sand (Ismail et al., 2002). The compressive strength of gypsum cured at a water content of 40% is about 20MPa. Gypsum starts to cure approximately 16 minutes after it is mixed with water, and the curing continues for about 40 minutes after the initial mixing. The expansion rate of gypsum during curing is about 0.03%, which is relatively small compared to that of ordinary gypsums.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1024

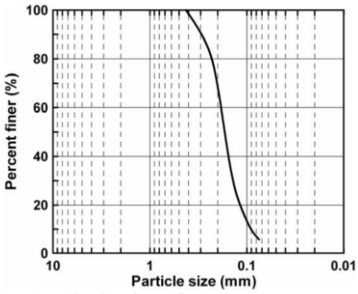

Figure 1. Particle size distribution of K-7 sand.

Table 1. Engineering properties of K-7 sand

Gs	D_{10}(㎜)	D_{50}(㎜)	Cu	Cc	e_{max}	e_{min}	USCS
2.647	0.09	0.17	2.111	0.988	1.054	0.719	SP

2.2 *Calibration Chamber System*

As illustrated in Figure 2, the calibration chamber system used in this study consists of a 1.0m high chamber cell with a diameter of 1.2m, a piston at the bottom, and a top plate with adaptors. The hydraulic pressures in the inner and outer cells of the chamber control the horizontal boundary condition of the specimen, while the vertical stress is applied by the piston assembly located below the specimen.

A rainer system, which consists of a 1.0m high split mold, a 1.0m high extension tube, a 1.2m high sand storage, and two diffuser sieves, is used to fabricate the homogeneous sand specimen of a wide range of dry densities. During pluviation, a constant drop height is maintained using four strings connecting the diffuser system to the cover plate of the sand storage.

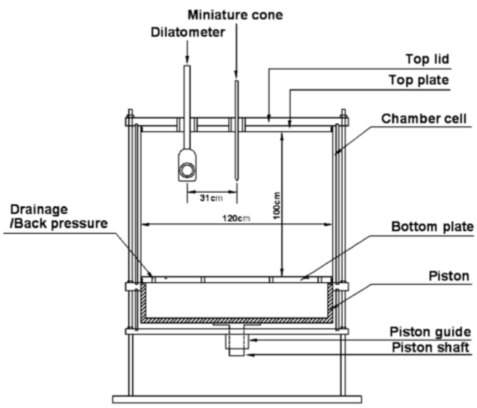

Figure 2. Calibration chamber system for CPT and DMT.

2.3 *Miniature Cone Penetrometer and Dilatometer*

The cone tip resistance measured in the calibration chamber is influenced by the chamber size and the boundary condition. The difference in the cone tip resistance measured in the chamber from the in-situ value decreases as the diameter ratio increases (Been et al., 1986; Jamiolkowski et al., 1985, 2003; Lunne and Christophersen, 1983; Parkin and Lunne, 1982). In order to minimize the boundary effect, a miniature cone was used in this study that has a $2cm^2$ cross-sectional area, a $40cm^2$ sleeve friction area, and a 60° apex angle.

The dilatometer, which was introduced by Marchetti (1980), is a 14 mm thick, 95 mm wide and 220 mm long flat plate with a 20° apex angle. A flexible stainless steel membrane of 60 mm diameter is located on one face of the blade. P_0 and P_1 pressures are obtained by correcting the A and B values which are measured by expanding the steel membrane up to 0.05 and 1.1mm, respectively. From these values, the horizontal stress index, $K_D=(P_0-u_0)/\sigma_{v0}'$, the material index, $I_D=(P_1-P_0)/(P_0-u_0)$, and the dilatometer modulus, $E_D=34.6(P_1-P_0)$ are evaluated. Here, u_0 is the in-situ hydrostatic water pressure and σ_{v0}' is the in-situ vertical effective stress.

2.4 *Specimen Preparation and Penetration Tests*

To minimize the particle segregation between the sand and the gypsum particles during air pluviation, the pre-wetting method proposed by Rad and Tumay (1986) and Puppala et al. (1995) was adopted in this study. An amount of water equivalent to 0.5% water content is manually mixed with dry sand. After 5, 7, and 10% weight of gypsum is added to the pre-wetted sand, both materials are re-mixed. The pre-wetting process moistens the surface of the sand particles and allows the grains to be uniformly and homogeneously coated with gypsum particles, minimizing the potential of segregation between the gypsum and the sand particles during pluviation (Puppala et al., 1995). After pluviating the sands or sand-gypsum mixtures, the chamber system is assembled, and the vertical stress and the corresponding K_0 horizontal stress are then applied to the specimen under the boundary condition 1 (σ_v'=constant, σ_h'=constant). To induce the cementation of the sand-gypsum mixtures, distilled water is injected from the bottom of the specimen at 30kPa after the application of the confining stress, and the specimen is cured for 24 hours.

After the completion of curing, the miniature cone penetration test and the flat dilatometer test are performed without changing the initial sitting pressure. The miniature cone is penetrated through the center of the specimen at a penetration rate of 2cm/sec. A dilatometer is then penetrated 31cm off from the center of the specimen at a 2cm/sec penetration rate and the P_0 and P_1 pressures are measured at every 10cm penetration from 30 to 70cm. Figure 3 presents typical profiles of q_c, K_D and E_D measured for uncemented and cemented K-7 sands in a calibration chamber. Test results show relatively constant values of cone tip resistance and DMT indices at depths between 30~70cm. The cone resistance at the top and bottom of the specimen is greater than that at the middle of the specimen due to the rigid boundary effects. The influence of the rigid top plate increases with an increasing gypsum content due to the higher dilation tendency of cemented sand. Each measurement appears to increase with an increase of gypsum content.

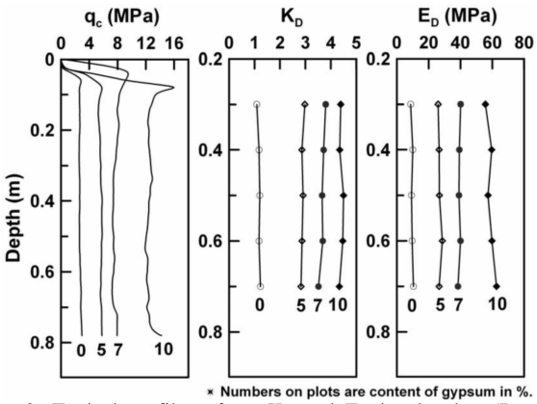

Figure 3. Typical profiles of q_c, K_D and E_D in chamber (Dr≈40%, σ_v'=100kPa).

3 ANALYSIS AND DISCUSSION

3.1 *Influencing Factors on* q_c

To understand the factors that influence the cone tip resistance of cemented sand, the $q_{c(cs)}/q_{c(us)}$ ratio is presented in terms of relative density, vertical effective stress, and gypsum content, as shown in Figure 4. Here, $q_{c(cs)}$ is the cone tip resistance of the cemented specimen, and $q_{c(us)}$ is that of the uncemented specimen at the same relative density and confining stress. The

$q_{c(cs)}/q_{c(us)}$ ratio increases with an increasing gypsum content. For example, at 40% relative density, the 5% cemented specimen under 100kPa vertical effective stress has a 2.1 times larger cone tip resistance than the uncemented specimen, and a 2.9 and 4.2 times larger cone tip resistance in the 7% and 10% cemented specimens, respectively.

It is also shown in Figure 4 that the $q_{c(cs)}/q_{c(us)}$ ratio of the cemented specimen decreases with an increasing vertical effective stress. This is because the vertical effective stress has a greater effect on the cone tip resistance of the uncemented specimen than that of the cemented specimen. And, with an increasing confining stress, the influence of cementation on cone tip resistance is less significant due to the larger effect of the frictional component on cone tip resistance. Therefore, the cementation effect needs to be reflected with more consideration at a low confining stress level such as for a shallow foundation (Puppala et al. 1995).

An increasing relative density results in a slight increase in the $q_{c(cs)}/q_{c(us)}$ ratio, and this effect is more distinctive at a higher cementation level. However, the overall effect of relative density on the cone tip resistance of cemented sand is relatively insignificant, compared to the effects of the gypsum content and the confining stress. This is because the behavior of cemented sand is mainly controlled not by the friction angle, which depends on the relative density, but by the cohesion intercept induced by cementation bonds.

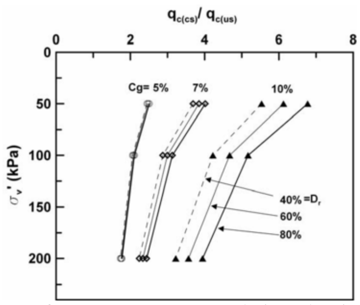

Figure 4. Effect of gypsum content, relative density, and vertical effective stress on cone tip resistance of cemented sand.

3.2 *Influencing Factors on E_D*

Figure 5 shows the effect of gypsum content, relative density, and vertical effective stress on the dilatometer modulus of sand. Here, $E_{D(cs)}$ and $E_{D(us)}$ are the dilatometer modulus of cemented sand and that of uncemented sand, respectively. The increase in gypsum content and the decrease in vertical stress result in an increase in the $E_{D(cs)}/E_{D(us)}$ ratio, and this is the same trend as that of the cone tip resistance of cemented sand. The 5% cemented specimen under a 50~200kPa vertical effective stress has a 1.8~3.1 times larger E_D than the uncemented specimen, and a 2.5~4.9 and 3.7~7.1 times larger E_D for the 7% and 10% cemented specimens, respectively. This result shows that, at a lower relative density, the E_D is a more sensitive index for the cementation than cone tip resistance. The increase in vertical effective stress from 50kPa to 200kPa causes about a 20~40% reduction in the $E_{D(cs)}/E_{D(us)}$ ratio of cemented sand.

Experimental results in this study show that by increasing the relative density from 40% to 80%, the $E_{D(cs)}/E_{D(us)}$ ratio of cemented sand is reduced by about 12~25%, in contrast to the case of cone tip resistance. This result means that the dilatometer modulus of cemented sand is affected more by cementation than the relative density as described by Marchetti et al. (2001). An interesting result is that the reduction of the $E_{D(cs)}/E_{D(us)}$ ratio due to relative density abruptly increases between 60%~80% relative density. This is because the effect of relative density on the dilatometer modulus of uncemented sand becomes more significant for medium to dense sands.

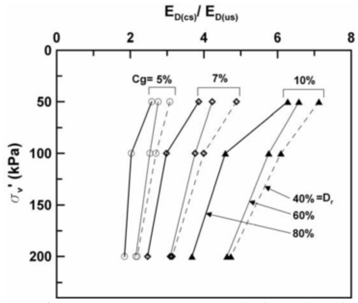

Figure 5. Effect of gypsum content, relative density, and vertical effective stress on dilatometer modulus of cemented sand.

3.3 *Influencing Factors on K_D*

Figure 6 shows the ratio of horizontal stress indices of cemented sand and uncemented sand, $K_{D(cs)}/K_{D(us)}$, in terms of relative density, vertical effective stress, and gypsum content. The 5% gypsum content causes about a 1.7~2.7 times increase in the K_D of sand, and a 2.1~3.5, 2.6~4.3 times increase is caused by 7% and 10% gypsum contents, respectively. The increasing ratio of K_D is slightly smaller than the increasing ratios of q_c and E_D. As the relative density and the vertical effective stress increase, the $K_{D(cs)}/K_{D(us)}$ ratio gradually decreases. This result means that the relative density and vertical stress have more significant effects on the K_D of uncemented sand than that of cemented sand.

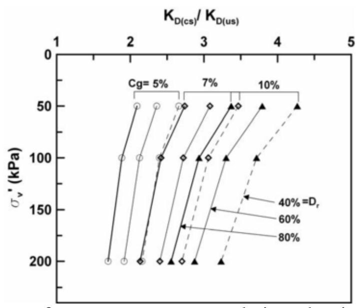

Figure 6. Effect of gypsum content, relative density, and vertical effective stress on horizontal stress index of cemented sand.

3.4 *Effect of Cementation on the E_D-q_c Relation*

Figure 7 shows the relationship between the dilatometer modulus and the cone tip resistance for both uncemented and cemented sands. The E_D/q_c of uncemented K-7 sand is 3.13 on average. Based on the relation proposed by Campanella and Robertson (1991), the relationship between cone tip resistance and the dilatometer modulus of uncemented K-7 sand can be expressed as:

$$E_{D(US)} = 3.13 q_{c(US)} \tag{1}$$

It was observed that the cemented K-7 sand always shows a higher E_D/q_c value than that of the uncemented K-7 sand at the same cone tip resistance. The E_D/q_c increases 1.1~1.8 times compared to those of uncemented sand at the same relative density and confining stress. Since this difference is intimately linked to the cementation level, the modulus difference between cemented and uncemented sands at the same cone tip resistance can be expressed by a cohesion intercept. The cohesion intercept of the cemented specimen can be obtained from a drained triaxial test under relatively low confining stresses, because the cementation bonds are broken at a high confining stress and the cohesion intercept gradually disappears. From the regression analysis, a q_c-E_D relation of cemented sand is given as Equation 2. Here, the units of $E_{D(CS)}$ and $q_{c(CS)}$ are MPa, and c' is a cohesion intercept of cemented sand in units of kPa.

$$E_{D(CS)} = 3.13 q_{c(CS)} + 0.24c' \quad (2)$$

It is noted that the difference between the E_D/q_c ratios reduces with an increasing cone tip resistance. As shown in Figures 4 and 5, E_D and q_c are subjected to similar influences of cementation and stress levels at a lower relative density. However, the increase of relative density has a greater effect on the q_c than on the E_D of cemented sand. Therefore, it is expected that the difference in the E_D/q_c ratio for uncemented and cemented sands becomes smaller as the cone tip resistance increases. Figure 7 can be used to determine whether or not the deposit is cemented.

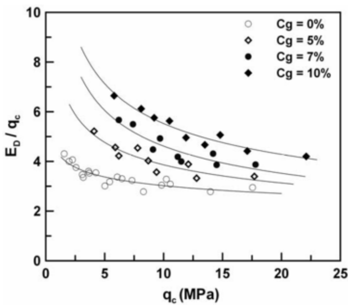

Figure 7. Effect of cementation on E_D/q_c of sand.

4 CONCLUSIONS

This study is concerned with the cementation effect on cone tip resistance (q_c) and DMT indices. From the calibration chamber tests, it is observed that the cone tip resistance (q_c), the dilatometer modulus (E_D), and the horizontal stress index (K_D), increase with the increase of cementation level. The E_D is found to be a more sensitive index for cementation than K_D and q_c. The increase of relative density results in a slight increase in the $q_{c(cs)}/q_{c(us)}$ ratio, while it causes a decrease in both the $E_{D(cs)}/E_{D(us)}$ and the $K_{D(cs)}/K_{D(us)}$ ratios. The cementation of granular soil appears to have a more significant influence on ground behavior at a lower stress level and its effect diminishes with an increasing stress level.

It is also observed that the cemented sand always shows a higher E_D/q_c value than the uncemented sand at the same cone tip resistance. This means that a more effective detection of existing cementation is possible by using the deformation characteristics than by using penetration resistance. Since the modulus difference between cemented and uncemented sands can be related to the cementation, the E_D/q_c-q_c relation of cemented sand is expressed in terms of a cohesion intercept. Since the relative density has a larger effect on the q_c than on the E_D of cemented sand, the difference in the E_D/q_c ratio between cemented and uncemented sands is found to decrease with an increasing cone tip resistance. The E_D/q_c-q_c relation suggested in this study can be used to determine that the soil sediment is cemented.

ACKNOWLEDGEMENTS

This paper is supported by the Construction Core Technology Program (C104A1000009-06A0200-00800) under the KICTEP grant.

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