Evaluation of cementation effect of sand using cone resistance

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ABSTRACT: In this study, the cone resistance of cemented sand is measured by performing a series of miniature cone penetration tests on the specimens prepared in a calibration chamber. The cementation effect is induced artificially with 5~10% gypsum content of sand weight. It is observed from the experimental results that the cone resistance of sand increases with increasing gypsum content. However, the cone resistance does not appear to properly evaluate the deformation modulus of cemented sand due to the damage of cementation bonds induced during the cone penetration. The M/q_c ratio of cemented sand is much higher than that of uncemented sand while it is gradually reduced with increasing cone resistance. Although the constrained modulus of sand increases significantly with the cementation, the relative density and confining stress seem to have more considerable effects on the cone resistance than constrained modulus. The ratio of cone resistance of cemented sand to that of uncemented sand is almost linearly related to the cohesion intercept normalized by vertical effective stress.

1 INTRODUCTION

The cementation, which involves the formation of contact bonding between particles caused by the precipitation of bonding materials from the solution, causes an increase of the CPT penetration resistance and deformation modulus of sand. Cementation has been known to cause an increase in the peak strength and stiffness of soil. The increase of penetration resistance due to cementation results in the overestimation of the relative density and friction angle (Puppala et al., 1995; Marchetti et al., 2001). Therefore, in many geotechnical problems, the cementation effect, which induces a cohesion component in granular soil, is one of the dominant factors on the behavior of soil.

A few cone penetration tests were reported on naturally cemented sediments (Beringen et al., 1982; Danziger et al., 1998; Puppala et al., 1998; Schnaid et al., 1998). However, the evaluation of the cementation effect using in-situ penetration tests is difficult due to non-homogeneity and unknown cementation level of natural sediments. Therefore, it has been necessary to carry out the calibration chamber test by preparing an artificially cemented specimen under strictly controlled conditions. A few studies have been performed to evaluate the cementation effect on cone penetration test using laboratory calibration chamber (Akili and Torrance, 1981; Rad and Tumay, 1986; Akili and Al-Joulani, 1988; Puppala et al., 1995). In general, it had been shown that the cementation causes an increase of the cone resistance and sleeve friction, with a decrease of the friction ratio.

In this study, CPTs are carried out on an artificially cemented specimen prepared using a large calibration chamber in order to investigate the effect of cementation on cone resistance. A series of 1-dimensional compression tests is also performed to evaluate the deformation characteristics of cemented sand. And the cohesion intercept of cemented sand is obtained from a series of triaxial tests. By analyzing the experimental results, the relationships between the cone resistance, cohesion intercept, and deformation modulus of cemented are investigated.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

K-7 sand, which is artificially crushed from a parent rock, was used in this study. Particle size distribution and basic properties of K-7 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. Gypsum, generally used for manufacturing ceramics, was used as the cementing agent in this study because the behavior of gypsum-cemented sand is known to be similar with that of naturally cemented sand (Ismail et al., 2002). The compressive strength of gypsum cured at a water content of 40% is about 20MPa.

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

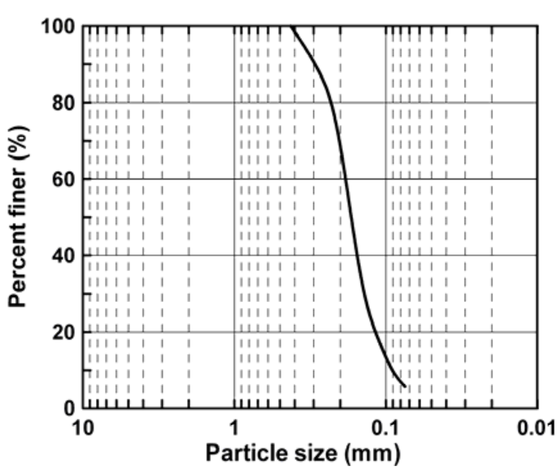

Figure 1. Particle size distribution of K-7 sand

2.2 *Miniature cone penetration test*

The cemented specimens were prepared in a double wall calibration chamber of 1.0m in height and 1.2m in diameter. The chamber system has 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. Vertical stress is applied by the piston assembly located below the specimen. For the fabrication of a uniform sand specimen in the chamber cell, 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 minimize the particle segregation between the sand and 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. After pluviating the sands or sand-gypsum mixtures, the chamber system is assembled, and then vertical stress and the corresponding K_0 horizontal stress are applied to the specimen under 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 with 30kPa pressure after the application of the confining stress, and the specimen is cured for 24 hours. After curing, the miniature cone penetration test is performed. The miniature cone, which has a 2cm^2 cross-sectional area, 40cm^2 area of friction sleeve, and 60° apex angle, is used to remove the boundary effects on the cone tip resistance. The miniature cone is penetrated through the center of the specimen at a penetration rate of 2cm/sec.

2.3 *One dimensional compression test*

The constrained modulus of a cemented specimen is obtained from one-dimensional compression tests in an oedometer cell of 74mm in diameter and 45mm in height. Cemented specimens are prepared by air-pluviating the sand-gypsum mixture in the cell. After applying vertical stress (50, 100, 200kPa), the distilled water is supplied through the bottom of the specimen for curing. The specimen is cured for 24 hours, and then the vertical load is incrementally increased to measure the vertical stress-strain relation, from which the constrained modulus is evaluated.

2.4 *Triaxial tests*

To prepare a cemented specimen for triaxial test, the sand-gypsum mixture is air-pluviated in a steel mold of 70mm in diameter and 150mm in height, and a 50~200kPa sitting pressure is applied to the specimen. Cementation is induced by circulating distilled water through the specimen. After 24 hours of curing, the specimen is assembled in the triaxial cell. 500ml of carbonated water is flushed through the specimen bottom to displace the air presented in voids and, then, 500ml of de-aired water is flushed from the specimen bottom. B values of at least 0.93 are obtained by applying the back-pressure up to 300kPa. Isotropic consolidation pressure is applied up to 50~400kPa, and the strain-controlled shear tests (CID) are performed with a 0.1%/min strain rate. From the test results, the cohesion intercept of cemented sand is calculated.

3 TEST RESULTS AND ANALYSIS

3.1 *Cone resistance of cemented sand*

The cone resistance of the granular soil has been known to be the function of state variables, such as the density and stress level. Figure 2 shows the variation of cone tip resistance of K-7 sand, which is compared with that of typical quartz sand of various compressibility from Jamiolkowski et al. (1985). It is observed that the q_c-D_R-σ_v' relation of uncemented K-7 sand roughly matches to that of highly compressible quartz sand. For the sands with same relative density, the cementation by 5~10% gypsum content is observed to induce a significant increase in the cone tip resistance. It is important to note that the cone tip resistances of cemented K-7 sands by 7~10% gypsum content mostly locate below the q_c-D_R-σ_v' relation of quartz sands with low compressibility. It means that the cementation process considerably reduces the compressibility of granular soil and the cementation is a more influential factor to the deformation modulus of sand than the density and stress level are.

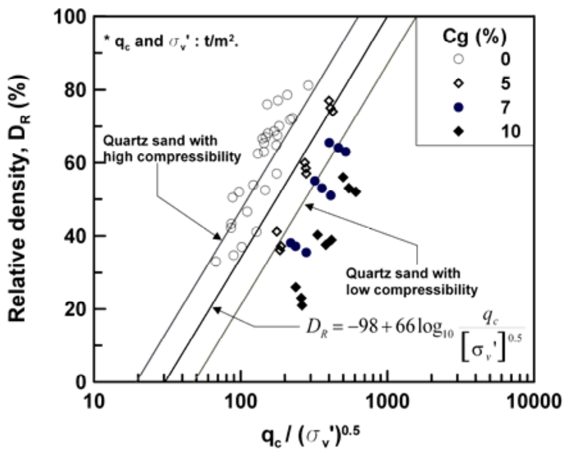

Figure 2. Effect of cementation of K-7 sand represented in q_c-D_R-σ_v' relation.

3.2 *Evaluation of M from q_c*

Lunne and Christophersen (1983) analyzed the results of CPTs on normally consolidated unaged uncemented silica sand and proposed the linear relation between constrained modulus and cone resistance. In this study, a linear M-q_c relation for uncemented K-7 sand is obtained as Equation 1.

$$M = 2.93q_c + 4.66 \qquad (1)$$

Also shown in Figure 3 is the comparison of M measured by a 1-D compression test on cemented sand with M estimated using Equation 1, which is believed to be adequate only for uncemented sand. It is observed that Equation 1 underestimates the M values of cemented sands by 68~87% and provides smaller values than those measured by one dimensional compression test. From these observations, it can be concluded that cone penetration tests cannot adequately evaluate the deformation characteristics of cemented sands even though the cementation effect is reflected in the penetration test results to a certain degree. Therefore, when the constrained modulus is estimated by in-situ penetration tests without considering the cementation of granular soils, it is likely to significantly underestimate the deformation modulus of in-situ ground.

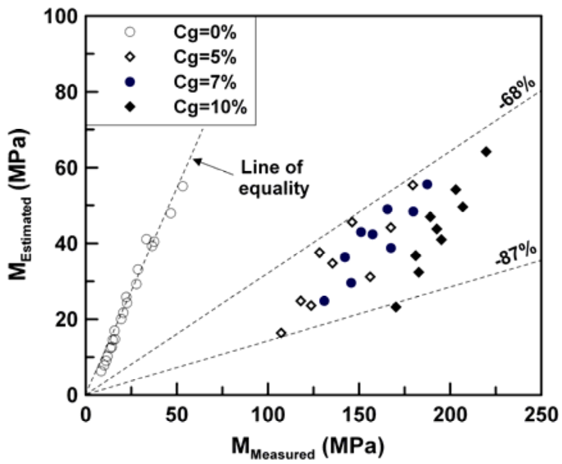

Figure 3. Under evaluation of constrained modulus of cemented sand.

3.3 *q_c-M relation of cemented sand*

In general, the factors affecting the behavior of granular soil show different degrees of influence on in-situ test results. Figure 4 is a plot of the M/q_c vs q_c relation for both uncemented and cemented K-7 sands. It is shown that the ratio M/q_c of uncemented K-7 sand ranges within 3.0~5.4. It is also noted that the ratio of M/q_c of cemented sand is 3~14 times larger than that of uncemented sand at the same cone resistance. This is because the cementation causes a larger increase in the constrained modulus than the cone resistance. It is also observed in Figure 4 that the M/q_c ratio of cemented sand gradually decreases as the cone resistance increases. The gradual decrease in the M/q_c value with q_c is due to the different degrees of influences of the density and stress level on the penetration resistance and deformation modulus. In other words, the increase in density and effective stress induces a larger increase in the cone resistance than the constrained modulus.

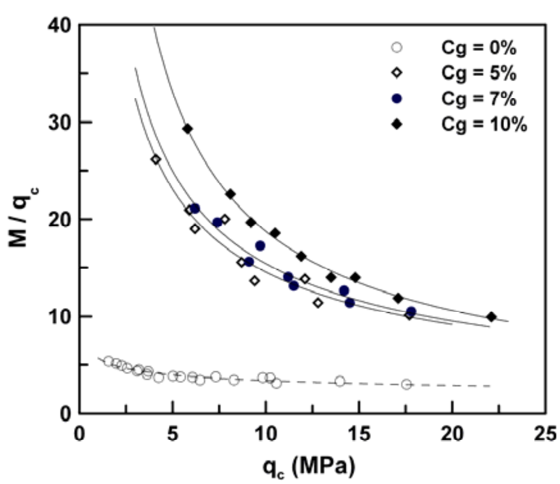

Figure 4. Variation of M/q_c ratio of cemented and uncemented sand.

3.4 *Effect of cohesion intercept on q_c*

An extensive investigation about the cementation effect on cone tip resistance was performed by Puppala et al. (1995), in which the 1~2% Portland cement was used as a cementing agent to prepare Monterey sand specimens in a calibration chamber. In Figure 5, for the cemented K-7 sand of D_R=51~60% and cemented Monterey sand of D_R=47~54%, the ratio of the cone resistance of cemented sand ($q_{c(cs)}$) to that of uncemented sand ($q_{c(us)}$) under same state variables is presented to evaluate the cementation effect. It is observed that the effect of cementation on cone resistance is larger for the K-7 sand than for the Monterey sand. Puppala et al. (1995) performed the CPTs at the confining stress of 50~300kPa, which was applied after the completion of specimen cementation under zero sitting stress. And the cohesion intercept of the cemented Monterey sand appears to be lower than that of the cemented K-7 sand. It is, therefore, likely that the cementation bonds of Monterey sand is damaged due to the application of the confining stress and the $q_{c(cs)}/q_{c(us)}$ ratio of Monterey sand increases with increasing stress level. Whereas, this study performed all the cementation process and penetration tests on K-7 sand without changing the stress level and, therefore, the $q_{c(cs)}/q_{c(us)}$ ratio of cemented K-7 sand decreases with increasing stress level. The stress level existed during the cementation process and the change of stress level after the cementation should be considered differently because the cementation bonds is likely to be degraded due to the increase of stress level on the specimen.

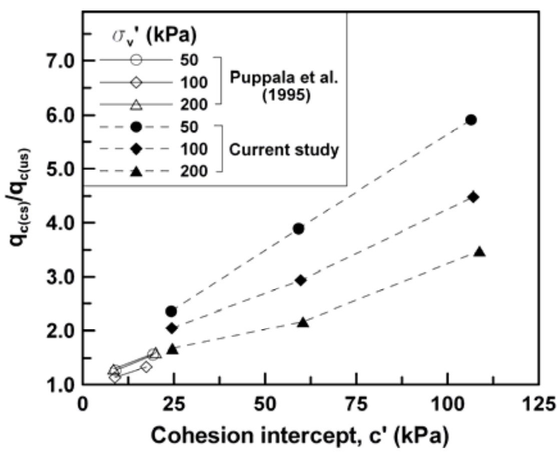

Figure 5. Effect of cohesion intercept on the increase in cone resistance of cemented sands.

The increase in cone resistance of cementation sand compared with that of uncemented sand results from the cohesion intercept induced by cementation bonds. Therefore, the ratio of cone resistance between the cemented and uncemented sands is related to the normalized cohesion intercept by vertical effective stress, as shown in Figure 6. It is shown that the ratio of cone resistance linearly increases as the normalized cohesion intercept does. From the regression analysis, a relation between $q_{c(cs)}/q_{c(us)}$ ratio and cohesion intercept is expressed as follows:

$$\frac{q_{c(cs)}}{q_{c(us)}} = 3.15\frac{c'/p_a}{\sqrt{\sigma_v'/p_a}} + 1 \quad (2)$$

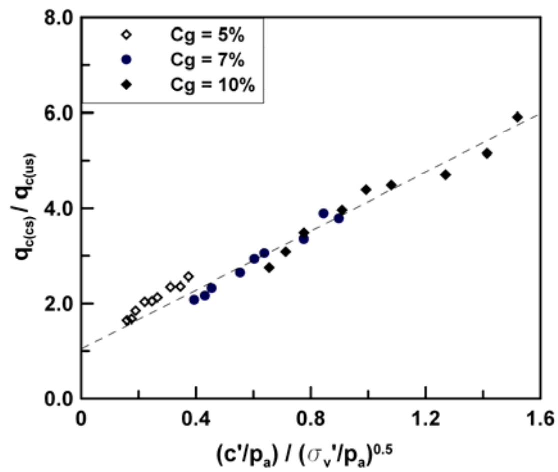

Figure 6. Relation of cohesion intercept and the ratio of cone resistance.

4 CONCLUSIONS

A series of CPTs are performed on artificially cemented K-7 sand specimens to investigate the cementation effect on the cone resistance and deformation modulus. Despite the q_c-D_R-σ_v' relation of uncemented K-7 sand roughly matches to that of highly compressible quartz sand, the cementation by 5~10% gypsum content induces a significant increase in the cone tip resistance. Even though the cementation effect is reflected in the penetration test results, the deformation modulus of cemented sands is underestimated when using the empirical relations previously suggested for uncemented sands. The M/q_c values of cemented sand are significantly larger than those of uncemented sand as the cementation causes a larger increase in the deformation modulus than the cone resistance. The M/q_c ratio of cemented sand gradually decreases as the cone resistance increases because the increase in density and effective stress induces a larger increase in the cone resistance than the constrained modulus. It is observed that the ratio of cone resistance of cemented sand to that of uncemented sand linearly increases as the normalized cohesion intercept does.

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