Evaluation of undrained shear strength of Busan clay using CPT

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ABSTRACT: A series of CPTu, DMT and triaxial tests were performed for clayey soils from the Busan new-port site to evaluate the cone factors of Busan clay. The cone factors, N_{kt}, N_{ke} and $N_{\Delta u}$, are determined by comparing CPT result with undrained shear strength obtained from DMT and triaxial tests. It is observed that N_{kt} and N_{ke} are inversely proportional to the pore-pressure ratio, and these values decrease with the progress of ground improvement. Whereas, $N_{\Delta u}$ appears to increase with plasticity index and is relatively independent of the progress of ground improvement. Using these relationships, the prediction methods of the undrained shear strength are suggested. It is shown that the prediction method using N_{kt} is suitable for evaluating the undrained shear strength of Busan clay.

1 INTRODUCTION

The undrained shear strength of clay is directly measured from field vane, triaxial and simple shear tests, or indirectly predicted by using the results of cone penetration test (CPT) and flat dilatometer test (DMT). For predicting undrained shear strength of clayey soil using the results of CPT, it is important to use appropriate method because CPT is affected by not only the undrained shear strength but also the complex behavior of geotechnical properties. Since in situ penetration tests provide the measurements which are obtained under different shear mode and strain rate from those of the direct tests, the cone factor is considered to be an empirical factor reflecting these incompatibility. The cone factor is also considered as the soil characteristics because it is affected by soil properties.

Several researchers suggested the empirical relationships between cone factors and soil properties, such as plasticity index, rigidity index, pore-pressure ratio (Vesic 1972, Baligh 1975, Teh & Houlsby 1991, Karlsrud et al. 1996). It is difficult to use rigidity index, because rigidity index is not easily determined. Whereas, pore-pressure ratio, which can be measured by CPTu, can reflect various soil conditions. Therefore, in this study, the relationships between the cone factors and the pore-pressure ratio are analyzed. For this, CPTu, DMT and triaxial tests are performed for Busan clay.

2 CONE FACTORS

Studies for predicting the undrained shear strength using CPT have been progressed empirically and theoretically. The results of these studies show that the relationship between the undrained shear strength and cone resistance is presented as equation (1). Because cone resistance (q_c) measured from u_2 type piezocone is affected by pore-pressure, Lunne et al. (1985) suggested a prediction method using corrected cone resistance (q_t) such as equation (2). Here, N_k & N_{kt} are cone factors, σ_{vo} is total vertical stress. Aas et al. (1986) showed that value of N_{kt} is 8~20 and it increases with increasing the plasticity index. Karlsrud et al. (1996) found that N_{kt} turned out to be 6~18 and it is related to the pore-pressure ratio.

$$s_u = \frac{q_c - \sigma_{v0}}{N_k} \quad (1)$$

$$s_u = \frac{q_t - \sigma_{v0}}{N_{kt}} \quad (2)$$

Senneset et al. (1982) suggested a prediction method of the undrained shear strength using effective cone resistance (q_e) as equation (3), and mentioned that the value of N_{ke} is 6~12. Lunne et al. (1985) found that the value of N_{ke} is 1~10 and it is related to the pore-pressure ratio.

$$s_u = \frac{q_e}{N_{ke}} = \frac{q_t - u_2}{N_{ke}} \quad (3)$$

Using several theoretical approaches, the relationships between the undrained shear strength and the excess pore-pressure have been suggested as equation (4) (Vesic 1972, Randolph & wroth 1972). According to cavity expansion theory, $N_{\Delta u}$ varies from 2 to 20, and Lunne et al. (1985) indicated that the value of $N_{\Delta u}$ is 4~10. Karlsrud et al. (1996) found that the $N_{\Delta u}$ value is turned out to be 6~8 and it has no relationship with pore-pressure ratio.

$$s_u = \frac{\Delta u}{N_{\Delta u}} = \frac{u_2 - u_0}{N_{\Delta u}} \quad (4)$$

3 TEST SITES AND PROGRAM

3.1 *Description of test site*

The test site is located at the construction site of the north container port in Busan new-port, Busan, Korea. The longitude and latitude of the test site are E128°47’56”, N35°04’30”, respectively. The test site were originally located below sea level, however, dredged sand up to a thickness of 6 m was dumped over the original clay deposit. Ground improvement was carried out by installing prefabricated vertical drains into the clay and applying additional surcharge load.

The natural water content of the clay layer, which was deposited to have a thickness of 40~45m varies from 40% to 80%. The liquid limit and the plastic limit of clay layers are 40~80% and 15~40%, respectively. Busan clay is classified CH or CL by

USCS classification, and the predominant clay mineral is illite (Locat and Tanaka 1999, Hong et al. 2008).

3.2 *Test program*

Before ground improvement, two series of CPTu, DMT and field vane test were carried out, and samples were extracted by a piston sampler in order to perform triaxial tests. CPT and DMT were conducted at G.L.-7m~G.L.-45m and G.L.-7m~G.L.-32m, respectively. The field vane tests were performed every 4m interval from G.L.-8m to G.L.-28m. The CK_0U triaxial tests were conducted about 2.5m intervals from G.L.-10m to G.L.-40m.

After completion of ground improvement, CPT and DMT were carried out again at the same location. Casings were installed at G.L.-18m through the 13m gravel surcharge layer and 6m sand-fill layer to do these tests. CPT and DMT were conducted from G.L.-20m to G.L.-35m. The strength of clay after the improvement is too high to perform the field vane tests.

4 TEST RESULTS

4.1 *Piezocone tests*

Figure 1 shows the results of CPTu tests. The depth in Figure 1 is the one from the ground level before ground improvement, and the depth after ground improvement is converted considering surcharge and settlement. Except for the data in thin sand layers, the q_t and u_2 values before the ground improvement linearly increase with depth, whereas, the q_t and u_2 values after the ground improvement are almost constant with depth in spite of some scatter. The normalized cone resistance (Q_t) of unimproved ground decreases from 7 to 3 with depth up to G.L.-30m, and Q_t of improved ground varies between 3 and 4. The pore-pressure ratio (B_q) of unimproved ground increases from 0.2 to 1.0 with depth up to G.L.-30m, and the pore-pressure ratio of unimproved ground distributes between 0.5 and 0.8.

4.2 *Undrained shear strength*

Figure 2 shows the profiles of undrained shear strength with depth. The undrained shear strength obtained from CK_0U triaxial compression test, $s_{u(CKU)}$, increases with increasing depth, and the value of the normalized undrained shear strength, $s_{u(CKU)}/\sigma'_v$, is constant with depth at 0.32. The undrained shear strength evaluated from DMT, $s_{u(DMT)}$, is calculated using Marchetti (1980). As shown in Figure 2, $s_{u(DMT)}$ of unimproved ground is similar to $s_{u(VST)}$. This may be because Marchetti suggested the estimation method by comparing the undrained shear strength with vane shear strength. It is observed from Figure 2 that the $s_{u(VST)}$ and $s_{u(DMT)}$ values of unimproved ground increase with increasing depth, and the value of $s_{u(DMT)}/\sigma'_v$ and $s_{u(VST)}/\sigma'_v$ is 0.22, approximately. It is also shown that the $s_{u(DMT)}$ increases about 50kPa due to the ground improvement. Although the $s_{u(DMT)}$ of improved ground shows some scatter, it slightly increases with depth.

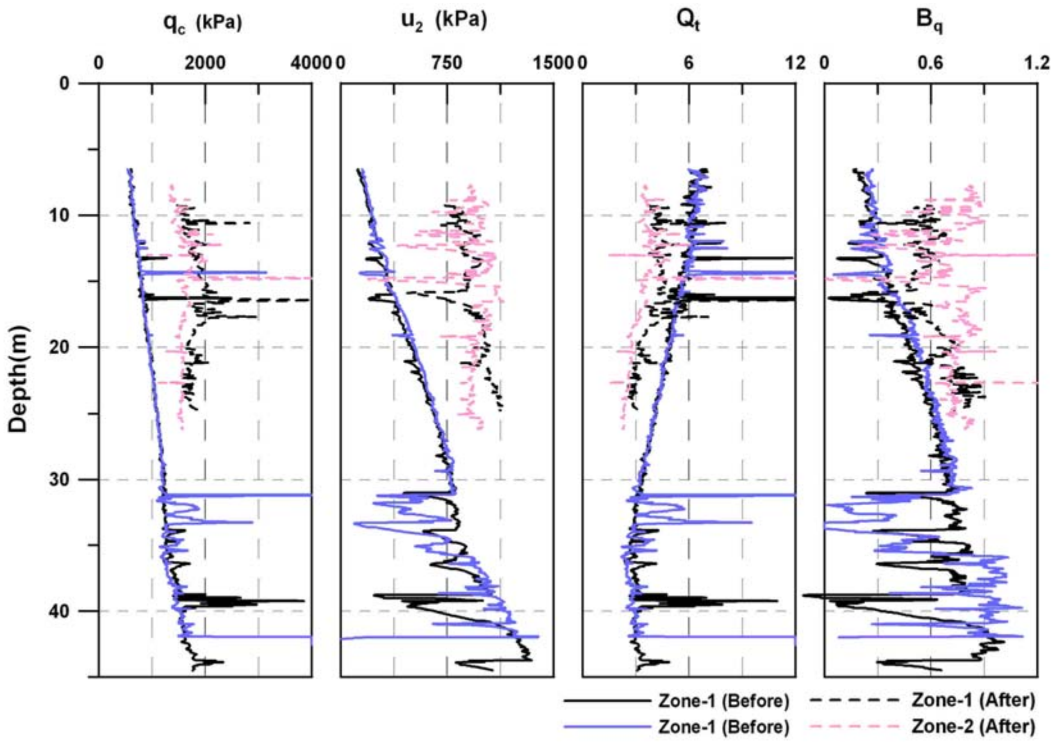

Figure 1. CPTu results.

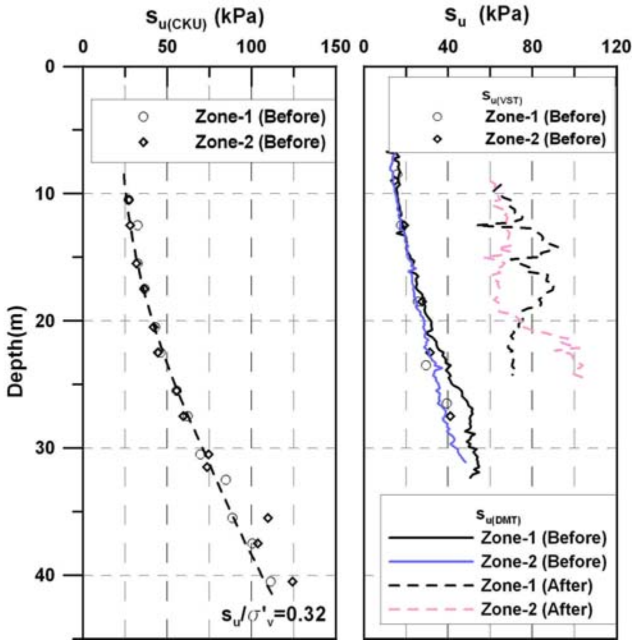

Figure 2. Profiles of undrained shear strength.

5 ANALYSIS

5.1 *Cone factors to evaluate $s_{u(CKU)}$*

Because the undrained shear strength can be determined by different test methods, different cone factor values are used according to the type of undrained shear strength. The cone factors, N_{kt}, N_{ke}, and $N_{\Delta u}$, are obtained by comparing CPTu results with $s_{u(CKU)}$. This study investigates how the cone factors are related to the plasticity index and the pore-pressure ratio.

Figure 3 shows the relationships between the cone factors and the plasticity index (PI). The values of N_{kt}, N_{ke} and $N_{\Delta u}$ are 7~20, 3~18 and 4~9, respectively. The N_{kt} and N_{ke} values appear not to be related to PI, whereas the $N_{\Delta u}$ value increases with increasing plasticity index. The coefficient of determination (R^2) for the $N_{\Delta u}$-PI relation is 0.54.

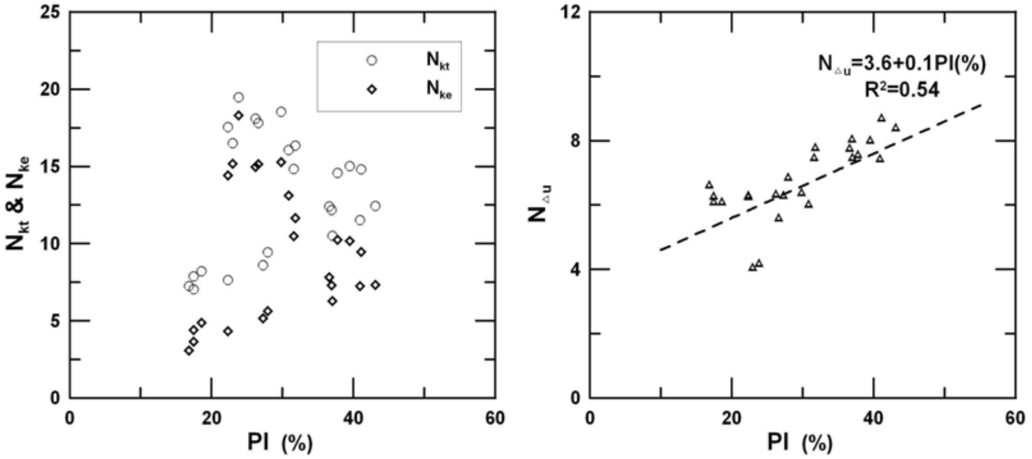

Figure 3. The relationship between the cone factors for $s_{u(CKU)}$ and the plasticity index.

Figure 4 is the relationships between the cone factors and pore-pressure ratio. In this figure, both N_{kt} and N_{ke} are inversely proportional to the pore-pressure ratio. Based on the data shown in Figure 4, N_{kt} and N_{ke} are expressed as $N_{kt} = 24\text{-}19B_q$ and $N_{ke} = 22\text{-}22B_q$, respectively. $N_{\Delta u}$ seem to be no clear relation with the pore-pressure ratio, however $N_{\Delta u}$ can be expressed as $N_{\Delta u} = 24B_q\text{-}19B^2_q$ in figure (4) because $N_{\Delta u}$ has relationship with B_q as equation (5).

$$\frac{\Delta u}{N_{\Delta u}} = \frac{q_t - \sigma_{v0}}{N_{kt}} \Rightarrow \frac{\Delta u}{q_t - \sigma_{v0}} N_{kt} = B_q \cdot N_{kt} = N_{\Delta u} \qquad (5)$$

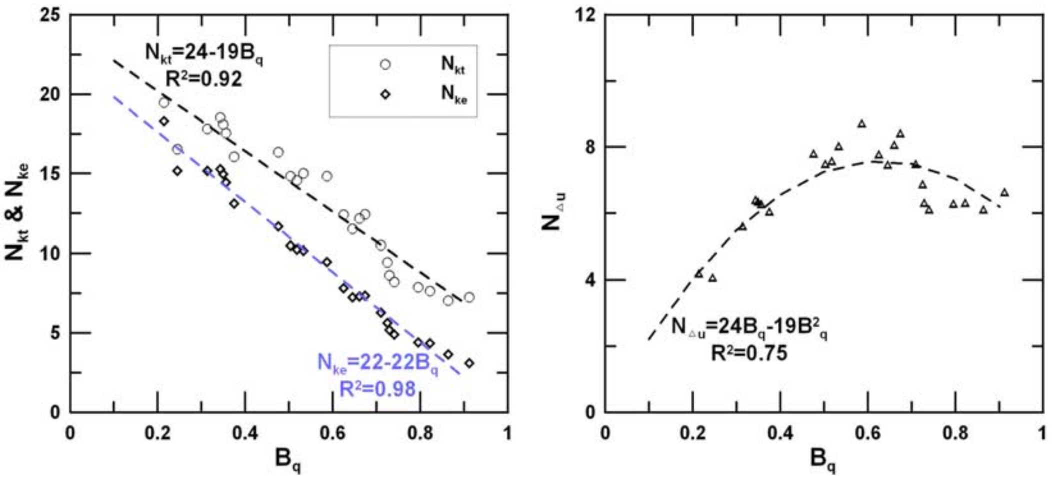

Figure 4. The relationship between the cone factors for $s_{u(CKU)}$ and the pore-pressure ratio.

5.2 *Cone factors to evaluate $s_{u(DMT)}$*

The relationship between the cone factor and plasticity index is shown in Figure 5. As the undrained shear strength evaluated from DMT results is about 1.5 times smaller than those from triaxial test results, the cone factor to predict $s_{u(DMT)}$ is larger than that for $s_{u(CKU)}$. It is observed from Figure 5 that the values of N_{kt} and N_{ke} decrease due to the ground improvement while the value of $N_{\Delta u}$ is almost unchanged. It is difficult to find good correlation between the N_{kt} (or N_{ke}) and plasticity index although N_{kt} and N_{ke} values show the tendency of decreasing with plasticity index. This is because N_{kt} and N_{ke} values decrease due to the ground improvement, whereas the plasticity index is not changed. In addition, although $N_{\Delta u}$ of unimproved ground increases with plasticity index, it is hard to correlate $N_{\Delta u}$ to the plasticity index.

Figure 6 is the relation between the cone factor and pore-pressure ratio. In Figure 6, N_{kt} and N_{ke} show a clear trend to decrease with the increase in pore-pressure ratio. This is because the pore-pressure ratio, as well as N_{kt} and N_{ke}, decreases due to the ground improvement. The correlations between the cone factors and the pore-pressure ratio are expressed as N_{kt} = 40-35B_q, N_{ke} = 38-42B_q, and the R^2 of these correlations are 0.72 and 0.86, respectively. Since the $s_{u(DMT)}$ values are similar to $s_{u(VST)}$, the results in Figure 5 and 6 should also apply to the cone factors linked to $s_{u(VST)}$.

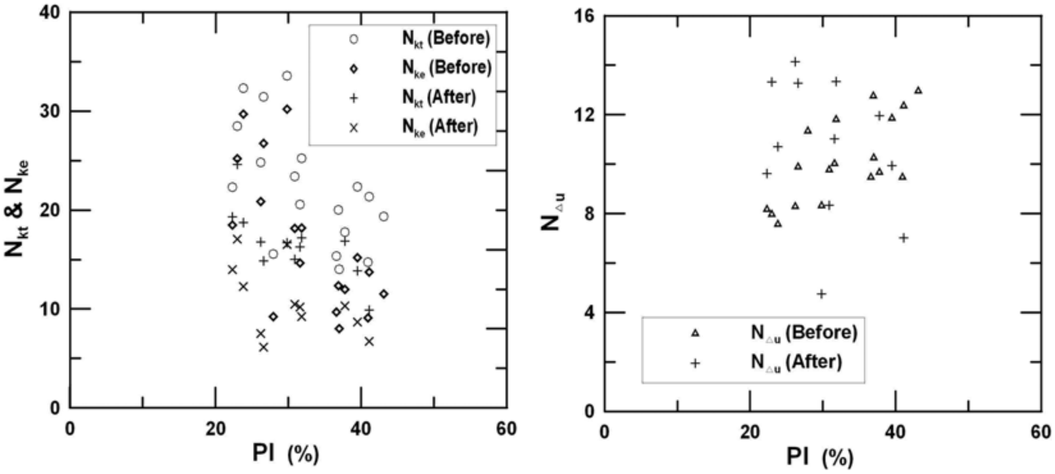

Figure 5. The relationship between the cone factors for $s_{u(DMT)}$ and the plasticity index.

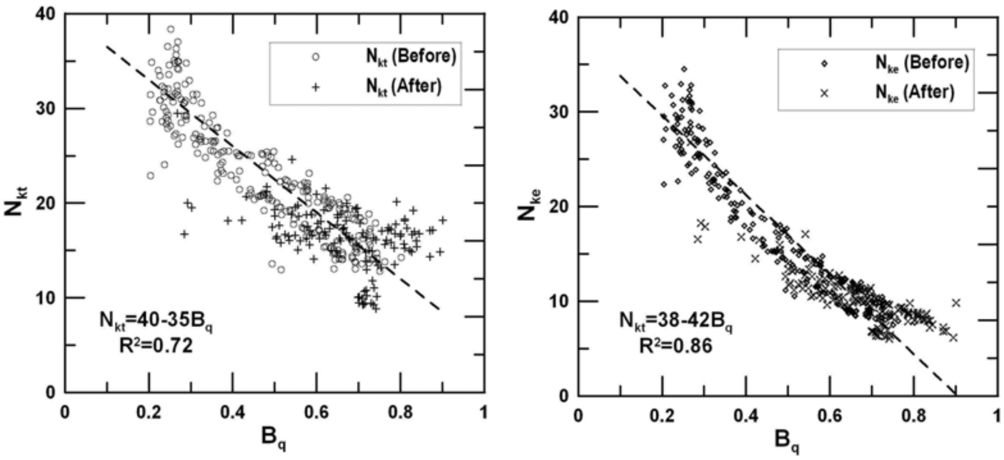

Figure 6. The relationship between the cone factors for $s_{u(DMT)}$ and the pore-pressure ratio.

5.3 *Comparison of measured and predicted shear strength*

The $s_{u(CKU)}$ and $s_{u(DMT)}$ can be evaluated by using the Equations given in Table 1. And Table 2 presents the standard deviations in percent errors for the undrained shear strength predicted using the equations in Table 1. Here, percent error can be calculated as equation (6). As shown in Figures 4~6, the correlations between N_{ke} and pore-pressure ratio have smallest value of R^2. However, the standard deviation of percent error expected when using N_{kt} prediction is smaller than that using N_{ke} prediction. Although N_{ke} and N_{kt} have similar values of error, it is found that the percent error of the undrained shear strength predicted by N_{ke} is larger, because magnitude of N_{ke} is smaller than that of N_{kt}. Consequently, the correlation between N_{kt} and pore-pressure ratio is more appropriate to evaluate the undrained shear strength of Busan clay.

$$Percent \quad error = \frac{predicted - measured}{measured} \quad (\%) \qquad (6)$$

Table 1. Suggested prediction equations.

	$s_{u(CKU)}$	$s_{u(DTM)}$
Equation using N_{kt}	$(q_t - \sigma_{v0})/(24-19B_q)$	$(q_t - \sigma_{v0})/(40-35B_q)$
Equation using N_{ke}	$(q_t - u_2)/(22-22B_q)$	$(q_t - u_2)/(38-42B_q)$

Table 2. Standard deviations in percent errors.

	$S_{u(CKU)}$	$S_{u(DTM)}$		
	Unimproved	Unimproved	Improved	Total
N_{kt}	14 %	12 %	31 %	20 %
N_{ke}	17 %	10 %	92 %	55 %

6 CONCLUSIONS

This paper discussed the evaluation of the undrained shear strength using CPTu for Busan clay. For this, CPTu, DMT and triaxial tests were performed. The cone factors calculated from test results are correlated with plasticity index and the CPT pore-pressure ratio, and the prediction methods are suggested using these correlations.

The values of N_{kt}, N_{ke} and $N_{\Delta u}$ for $s_{u(CKU)}$ are 7~20, 3~18 and 4~9, respectively. N_{kt} and N_{ke} are reversely proportional to the pore-pressure ratio, and $N_{\Delta u}$ increases as the plasticity index increases. The correlations between the cone factors for $s_{u(CKU)}$ and the pore-pressure ratio are expressed as $N_{kt} = 24\text{-}19B_q$, $N_{ke} = 22\text{-}22B_q$, and R^2 of these relations are 0.92 and 0.98, respectively.

Because, $s_{u(DMT)}$ is smaller than $s_{u(CKU)}$, the values of N_{kt}, N_{ke} and $N_{\Delta u}$ for $s_{u(DMT)}$ are about 1.5 times larger than those for $s_{u(CKU)}$. The values of N_{kt} and N_{ke} decrease due to the ground improvement while the value of $N_{\Delta u}$ is almost unchanged. Because the pore-pressure ratio, as well as N_{kt} and N_{ke}, decreases due to the ground improvement, N_{kt} and N_{ke} show the clear trend with pore-pressure ratio. The correlations between the cone factors for $s_{u(DMT)}$ and the pore-pressure ratio are expressed as $N_{kt} = 40\text{-}35B_q$, $N_{ke} = 38\text{-}42B_q$, and the R^2 of these correlations are 0.72 and 0.86, respectively.

Although, the correlations between N_{ke} and pore-pressure ratio have smallest value of R^2, the prediction methods using N_{kt} is more exact than one using N_{ke} in terms of the standard deviation of percent error. Consequently, using N_{kt} prediction is more suitable to evaluate the undrained shear strength of Busan clay.

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