Characterization of in-situ properties of Korean marine clays using CPTU and DMT

Caractérisation des propriétés in-situ pour des argiles marines coréennes en utilisant le CPTU et le DMT

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ABSTRACT: In Korea, a number of huge construction projects such as a reclamation project for an international airport, a west-south highway project, and many harbor constructions are in progress in coastal areas. Most of the projects require large-scale reclamation and ground improvement. In order to select a proper ground improvement technology and to assess the quality and rate of improvement, it is essential to characterize in-situ properties of the soft marine clay layer which may have many thin silt or sand seams. In this paper, both CPTU and DMT were performed to characterize in situ properties of Korean marine clay. Both tests provided quite similar site classifications, and using the penetration pore water pressure was a better indicator for the classification of Korean marine clay layer where sand or silt seams are frequently interbedded. Undrained strengths determined by the tip resistance and the excess pore water pressure from CPTU were very similar in clayey soil layers, and strength determined by DMT was an approximately average value of strengths obtained from CPTU. The theoretical time factor proposed by Gupta may provide the reliable estimation of coefficient of consolidation, especially for the Korean coastal site where there are many silt or sand fractions and seams.

RESUME: En Corée, un certain nombre des projets de construction de grande envergure, comme un projet de récupération pour un chantier d'aéroport international, un projet d'autoroute sud-ouest et des constructions de port, sont en cours dans des régions côtières. La plupart des projets nécessitent la récupération à grande échelle et l'amélioration de terrain. Pour choisir la technologie adéquate de l'amélioration de terrain et pour estimer la qualité et le taux d'amélioration, il est essentiel de caractériser les propriétés in-situ de la couche des argiles marines tendres qui peut avoir un grand nombre de veines minces de limon ou de sable. Dans cet article, CPTU et DMT sont réalisés pour caractériser les propriétés in-situ des argiles marines coréennes. Les deux essais founissent la classification de zone similaire, et en utilisant la pénétration, la pression interstitielle hydraulique pour la classification était meilleur index dans la couche des argiles marines coréennes où les sables de la veine de limon sont interstratifiés fréquemment. Les résistances non draînées déterminées par la résistance d'extrémité et l'exces de pression interstitielle hydraulique de CPTU, étaient très similare dans les couches de sable argilieux, et la résistance déterminée par DMT était approximativement la valeur moyenne de la résistance obtenue de CPTU. Le facteur du temps théorique proposé par Gupta peut fournir la plus petite différence avec le data d'essai oedométrique que l'autre solutions, surtout pour la zone côtière coréenne où il y a des fractions et des veines de limon ou de sable.

1 INTRODUCTION

In Korean coastal area, soft marine clay broadly exists in a depth ranging from 9 to 18m in the west-coast and 9 to 25m in the south-coast. The soft clay layer is underlain by about 2m thick dark gray gravelly or silty sand, and then weathered rocks. The geotechnical problems in these areas are mostly associated with this soft clay layer. Almost all of the marine clays are inorganic and classified as ML and CL, with low plasticity index ranging from 12 to 24%. The average natural water content ranges from 36% to 52%, which is higher than the liquid limit. The average initial void ratio is almost 1.0 and the degree of saturation increases with depth. The compression indices range from 0.2 to 0.26 and the average OCR ranges from 1.9 to 3.1 for the upper layer, which is affected by the tidal action, desiccation, and the lowering of ground water table and the lower layer is almost normally consolidated (Park et al.,1996).

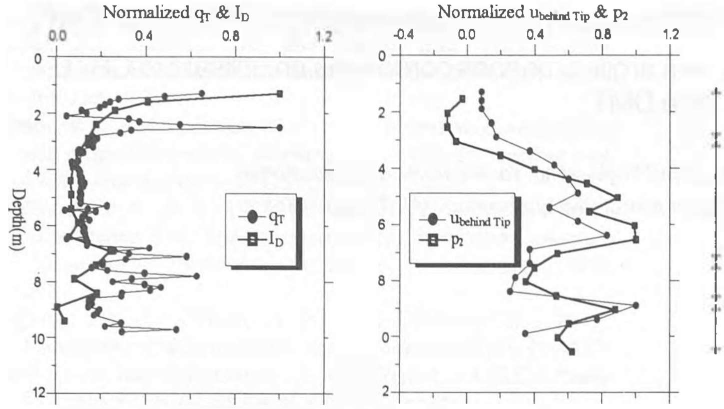
Korean marine clay layers are relatively uniform in the horizontal direction but considerably vary in the vertical direction due to many embedded sand and silt seams. Because the clay layer sometimes contains large amounts of silt fractions, the sample disturbance caused during sampling, transportation, and sample preparation is also inevitable. Therefore, in order to find out the proper geotechnical characteristics, it is preferable to conduct in-situ tests such as CPTU and DMT. Both CPTU and DMT are simple, repeatable, and economical testing methods, and can also provide very reliable information on the soil classification, undrained shear strengths, and in-situ consolidation properties. Nowadays, in Korea, efforts are focused on finding out the site specific cone factors, and assessing the applicability of the current soil classification chart and the theoretical solution for evaluating the coefficient of consolidation.

In this paper, in-situ properties of Korean marine clay were characterized using CPTU and DMT. Both tests were performed at the same sites to assess the applicability in the Korean marine clay, focusing on the evaluation of soil classification, undrained shear strength, and consolidation characteristics.

2 DESCRIPTION OF CPTU AND DMT

Conventional piezocone tests continuously provide three individual measurements of cone tip resistance (q_c), sleeve friction (f_s), and pore water pressure ($u_{behind\ tip}$). The standard penetrometer has an $60°$ of apex angle, $10cm^2$ of projected cone area, and $150cm^2$ of sleeve area. The cone is advanced at a constant rate of $20mm/sec$. The CPTU equipment used in this study has the pore water pressure measuring element located immediately behind cone tip, and the measured cone tip resistance, q_c, was corrected to q_T using $u_{behind\ tip}$. Unequal end area adjustment coefficient, a, was found to be 0.85 from the laboratory experimental data.

The Marchetti type flat dilatometer was used in this study. The blade has a dimension of $14mm$-thick, $95mm$-wide, and $220mm$-long. A flexible stainless steel membrane of $60mm$ in diameter is located on one face of the blade. The penetrometer was advanced at a constant rate of $20mm/sec$. At a selected depth, the pressure readings of A, B, and C were measured with a control box and the measured pressures were corrected to the



Classification Results

DMT	CPTU(B_q)	CPTU(q_T)
Sandy silt & Silt	Sandy silt & Silty Clay	Clayey silt & Clay
Clay	Clay	Sensitive fine grained
Clayey silt	Clayey silt	Clayey silt
Mud	Clay	Sensitive fine grained

Figure 1. Comparison of soil classification results by CPTU & DMT

pressures of P_o, P_1, and P_2 using membrane stiffness factors.

3 TEST RESULTS

3.1 Soil classification

In the coastal projects, the determination of the rate of consolidation is essential in assessing the quality and rate of ground improvement. Because a single sand stratum in the middle of a clay layer can reduce the length of drainage path by a factor of two, thereby increasing the rate of settlement by a factor of four. Whether or not embedded sand strata are capable of providing internal drainage layer, it has an important effect on the rate of consolidation and settlement estimation. In such a view point, classification of the embedded silt or sand layers and lenses during the phase of site investigation governs the success of the projects.

One of the primary applications of penetration test such as CPTU and DMT is to determine the continuous stratigraphic profiling. Among the soil classification charts for CPT and CPTU, the charts recommended by Robertson et al.(1986) which utilizes the cone tip resistance q_T - the friction ratio R_f and the cone tip resistance q_T - the pore pressure ratio B_q were used.

Typical site classifications determined by q_T-R_f and q_T-B_q relationships were compared in Figure 1. Both classification systems provided similar results, and were able to detect the interbedded sand or silt layer by monitoring either the increase of q_T or the decrease of the generated pore water pressure. The response of pore water pressure when penetrating the silt seams consistently decreased whereas the response of q_T was not consistent, particularly when the thickness of silt seam was thin. For the detection of interbedded silt layers, monitoring the variation of pore water pressure using CPTU appears to be a superior method. The existence of thin layered silt seams was verified by obtaining undisturbed samples, and the interbedded silt seams(thin bright strips) were shown in Figure 2.

The clay layers located at the depths ranging from 3 to 7m and from 8.5 to 10m were classified as sensitive clay based on the q_T-R_f chart. Since the sensitive clay rarely exists in Korea, q_T-R_f classification chart should be modified based on the national geotechnical characteristics. In order to determine the site-specific classification charts, on-going researches are being performed in Korea.

For the soil classification, DMT chart using material index, I_D, and dilatometer index, E_D, and the chart using I_D and pore pressure index, U_D, were used and the results were compared with those determined by CPTU in Figure 1. Even though slight differences caused by discontinuous DMT readings in depth exist, DMT provides similar site classification compared with CPTU result, and both tests predicted quite well the existence of interbedded silt layer, yet without knowing exact embedded characteristics of the layer.

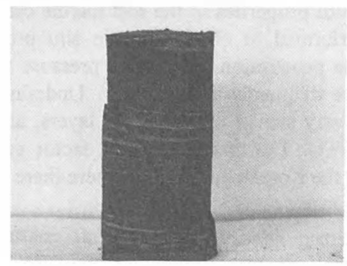


Figure 2. Typical undisturbed clay sample showing the embedded thin silt lenses.

P_2 value obtained from DMT is known to represent the penetration pore water pressure. It is interesting to note that normalized P_2 value has very similar shape to the normalized penetration pore water pressure $u_{behind\ Tip}$ measured from CPTU, and both values were more sensitive to the existence of sand or silt seams compared with the material index I_D and the cone tip resistance q_T. From such a view point, the soil classification system based on the generated pore water pressure during penetration may be a better indicator in Korean coastal area where the interbedded silt or sand layers are not unusual.

3.2 Undrained shear strength

Several methods have been proposed in predicting the undrained strength of soils using CPTU. In Korea, engineers usually use the following two methods. One method is to use the cone factor, N_{kt} and the cone tip resistance, q_T, and the other is to use the pore pressure ratio, $N_{\Delta u}$ and the excess pore water pressure, $\Delta u\,(= u_{behind\ tip} - u_o)$ generated during the cone penetration. Generally, the cone factor, N_{kt} was largely scattered due to the problems of measuring accuracy of q_T and pore pressure effects, particularly in soft and fine grained soils. From the authors' experiences the cone factor, N_{kt}, can be influenced by the existence of silt and/or sand fraction in clay deposits. In this study, N_{kt} was determined as 14.4 using laboratory tests with undisturbed samples accounting for the silt layers.

During the cone penetration through the soft and fine grained soils, pore pressures generated is so large that the measured pore pressure may often be very accurate and reliable. Therefore, estimates of soil parameters, such as S_u, will be inherently more accurate when using the pore pressure data. The pore pressure ratio, $N_{\Delta u}$ was originally based on the cavity expansion theory and it included the effects of OCR and sensitivity by using Skempton's pore pressure parameter at failure(A_f). In this study the $N_{\Delta u}$ value was selected as 5.7 based on the FHWA recommendation (1988) with the values of A_f of 0.8 and rigidity index of 100.

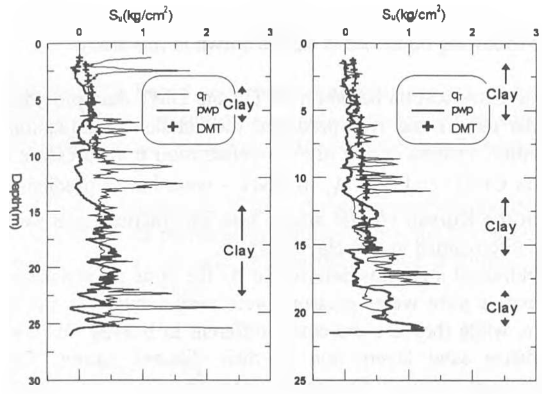


Figure 3. Typical undrained shear strength profiles estimated by CPTU and DMT data.

Typical undrained shear strength profiles estimated by CPTU and DMT are shown in Figure 3. The undrained strength estimated by the cone tip resistance was very similar to that estimated by the excess pore water pressure in clayey soil. However, they exhibited quite differences in the silty or sandy soils where the excess pore pressure measured at immediately behind the cone tip was close to the static pore water pressure, u_o due to fast drainage of excess pore water pressure, or even negative in heavily OC clay and dense sand layers due to their dilatant nature. Referring to the soil classification result, it is clearly shown that the present method is quite effective to determine the undrained strength of the soft and fine grained soils, which have many embedded silt or sands seams.

The undrained strength of clays($I_D \leq 0.6$) can be expressed as follows using Marchetti's empirical relationship between K_D and (S_u/σ'_v):

$$S_u = 0.22\sigma'_v(0.5K_D)^{1.25} \quad (1)$$

where, K_D is the horizontal stress index and σ'_v is the vertical effective stress.

As shown in Figure 3, the undrained strength profile of the clay layer determined by equation(1) represents approximately mean values of those predicted by two different methods using CPTU. The same trends have been obtained at various other sites, and it could be concluded carefully that the undrained shear strength determined from DMT gives an approximate mean value of undrained shear strength of clays obtained from two different methods using CPTU in Korean coastal area.

3.3 Consolidation characteristics

Estimating the rate of consolidation is substantially important in geotechnical engineering project, especially in coastal area. The coefficient of consolidation is usually obtained from the oedometer test. However, test results are very sensitive to sampling disturbance and sometimes, laboratory values cannot be a representative value for the whole site because of the localization of sampling. Therefore, in order to get a more appropriate coefficient of consolidation for the whole site, it is preferable to conduct in-situ dissipation tests using CPTU and/or DMT.

By monitoring the dissipation rate of the excess pore pressures generated during the cone penetration, the horizontal coefficient of consolidation can be estimated as follows:

$$C_h = \frac{T_{50} \cdot R^2}{t_{50}} \quad (2)$$

where:
C_h = horizontal coefficient of consolidation
T_{50} = theoretical time factor for 50% dissipation
R = probe radius
t_{50} = time elapsed for 50% dissipation

Several theoretical solutions have been suggested to obtain the coefficient of consolidation from the dissipation test (Torstensson, 1978; Gupta,1983; Levadoux & Baligh,1986; Teh & Houlsby, 1991). However, it is not easy to select the time factor because it varies significantly with many factors, such as cavity shape, rigidity index, I_R, sensitivity and over consolidation ratio.

Table 1 shows time factors proposed by several researchers. Using their values, the coefficients of consolidation obtained from CPTU were compared with those from oedometer test to find out which time factor could provide the smallest difference between them.

Table 1. Predicted values of time factors

	I_R	T_{50}	Remarks
Torstensson	100	3	cylindrical cavity, 1978
Gupta	100	1.79	spherical cavity, 1983
Levadoux & Baligh	-	5.6	strain path method, 1986
Teh & Houlsby	100	2.45	$T^* = \frac{C_h \cdot t}{R^2\sqrt{I_R}}$, strain path method, 1991

For the effective comparison between in-situ and laboratory coefficients of consolidation, the in-situ horizontal coefficient of consolidation was converted to the vertical value by using equation(3).

$$C_v = C_h \times \frac{k_v}{k_h} \quad (3)$$

where k_h/k_v was selected as 3.5 assuming that the soil compressibility is isotropic and the site is slightly layered based on classification results (Ladd,1976).

As shown in Figure 4, the coefficients of consolidation obtained by the oedometer test are generally smaller than that obtained by in-situ test. In spite of this general trend, it is very interesting to note that coefficients of consolidation estimated from the CPTU data using Gupta's solution match well with the coefficients obtained from the laboratory oedometer tests. Furthermore, Gupta's solution provides more consistent consolidation coefficient than any other's solution. Such a result may be due to the basic assumption and the analysis technique provided by Gupta.

That is: as the cone advances, it produces a series of successive spherical cavity expansions in its immediate vicinity, and the penetration pore pressures developed due to the undrained cavity expansion are subjected to significant dissipation by the time the cone advances to its final location. There must be a significant dissipation of the pore pressures during the cone penetration in the field where embedded silt or sand seams are included, which is typical in Korean coastal area. Therefore, the Gupta's assumptions are more realistic in this case and hence it shows small differences in the values of coefficient of consolidation obtained from the oedometer test and in-situ test. Also the predicted coefficients using the solution by Teh & Houlsby(1991) provide relatively small differences. It might be caused by the fact that they presented a modified time factor considering the rigidity index in the calculation of the time factor as shown in Table 1.

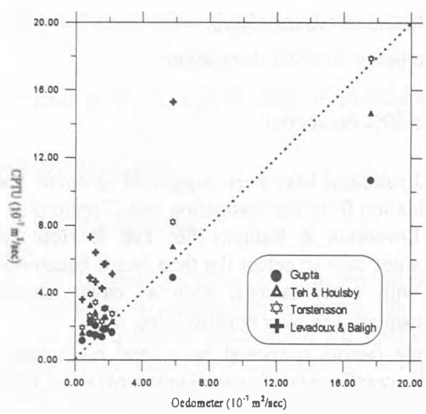


Figure 4. Comparison of coefficients of consolidation determined by various methods

It has been mentioned that the closing pressure (P_2) obtained from a standard Marchetti DMT is very similar to the penetration pore pressure for clean sand and soft clays(Robertson et al., 1988). Thus the coefficient of consolidation can also be estimated by simply measuring the C-values during DMT, similarly in the CPTU dissipation test. However, no theoretical solution has been proposed for the DMT dissipation test. Thus, it was assumed that as the simplest approach, the Gupta's theoretical solution in CPTU could be employed with an equivalent cylindrical radius for the $95 \times 14mm$ rectangular cross-section of the DMT blade. The value of t_{50} was assumed to be decided from $P_2 - \sqrt{t}$ plot method(FHWA,1988).

Limited number of DMT dissipation tests were performed at the same depth where the CPTU dissipation tests were conducted. Then, the coefficients of consolidation were calculated by using $P_2 - \sqrt{t}$ plot method to compare those with the results of the oedometer tests. The detailed procedures were followed FHWA method(1988). Since this procedure was applicable only for soft clays, which have $I_D \leq 0.6$ and $K_D \leq 5.0$, tests were performed at the soft clay layers. Analysis conditions and the results are shown in Table 2.

It seems that the method proposed for the analysis of DMT data could be applicable. However, the result can vary widely by the experiences of analysts and thus it must be noticed that the procedure to estimate C_h from the C-readings is carefully applied and more researches are required.

4 CONCLUSIONS

In order to characterize the in-situ properties of Korean marine clay, both CPTU and DMT were performed in the Korean coastal area. The following conclusions can be drawn in this study.

Table 2. Comparison of coefficients of consolidation determined by CPTU, DMT, and oedometer tests.

Depth	I_D	K_D	T^*_{50}	C_h (DMT)	C_h^{**} (CPTU)	C_h (oedometer)
3.5m	0.38	4.43	1.7	7.2	10.7	11.4
13.0m	0.39	3.81	1.7	11.7	3.6	21.1

* from Gupta's solution(1983) using $I_R = 100$ and piez. element of 4R behind cone tip.

** using Gupta's theoretical solution

*** unit: $\times 10^{-7} m^2/s$

1. Soil classification based on CPTU and DMT data provided very similar results and well predicted the detailed stratification. (Classification systems which use the penetration pore pressure - q_T & B_q in CPTU and I_D & U_D in DMT - were better prediction systems in the Korean coastal area where silt fractions and sand seams are interbedded in soft clay layer).
2. Undrained strengths determined by the cone tip resistance and the excess pore water pressure were very similar for clayey soil layers, while they are extremely different in heavily OC clay and in dense sand layers due to their dilatant nature. The undrained shear strength determined from the DMT data using equation(1) gives an approximate mean value of those obtained from two different CPTU methods.
3. Since there is significant dissipation of pore water pressures during the cone penetration in the site which has embedded silt or sand seams, it can be carefully concluded that the Gupta's theoretical solution is reliable in the estimation of the coefficient of consolidation in the Korean coastal area. To prove this conclusion, more researches are being conducted. DMT dissipation test could be applicable to a preliminary determination of coefficient of consolidation in situ.

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