→ Fig. 3!

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EVALUATION OF UNDRAINED SHEAR STRENGTH OF COHESIVE SOILS USING A FLAT DILATOMETER

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ABSTRACT

The flat dilatometer (in-situ) testing device (DMT) has been used frequently in North America and Europe during the short period of time since its introduction. The main advantages of the DMT are its simplicity, rapid and repetitive use for geotechnical engineering practice.

This paper describes the use of the flat dilatometer (in-situ) testing device (DMT) in Japan. The discussion concentrates on the evaluation of undrained shear strength. Based on the limited available test data in Japan, an attempt has been made to determine the usefulness of Marchetti's equation related to undrained shear strength and to show the important modifications of the Marchetti's equations concerning the evaluation of undrained shear strength. In addition, a new equation has been developed to estimate the undrained shear strength c_u obtained from an unconfined compression test to establish a Japanese design manual for clay foundations.

Key words: cohesive soil, compressive strength, in-situ test, shear strength, sounding, test equipment, unconfined compression test (**IGC:** C3/D6)

INTRODUCTION

The flat dilatometer (in-situ) testing device (DMT) was developed by Marchetti (1980) in Italy. The DMT has been used frequently in North America and Europe during the short period of time since its introduction. The main advantages of the DMT are its simplicity, and ability to be used repetitive, and rapidly in geotechnical engineering practice. The DMT was introduced to Japan in 1989. Very little experience has therefore been accumulated for the DMT in Japan. Based on limited available test data in Japan, an attempt was made to determine the usufulness of the Marchetti's equations regarding some soil parameters and the new equations developed by (Kamei and Yamamoto, 1994; Iwasaki and Kamei, 1994a, 1994b).

The flat dilatometer test results were interpreted using the material index, $I_D=(p_1-p_0)/(p_0-u_0)$, horizontal stress index $K_D=(p_0-u_0)/\sigma'_{vc}$, and dilatometer modulus, $E_D=34.7(p_1-p_0)$, defined by Marchetti (1980). Where p_0 is the contact pressure, p_1 is the 1 mm expansion pressure, u_0 is the in-situ pore water pressure prior to dilatometer insertion, and σ'_{vc} is the effective overburden stress. A summary of methods for performing the DMT were previously described in detail elsewhere (Marchetti, 1980; Schmertmann, 1986; Robertson et al., 1988).

Marchetti (1980) suggested estimating the undrained shear strength c_u as a function of the K_D-value. He showed the empirical relationship between the overconsolidation ratio, OCR, obtained from oedometer tests and the K_D value obtained from the DMT results. The results are satisfactory in uncemented fine-grained soils ($I_D<1.2$) if they are in a state of simple unloading:

$$\mathrm{OCR}=(0.5K_D)^{1.56} \tag{1}$$

The dependence of c_u/σ'_{vc} on OCR is well recognized. The indication of a relationship between K_D and OCR prompted an investigation on the correlation c_u/σ'_{vc} versus K_D. This relationship is based on the suggestion by Ladd et al. (1977). It was suggested that the data can be well defined by the expression:

$$(c_u/\sigma'_{vc})_{oc}=(c_u/\sigma'_{vc})_{nc}(\mathrm{OCR})^{\Lambda} \tag{2}$$

with $\Lambda=0.8$, although a better correlation is obtained if Λ is decreased from 0.85 to 0.75 with an increasing OCR. This result agrees with that reported by Mayne (1988). By combining Eqs. (1) and (2), the undrained shear strength can be expressed as

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$$(c_u/\sigma'_{vc})_{oc}=(c_u/\sigma'_{vc})_{nc}(0.5K_D)^{1.25} \quad (3)$$

Equation (3) can be rearranged as follows.

$$c_u=(c_u/\sigma'_{vc})_{nc}\sigma'_{vc}(0.5K_D)^{1.25}=0.22\,\sigma'_{vc}(0.5K_D)^{1.25} \quad (4)$$

As seen in Eq. (4), Marchetti (1980) assigned to $(c_u/\sigma'_{vc})_{nc}=0.22$ obtained from the field vane tests as suggested by Mesri (1975). It has long been recognized, however, that the undrained shear strength depends on the mode of testing, boundary conditions, strain rate, confining stress level, initial consolidation state, in-situ testing device, and other variables. It is expected, therefore, that different test types produce different test results for undrained shear strength.

The undrained shear strength c_u of cohesive soils has been widely used in the $\phi=0$ analysis of stability. Undrained shear strength is obtained from unconfined compression tests or unconsolidated undrained triaxial compression tests on undisturbed samples, or from vane tests in the field. It is also recommended for use in soils where past experience has shown that a reasonable result is obtained. In most cases, c_u is determined from the unconfined compression test in Japan (Nakase, 1967). As mentioned above, however, Marchetti (1980) assigned a value of $(c_u/\sigma'_{vc})_{nc}$ obtained from the field vane tests as suggested by Mesri (1975).

The purpose of this paper was to investigate the usefulness of the flat dilatometer in-situ testing device (DMT) in Japan. The discussion concentrates on the evaluation of undrained shear strength of cohesive soils. The information presented is based on the experience gained in performing DMT at several sites. Some data for the analyses were collected from previously published test results. Based on limited available test data, the usefulness of the Marchetti's equation regarding undrained shear strength, was investigated.

TEST RESULTS AND DISCUSSIONS

Figure 1 shows the relationship between undrained shear strength c_u obtained from unconfined compression tests and preconsolidation pressure p_c in the normally consolidated region (Ogawa and Matsumoto, 1978). The soils tested were obtained from various places along the coastal areas of Japan. As shown in this figure, c_u increases with increasing p_c. The regression line for this relationship can be given as $c_u=0.35p_c$ with reasonable accuracy. As mentioned earlier, the undrained shear strength will be determined from unconfined compression tests on undisturbed samples as presented in the Japanese design manual for clay foundations. If we consider the Japanese design manual, therefore, the $(c_u/\sigma'_{vc})_{nc}=0.35$ can be recommended.

Figure 2 shows the relationship between the Λ-value previously published data with consolidation tests and PI (Mayne, 1980; Kamei, 1985; Mitachi and Ono, 1985). As seen in this figure, the Λ-value is independent of *PI* with an average value of 0.79. This value appears to be a reasonable value for that obtained using direct simple shear tests. We reconfirmed, therefore, the usefulness of the $\Lambda=0.8$ proposed by Ladd et al. (1977) and Mayne (1988) from the geotechnical engineering point of view.

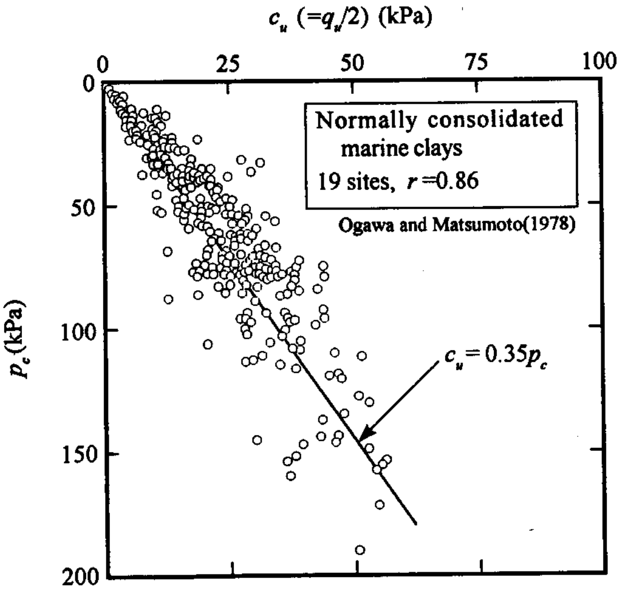

Fig. 1. Relationship between undrained shear strength c_u obtained from unconfined compression tests and preconsolidation pressure p_c in the normally consolidated region

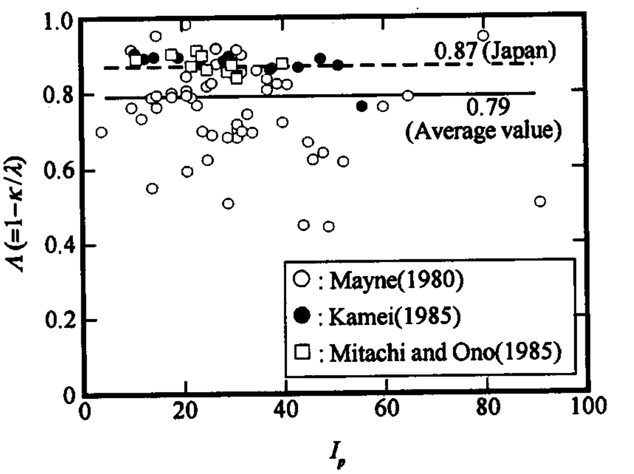

Fig. 2. Relationship between strength rebound parameter Λ obtained from consolidation tests and plasticity index I_p

Mayne (1987) reconfirmed Eq. (1) and also offered a probable explanation for the existence of the K_D-OCR correlation. Figure 3 shows the relationship between OCR and K_D based on previously published data compared to the present data. As shown in the figure, the OCR increases with increasing K_D. A similar relationship between the OCR and the K_D was pointed out by Marchetti (1980) and Mayne (1987). The final regression line for these relationships obtained from the present data and previously published data (Marchetti, 1980; Mayne, 1987; Lacasse and Lunne, 1988; Chang, 1991) can be given as

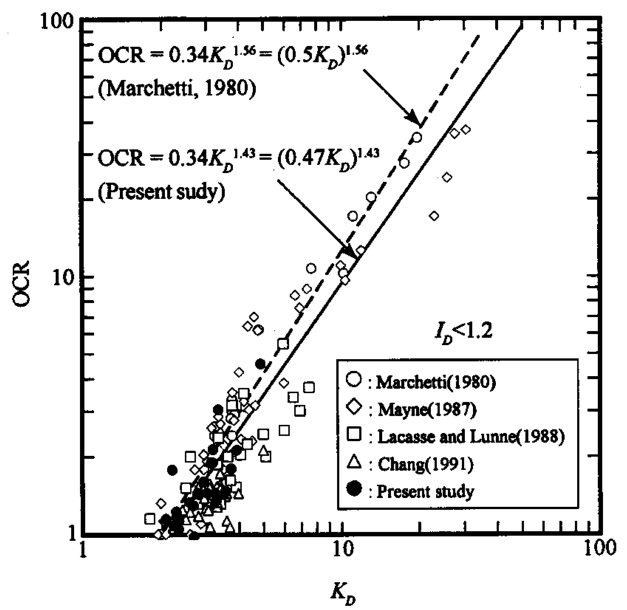

Fig. 3. Correlation between K_D and OCR for cohesive soils all over the world

$$\mathrm{OCR}=0.34K_D^{1.43}=(0.47K_D)^{1.43} \tag{5}$$

This equation is very similar to Marchetti's equation (1). Accordingly, it was reconfirmed that the K_D-OCR correlation proposed by Marchetti (1980) showed a modified equation containing the previously published data and present data. By combining Eq. (5) and $(c_u/\sigma'_{vc})_{nc}=0.35$, Equation (4) can be rearranged as follows.

$$c_u=(c_u/\sigma'_{vc})_{nc}\sigma'_{vc}(0.47K_D)^{1.14}=0.35\sigma'_{vc}(0.47K_D)^{1.14} \tag{6}$$

Figure 4 shows profiles of DMT horizontal stress index K_D, dilatometer modulus E_D and undrained shear strength c_u obtained from unconfined compression tests at Kanagawa (Kurihama) site. The horizontal stress index, K_D, was found to be almost constant at the Kanagawa (Kurihama) and Tokyo (Komatsugawa) sites, however, the dilatometer modulus E_D increases almost linearly with depth as shown in the figure. The same trend has also been observed at other locations (Marchetti, 1980). It would be interesting, therefore, to determine a possible correlation between undrained shear strength and the E_D-values. Figure 5 shows the relationship between undrained shear strength obtained from unconsolidated undrained triaxial compression (UU) or unconfined compression (U) tests and dilatometer modulus E_D. As shown in the figure, the undrained shear strength increases with increasing dilatometer modulus E_D. The regression line for this relationship obtained from the present data can be given as

$$c_u=0.018E_D \quad \text{(Iwasaki and Kamei, 1994a)} \tag{7}$$

Table 1 shows the summary of equations for predicting the c_u using DMT.

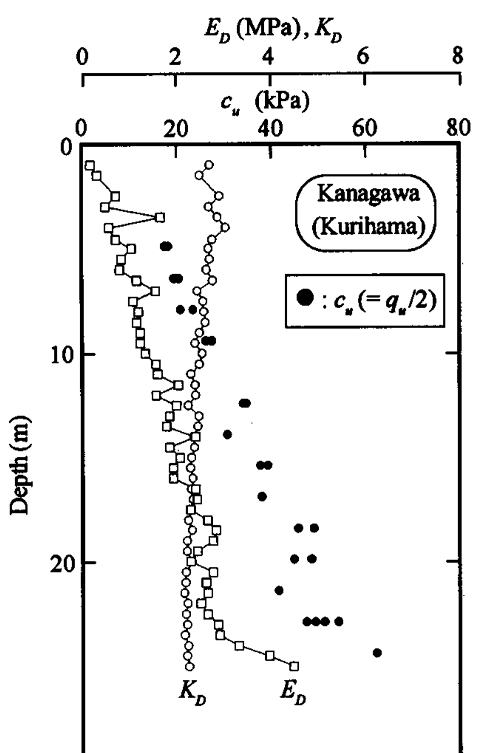

Fig. 4. Profiles of DMT horizontal stress index K_D, dilatometer modulus E_D and undrained shear strength c_u obtained from unconfined compression tests at Kanagawa (Kurihama) site.

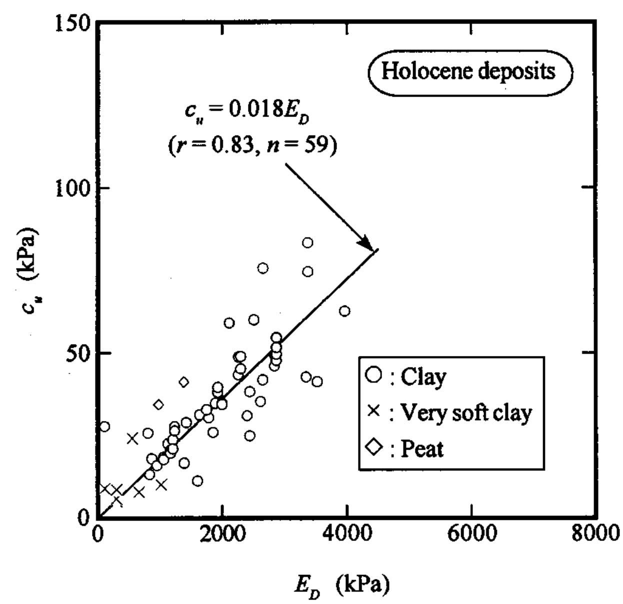

Fig. 5. Relationship between undrained shear strength obtained from unconsolidated undrained triaxial compression (UU) or unconfined compression (U) tests and dilatometer modulus E_D (Iwasaki and Kamei, 1994a).

Table 1. Summary of equations for predicting the c_u using DMT

$c_u=0.22\sigma'_{vc}\,(0.5K_D)^{1.25}$	Marchetti (1980)
$c_u=0.35\sigma'_{vc}\,(0.47K_D)^{1.14}$	Present study (K_D-c_u Eq.)
$c_u=0.018E_D$	Iwasaki and Kamei (1994a) (E_D-c_u Eq.)

Figure 6 shows the comparison of undrained shear strength obtained from unconsolidated undrained triaxial compression (UU) or unconfined compression (U) tests and that from Eq. (4) proposed by Marchetti and Eq. (6) proposed by the study presented in this paper. A comparison of undrained shear strength obtained from unconsolidated undrained triaxial compression (UU) or unconfined compression (U) tests and that from Eq. (4) proposed by Marchetti and Eq. (7) proposed by the present paper is also shown in Fig. 7. Reasonable agreements have been obtained between the observed and the calculated results for the undrained shear strength determined by the present equations. The reasons for the underestimate of undrained shear strength c_u using Marchetti's equation for cohesive soils include the assumption of the value of $(c_u/\sigma'_{vc})_{nc}$ obtained by the differ-

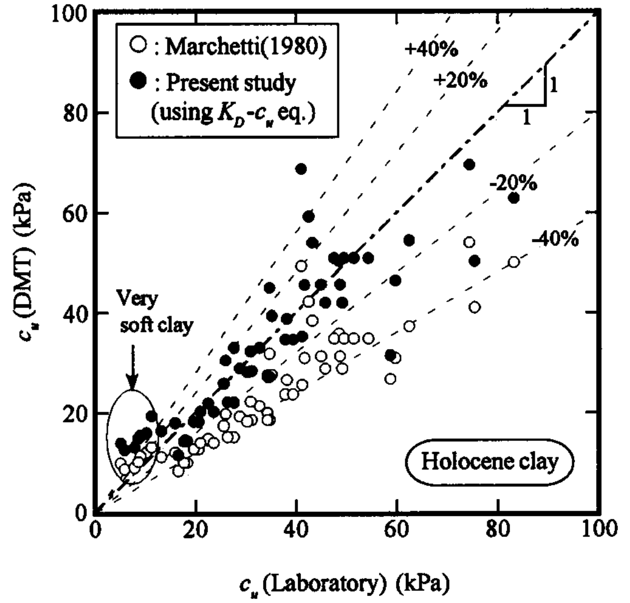

Fig. 6. Comparison of undrained shear strength obtained from unconsolidated undrained triaxial compression (UU) or unconfined compression (U) tests and that from DMT horizontal stress index K_D

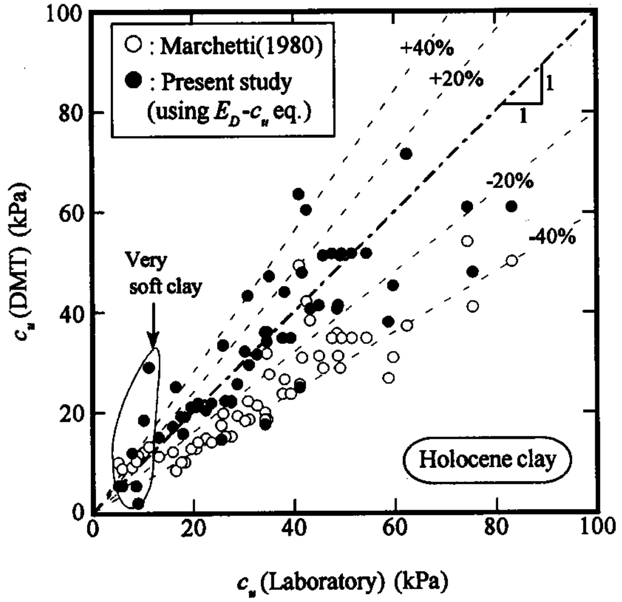

Fig. 7. Comparison of undrained shear strength obtained from unconsolidated undrained triaxial compression (UU) or unconfined compression (U) tests and that from dilatometer modulus E_D (Iwasaki and Kamei, 1994a)

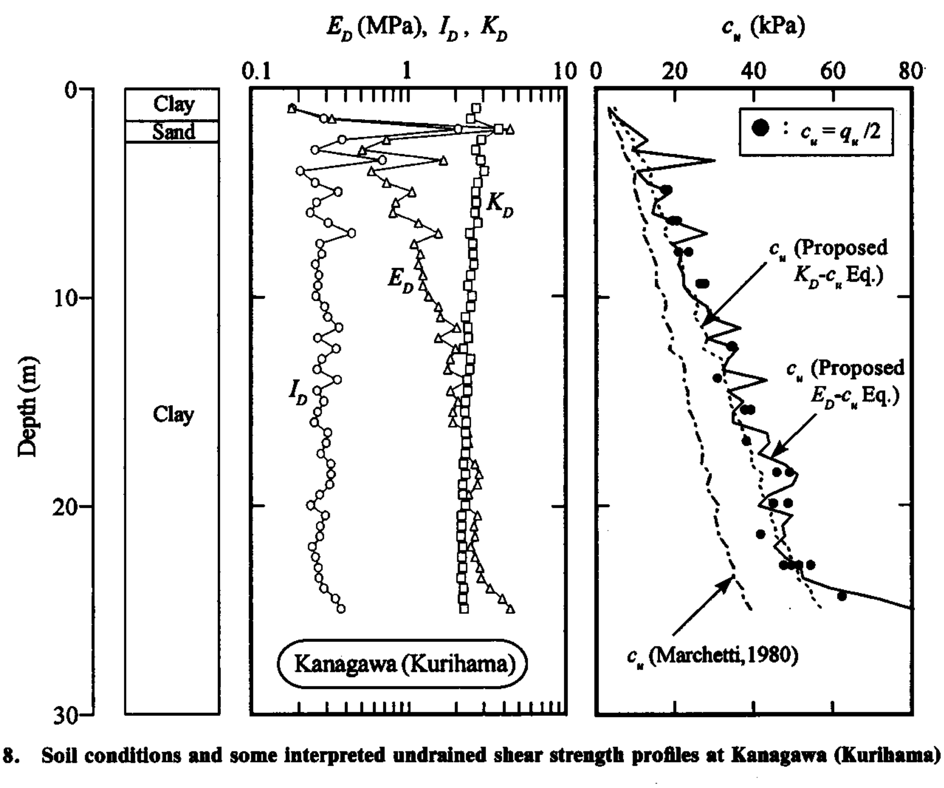

Fig. 8. Soil conditions and some interpreted undrained shear strength profiles at Kanagawa (Kurihama) site

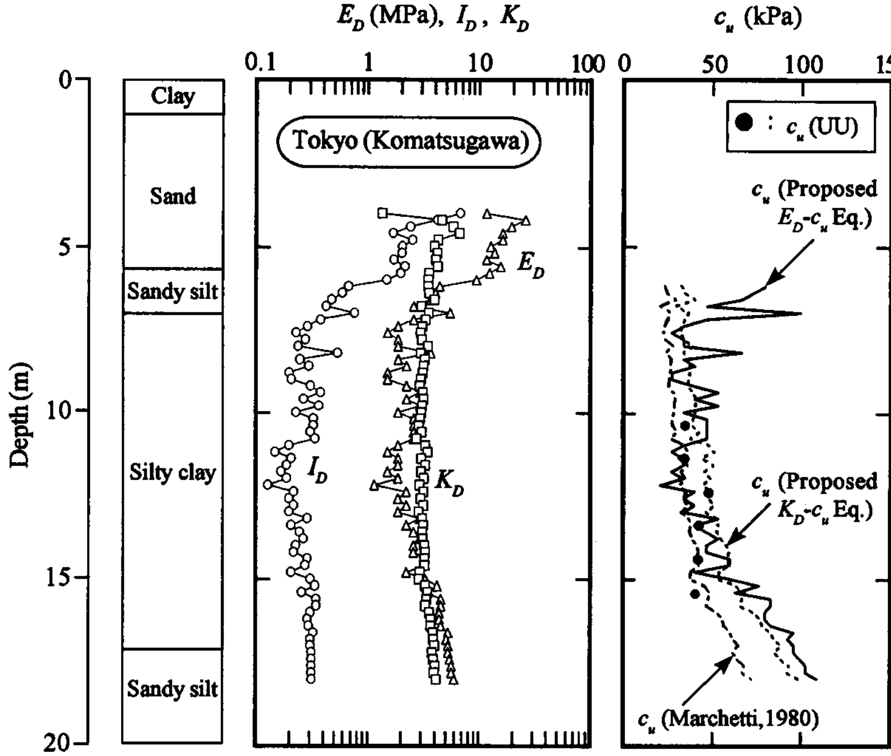

Fig. 9. Soil conditions and some interpreted undrained shear strength profiles at Tokyo (Komatsugawa) site

ent testing conditions (vane shear test). The calculated results obtained using the new equations are found to be reasonable and therefore the use of these equations in geotechnical engineering practice is encouraged.

In order to investigate the applicability of the proposed equations to the field, DMT was carried out at Kanagawa (Kurihama) and Tokyo (Komatsugawa) sites. Soil conditions and some interpreted undrained shear strength profiles at Kanagawa (Kurihama) and Tokyo (Komatsugawa) sites are shown in Figures 8 and 9 (Tanaka et al., 1992; Kamei and Yamamoto, 1994). Reasonable agreements were obtained between the observed and the calculated results of the undrained shear strength proposed from the present equations. As shown in the figures, the abilities of the proposed correlations in predicting undrained shear strength from K_D and E_D were verified using the comparisons with the measured undrained shear strength. A larger data base may enable a more definitive relationship to be established.

It is therefore concluded that the applicability of the new equations to other fields will require further research.

CONCLUSIONS

Based on limited available test data, an attempt was made to determine the usefulness of the Marchetti's equation regarding undrained shear strength. The authors' experience in Japan indicate that using the DMT to determine the undrained shear strength is very encouraging. Although the K_D-OCR correlation proposed by Marchetti (1980) was reconfirmed, the equations may require modification in order to be compatible with Japanese soil conditions and design manual. In addition, the applicability of the proposed equations for prediction of undrained shear strength from K_D and E_D was verified by the comparisons with the measured undrained shear strength.

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