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Ratio of Undrained Shear Strength to Vertical Effective Stress

by

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Abstract

In this paper, we describe an attempt to derive a simplified method for the quantitative estimation of the shear strength increase induced by primary and secondary consolidation. The influence of a negative time-dependent dilatancy on the undrained strength of saturated cohesive soil was investigated. It is clear that the ratio of the undrained strength to the vertical effective stress is affected by the anisotropic consolidation stress ratio and consolidation period. The effective equivalent stress, defined as the water content after the completion of consolidation, is proposed and proved to be suitable for estimating the undrained strength ratio, which is independent of the consolidation period.

Keywords: *Consolidated undrained shear strength, Dilatancy, Stress path, Secondary compression*

1. *Introduction*

Most frequently, the cohesive soil strength required to assess stability is the undrained strength, because the low permeability of clayey soil restricts drainage. The undrained strength or shearing resistance S_u is most conveniently related to the in situ vertical effective stress σ'_{vo} as the ratio S_u/σ'_{vo} (classically, the C_u/p ratio). Many investigators have developed methods for predicting the undrained strength where parameters of failure and initial stress are known[1]. However, in determining the undrained shear strength of saturated cohesive soil in the laboratory, it seems that, for practical purposes, little attention has been paid to the consolidation period. Undrained shear strength is increased due to secondary consolidation[2),3)]. Different strength ratios are provided by adjusting the testing conditions. It is not easy to evaluate the consolidation period in the consolidated undrained shear test. If secondary consolidation is in proportion to the logarithm of time, the void ratio decreases with consolidation. The shearing strength of normally consolidated cohesive soil is influenced by the consolidation period. However, in the current testing method, the shearing strength at the end of primary consolidation is sought and the strength increase during secondary consolidation is ignored.

This paper concerns the evaluation of the undrained shear strength taking account of the effect of effective stress change in primary and secondary consolidation.

Table 1 Physical property of soils tested

sample	ρ_s (g/cm³)	ω_L (%)	ω_p (%)	Grading (%) clay	silt	sand
Soka clay(1)	2.64	82.6	20.8	54	41	5
Soka clay(2)	2.65	63.4	32.5	14	35	51
Kashiwaclay	2.64	112.0	50.5	47	38	15
Moriya peat	2.05	463.0	194.0	——	——	——

2. *Experimental procedure*

Cohesive soils were sampled at housing sites in the suburbs of Tokyo. Physical properties are given in Table 1. Slurry-state samples mixed and remolded with water content greater than the liquid limit, were initially consolidated one dimensionally under an axial stress of 19.6 kPa.

2.1 *Triaxial compression test*

Cylindrical specimens, 10 cm high and 5 cm in diameter, were trimmed from the preconsolidated soil and further consolidated isotropically or anisotropically in a triaxial cell for 3 days and then sheared under an undrained condition.

A back pressure of 98 kPa was used for all samples to ensure saturation. The pore pressure parameter B was checked at the end of consolidation. The rate of axial strain in undrained shear was 0.1%/min in all tests,

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and pore pressure was measured at the bottom of specimens. The purpose of this test is to investigate the influence of the effective stress ratio in consolidation on the shearing strength.

2.2 *Direct shear test*

Samples 2 cm high and 6 cm in diameter were trimmed from large preconsolidated soil blocks. During the direct shear test, the volume of the specimen was kept constant by controlling the vertical stress. The rate of horizontal displacement was 0.5mm/min. Two types of shear test were performed under the following conditions.

Test A : Specimens are consolidated for period of 1 minute and 28 days and then sheared under the constant-volume condition. The purpose of this test is to investigate the strength increase during one-dimensional consolidation.

Test B : Before the direct shear test, successive incremental pressures is applied to specimens. Each incremental pressures are allowed to consolidate the specimen for a different consolidation period from the end of primary consolidation up to one week. The purpose of this test is to investigate the influence of the consolidation period on the shearing strength.

3. *Test results and discussion*

3.1 *Major and minor principal effective stress ratios in consolidation*

Fig. 1 illustrates effective stress paths of deviator stress q and effective mean stress p' obtained by the undrained triaxial test. As can be seen from Fig. 1, the failure lines is independent of the principal effective stress ratio $K(=\sigma_3'/\sigma_1')$ in consolidation, and there is an increase in the maximum deviator stress $q_{\max}$ with the reduction of K. The relations of $e-\log p'$ in Fig.2 are parallel to one another provided that K is identical. The reduction of void ratio e under the same isotropic effective stress seem to be controlled by the value of q. Therefore, the void ratio change appears to be related to negative dilatancy.

The volumetric change due to anisotropic consolidation may be expressed as a function of q and p'. Eq. 1 denotes the $e-\log p'$ relationship and the effective stress which corresponds to the amount of decrease of excess pore water pressure dissipated by consolidation[4).

$$e = e_0 - C_c \log \sigma' \qquad (1.a)$$

$$\sigma_e' = p' + Dq = p' + a\log(t/t_0)q \qquad (1.b)$$

where, C_c : compression index, D : coefficient of

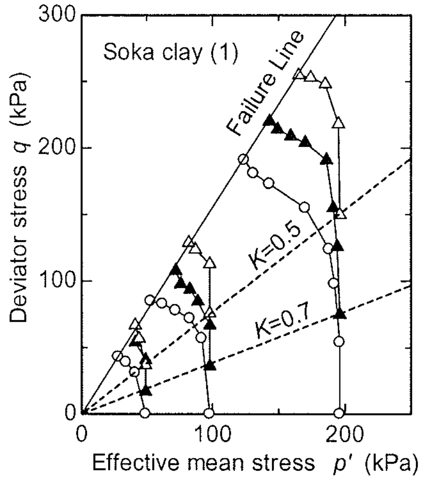

Fig. 1 Effective stress paths

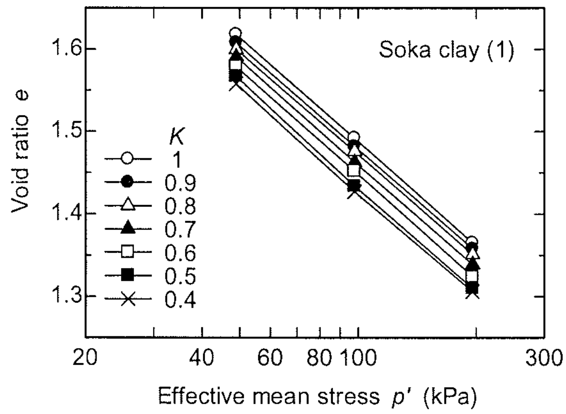

Fig. 2 e-log p' relationships

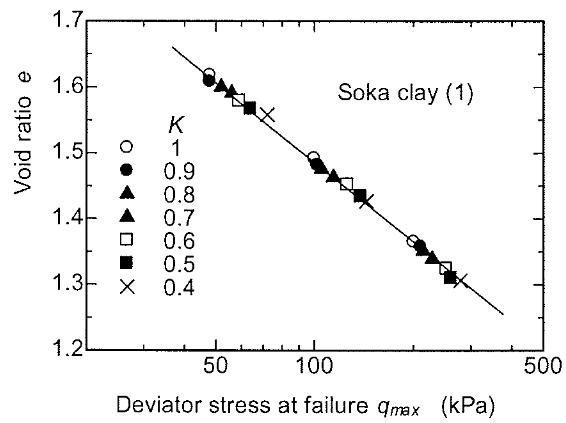

Fig. 3 e-log q_{max} relationship

dilatancy, a : constant, t : time, t_0 : time when dilatancy begins to occur. This effective stress, σ_e', herein termed equivalent effective stress, reflects the volume change of saturated soil.

The equivalent effective stress in anisotropically consolidated soil can be calculated by Eq. 1. Maximum deviator stress $q_{\max}$ shown in Fig. 1 is plotted against void ratio in Fig. 3. The linear relatioship between e and $\log q_{\max}$ can be observed. The results indicate undrained strength to be a function of σ_e'.

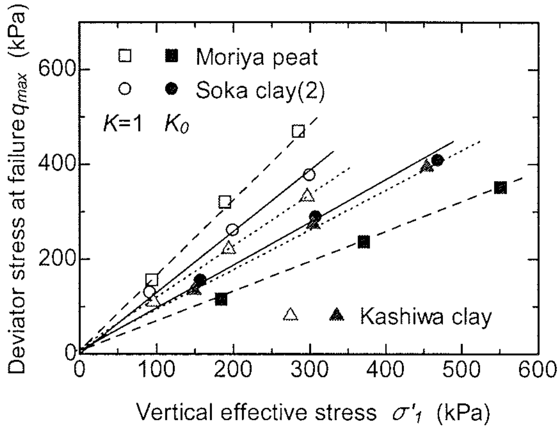

Fig. 4 Vertical effective stress vs deviator stress at failure

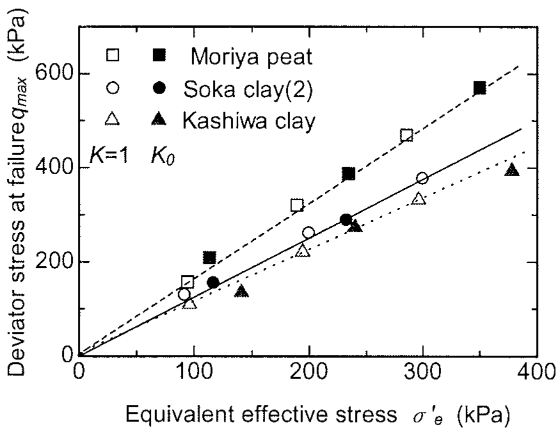

Fig. 5 Equivalent effective stress vs deviator stress at failure

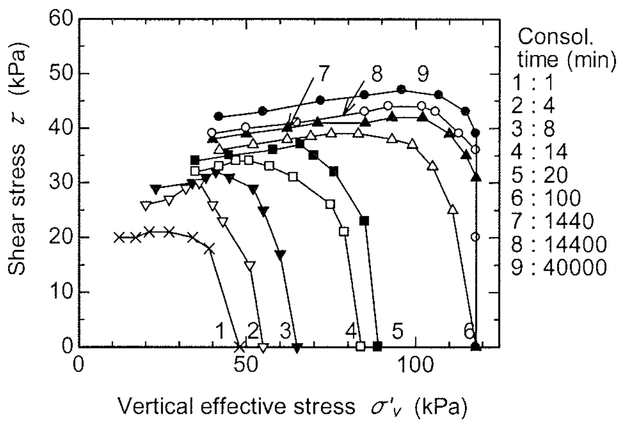

Fig. 6 Vector curves vs consolidation time

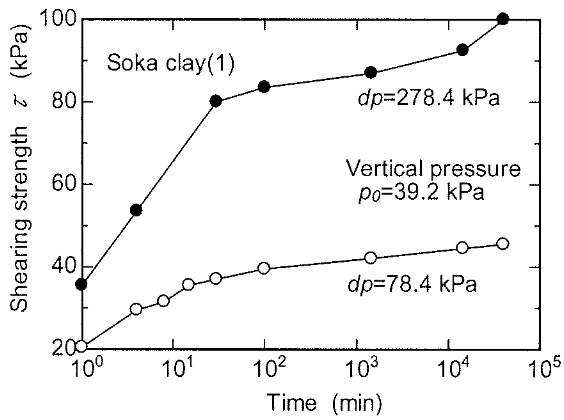

Fig. 7 Shearing stress vs consolidation time

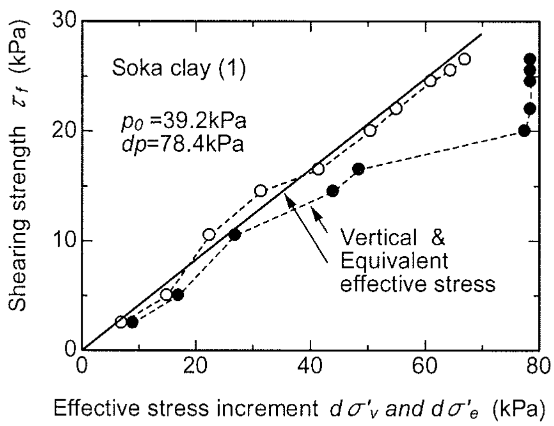

Fig. 8 Shearing stress increment vs effective stress increment

Fig. 4 and Fig. 5 illustrate the relationships among $q_{\max}$, σ_1' and σ_e'. It can be seen in Fig. 4 that there is a large difference between $q_{\max}$ and σ_1' under the influence of K in consolidation. However, no such influence of K on the $q_{\max}$ and σ_e' relationship can be seen in Fig. 5. These results suggest that undrained strength defined by the equivalent effective stress, is independent of the effective stress ratio in anisotropic consolidation.

3.2 *Consolidation period*

Fig. 6 shows the shear the stress τ and vertical effective stress σ_v' relationship, that is, the vector curve, obtained by constant-volume direct shear test A. Vector curves with long consolidation time tend to rise vertically at the beginning of shear. The initial value of σ_v' at $\tau = 0$ corresponds to the effective stress increase due to the consolidation. The effect of the consolidation period on the shearing strength is shown in Fig. 7. With the primary consolidation time of 30-60 min, secondary consolidation causes an increase in shearing strength; the longer the consolidation period, the greater is the shearing strength.

The coefficient of time-dependent dilatancy in Eq. 1 can be related to the rate of secondary consolidation $C_\alpha (= d\varepsilon_v / d\log t)$ as follows.

$$C_\alpha = m_v * a * \log(10t_s / t_s) * dq$$
$$= m_v * a * dq \quad (2)$$

By substituting consolidation test results into Eq. 2, the increments of the equivalent effective stress can be calculated. The shearing strength is plotted against the effective stress in Fig. 8. It can be observed that the ratio of shearing strength normalized by the equivalent effective stress, $d\tau_f / d\sigma_e'$, is constant throughout primary and secondary consolidation processes.

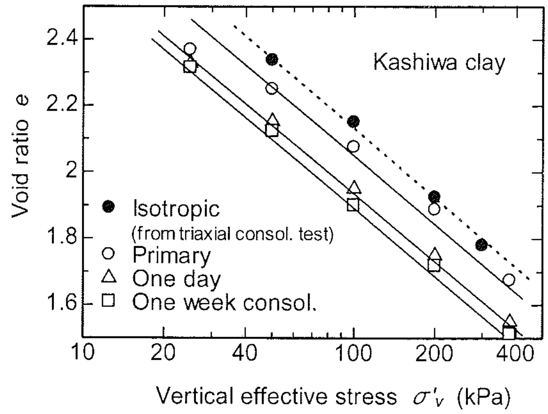

Fig. 9 e-log σ'_v relationships

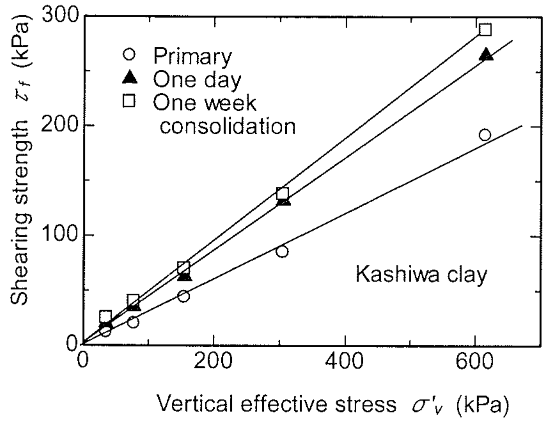

Fig. 10 Shearing strength vs vertical effective stress

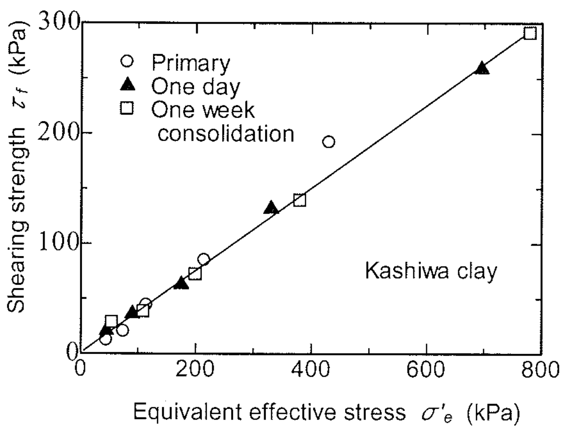

Fig. 11 Equivalent effective stress vs shearing strength

3.3 *Interval of loading time*

Fig. 9 and Fig.10 show the influence of loading time interval on the $e-\log p'$ relation and the shear strength obtained by direct shear test B. There is a decrease in void ratio with an increase in the loading time interval. This reduction of void ratio due to secondary consolidation is related to the increase of shearing strength. It is also clearly shown in Fig.10 that the relationship of shearing strength to the vertical effective stress ratio τ_f/σ'_v is time dependent. This shearing strength can be expressed by a linear relation

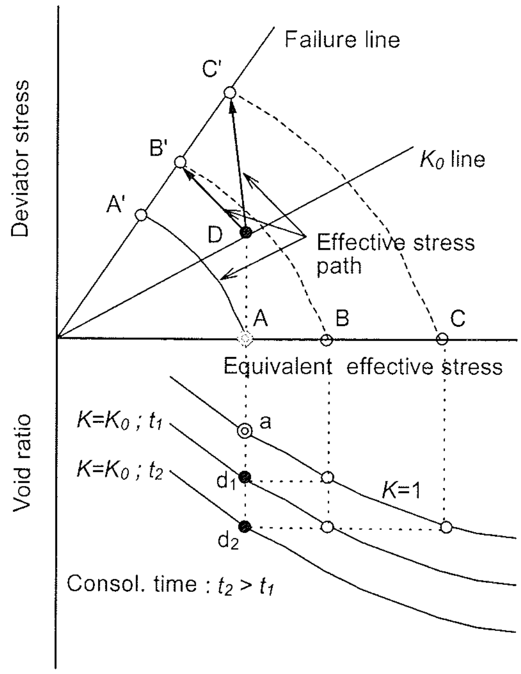

Fig. 12 Deviator stress at failure vs equivalent effective stress

with σ'_e, as shown in Fig. 11. The ratio of τ_f/σ'_e is not affected by the loading time interval.

3.4 *Strength defined by equivalent effective stress*

Fig.12 is a conceptual diagram of $e-\log p'$ relations and $q-p'$ paths obtained by undrained shear tests for anisotropically consolidated cohesive soil. As normally consolidated samples are subjected to isotropic and anisotropic stress at A & D and allowed to consolidate for a long period of time, secondary consolidation and a decrease of void ratio would occur, which are time and stress dependent. Three different void ratios at an effective mean stress correspond to three different equivalent effective stresses, A, B and C. Samples with different equivalent effective stresses exhibit parallel stress paths, e.g. curve AA' and CC' shown in Fig.12[5]. The effective stress path obtained by undrained shear tests is not unique and depends upon the stress history. In order to better represent the strength, the undrained shear strength $S_u(=q_{\max}/2)$ is most conveniently related to the equivalent effective σ'_e as a ratio,

$$S_u/\sigma'_e = \frac{\sin\varphi'}{1+(2A_f-1)\sin\varphi'} \tag{3}$$

where, A_f : coefficient of pore pressure at failure and φ' : effective angle of shearing resistance.

4. *Conclusions*

A simplified method has been proposed for predicting undrained shear strength on the basis of properties measured from remolded soil samples. The conclusion of this study may be summarized as follows.

(1) The ratio of undrained shear strength to effective vertical stress is influenced by the effective principal stress ratio $K(=\sigma_3'/\sigma_1')$.

(2) Isotropic and anisotropic consolidation test results confirm that void ratio is a function of equivalent effective stress σ_e' defined by effective mean stress p' and deviator stress q.

(3) The time-dependent dilatancy induced during consolidation appears to be related to secondary consolidation.

(4) Secondary consolidation causes an increase in undrained shear strength.

(5) The equivalent effective stress at the equal void ratio provides a unique value of the undrained strength of saturated cohesive soil. The undrained shear strength defined by σ_e' is independent of the consolidation period.

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