Effects of anisotropic consolidation on flow failure behavior of a silty sand

Les effets de conslidation anisotrope sur comportement d'échec de flux d'un sable limoneux

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ABSTRACT: A series of consolidated-undrained compression tests was performed to investigate the influence of the anisotropic consolidation on the flow failure behavior of a saturated loose sand. The specimens were formed initially at the relative density of about 17% by the wet tamping method and consolidated with four different consolidation pressure ratios ($K_c = \sigma'_{hc}/\sigma'_{vc}$), 1.0, 0.7, 0.55, K_o. The test results show that the steady state line is a unique straight line on p' - q plane for all values of K_c. The relationship between the undrained residual strength (S_{us}) and the peak strength (S_p) of the loose silty sand, showing the flow failure behavior, is found to be represented as a general equation, $S_p/P_c' = A_L + B_L(S_{us}/P_c')$, irrespective of the value of K_c. These coefficients, A_L and B_L, tend to vary linearly with the value of K_c.

RÉSUMÉ : Une série d'essais de compression nondrainés-consolidé a été exécutée pour examiner l'influence de consilodation anisotrope sur le comportement d'échec de flux d'un sable lâche saturé. Les spécimens ont été formés au commencement à la densité relative d'environ 17 % par la méthode de bourrage humide et consolidés avec quatre proportions de pression de consolidation différentes($K_c = \sigma'_{hc}/\sigma'_{vc}$), 1.0, 0.7, 0.55, K_o. Les résultats d'essai montrent que la ligne stable d'état est une ligne droite unique sur p' - q plat pour toutes les valeurs de K_c. Le rapport entre la force résiduelle non drainée (S_{us}) et la force maximale (S_p) du sable limoneux lâche, montrant le comportement d'échec de flux, est trouvé pour être représenté comme une équation géneral, $S_p/P_c' = A_L + B_L(S_{us}/P_c')$ sans tenir compte de la valeur de K_c. Ces cofficients, A_L et B_L ont tendance à varier linéairement avec la valeur de K_c.

1 INTRODUCTION

The collapse line in the stress space normalized with the effective mean principal stress at quasi-steady state, $q_p/p_s' - p_p'/p_s'$, is represented as a straight line for the isotropically consolidated sand specimen showing the undrained behavior as in Fig. 1. The minimum value of the shear stress at steady state or quasi-steady state was taken as the residual strength (S_{us}) to be used for stability analysis, and then, by associating this residual strength and the peak strength (S_p) with $q_p/p_s' - p_p'/p_s'$ relationship, the following equation was formulated by Ishihara (1993).

$$\frac{S_p}{p_c'} = \frac{1}{2}M_L\frac{p_p'}{p_c'} + \frac{1}{\cos\phi_s}\left(1 - \frac{M_L}{M}\right)\frac{S_{us}}{p_c'} \qquad (1)$$

In the above equation, M and M_L indicate the slopes of the steady state line and the collapse line respectively, and ϕ_s the angle of internal friction at steady state. P_p' and P_c' are the effective mean principal pressure at peak strength and the mean confining pressure respectively as shown in Fig.1. And also Ishihara(1993) reported that the values of P_p'/P_c' and ϕ_s or M were almost independent of the soil fabric and unique values for the materials tested, whereas the value of M_L was dependent of the soil fabric formed by the preparation method of the soil specimen.

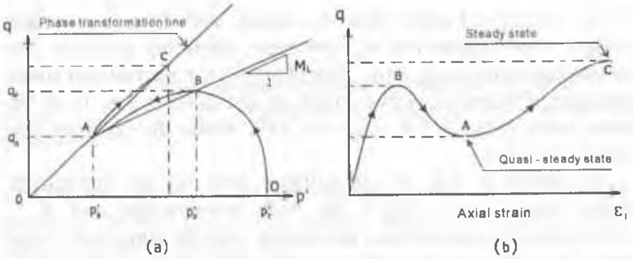


Figure 1. Characteristics of undrained behavior of loose sand (Ishihara, 1993)

Thus, the relation estabilished in equation (1) may have to be regarded as generally fabric dependent, and can not be fixed uniquely for a given soil material.

As mentioned above, the equation (1) was formulated from the test results for the isotropically consolidated specimen. Therefore, it is questionable whether equation (1) can be applied to the anisotropically consolidated specimen with every K_c value as well as the isotropically consolidated specimen.

This study aims at investigating the effects of the anisotropic consolidation on such flow failure behavior of the loose silty sand as described in equation (1).

2 EXPERINMENTAL PROGRAM

The soil sample used in this study is the silty sand (SM), of which gradation represents no clay fraction, silt fraction 30%, No. 40 sieve passing 100%, mean grain size 0.07 mm and uniformity coefficient 3.7. The maximum and minimum void ratios are 0.898 and 0.449 respectively, and the specific gravity of solid particles is 2.65.

The cylindrical specimens measuring 100 mm high and 50 mm in diameter were prepared at the relative density of about 17% by the wet tamping method and then saturated by flushing the carbon dioxide and water, and by applying the back pressure of 100 kPa subsequently. The B values were measured over 0.97 for all specimens. And then the specimens were consolidated under the mean confining pressures of 50, 100, 200, 300 kPa with four different consolidation pressure ratios 1.0, 0.7, 0.55, K_o(0.45). Finally, the specimens were deformed to failure under the strain - controlled monotonic loading in undrained condition.

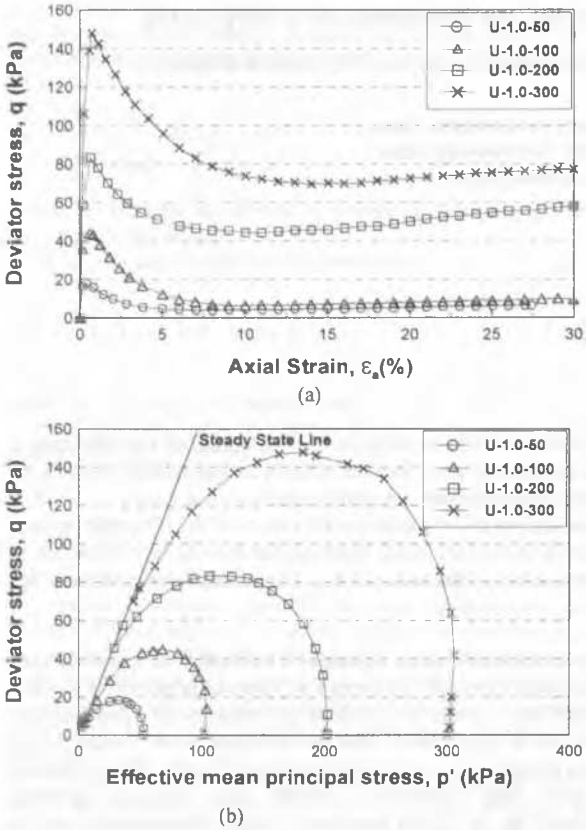


Figure 2. Undrained behavior for isotropic consolidation

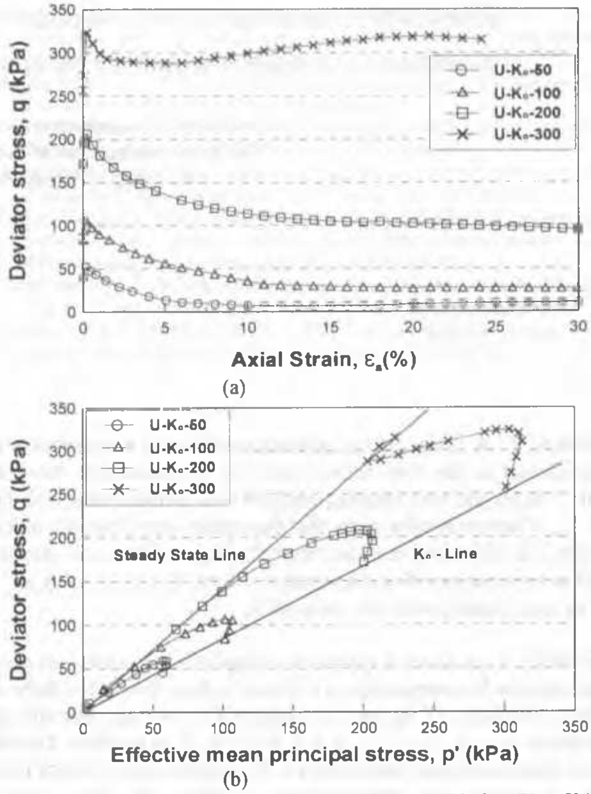


Figure 3. Undrained behavior for anisotropic consolidation ($K_c = K_o$)

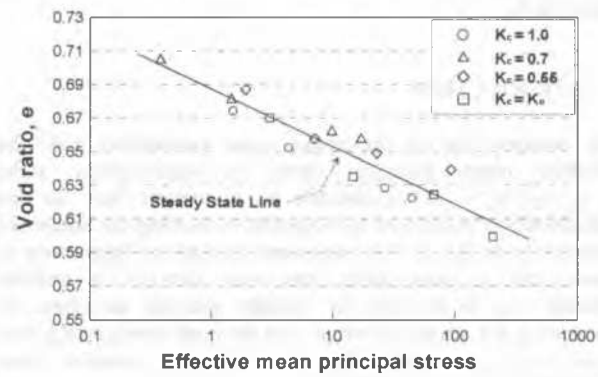


Figure 4. Relationship between void ratio and effective mean principal stress at steady state

3 RESULTS AND DISCUSSIONS

3.1 *Steady state and quasi-steady state*

As shown in Fig. 2(a), the stress - strain curves for the isotropically consolidated specimens reach the peak point within 1% of axial strain and then decrease steeply to the lowest stress level at steady state or quasi-steady state near 10 ~ 15% of strain. If the confining pressure is sufficiently low, the loose silty sand tends to exhibit the contractive characteristics showing the lowest stress at steady state. However, for high confining pressures, it tends to exhibit the contractive behavior showing the quasi-steady state at first and then to dilate approaching the steady state at the end. This behavior pattern is opposite to that of the normal soil reported by some prior studies (Vaid and Chern 1985, Alarcon-Guzman et al 1988), which indicate increasing the contractive tendencies with increasing the confining pressure. But Lade and Yamamuro(1997) stated that the soil with high fines content exhibited the dilatant tendencies at higher confining pressure.

As shown in Fig. 2(b), the shapes of the stress path for each confining pressure are similar, but the lowest stress levels at steady state or quasi-steady state are different mainly due to the difference in void ratio after consolidation under different confining pressure. These lowest stress points fall on a straight line, called the steady state line.

The undrained behaviors for an anisotropic consolidation ($K_c = K_o$) are illustrated in Fig. 3, where the same tendencies are observed in the overall behaviors with respect to the influence of the initial confining pressure on the stress-strain curve and the stress path in p'-q plane. In cases of the anisotropic consolidation with the K_c values of 0.7, 0.55 , almost the same behavioral tendencies as those for the K_c value of K_o are also observed.

All the lowest stress points at steady state including the quasi-steady state points are plotted on e-log p_s' plane in Fig. 4, which shows a linear relation regardless of the magnitude of the confining pressure and the consolidation pressure ratio. The higher the void ratio after consolidation, the lower effective mean principal stress at steady state or quasi-steady state. These lowest stresses at steady state or quasi-steady state obtained from the experiments for each consolidation pressure ratio are represented on a plot of p'-q plane in Fig. 5. This figure indicates that the steady state line is a unique straight line on p'-q plane for all K_c values.

3.2 *Undrained shear strength*

It was mentioned above that the steady state line is a unique straight line irrespective of void ratio, confining pressure and consolidation pressure ratio. Therefore, all the normalized stress paths for different K_c values meet, as indicated in Fig. 6, at the same point, $p'/p_s' = 1.0$, $q/p_s' = 1.439$, where the collapse line passes through.

As shown in Fig. 6, the collapse lines on the normalized stress plane (q/p_s'- p'/p_s') for both isotropically and K_o - anisotropically consolidated specimens with the same initial void ratio show the straight line with the slope of 0.557 and 0.87, respectively. According to Sladen et al (1985), an infinite

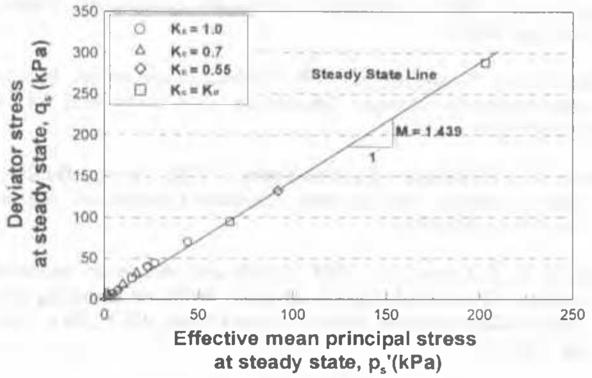
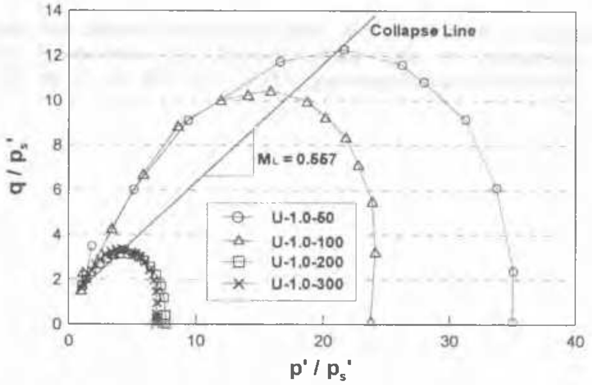
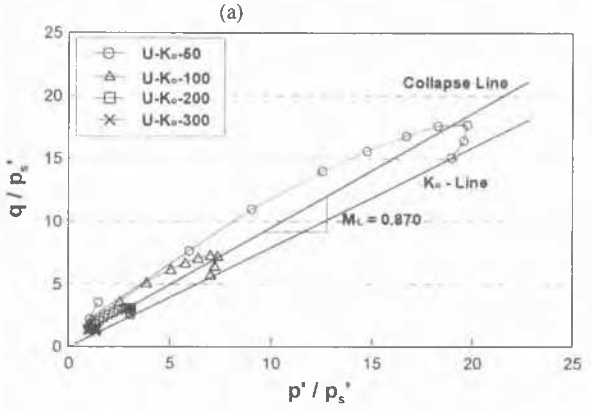


Figure 5. Unique relationship between deviator stress and effective mean principal stress at steady state



(a)



(b)

Figure 6. Normalized stress path for isotropic and anisotropic consolidation

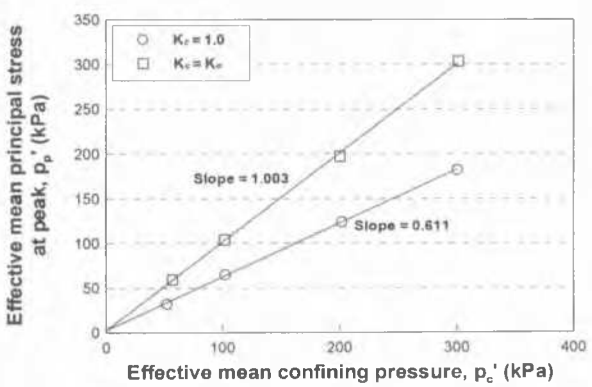


Figure 7. p_p' - p_c' relationship for isotropic and anisotropic consolidations

number of collapse lines for different void ratios form the collapse surface on e-p'-q space, and the collapse lines themselves have a unique slope.

The relation between the mean effective principal stress at peak (p_p') and the effective mean confining pressure (p_c') shows

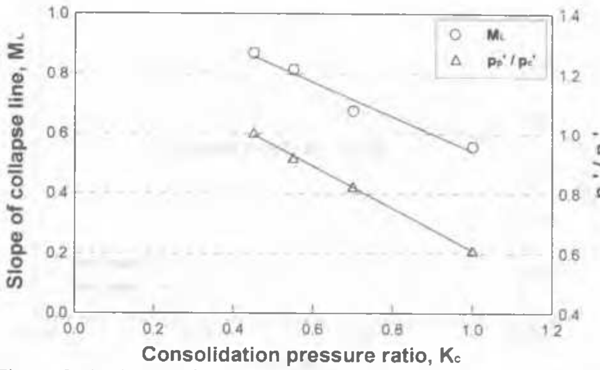


Figure 8. Variation of the slope of collapse line M_L and p_p'/p_c' with different consolidation pressure ratio

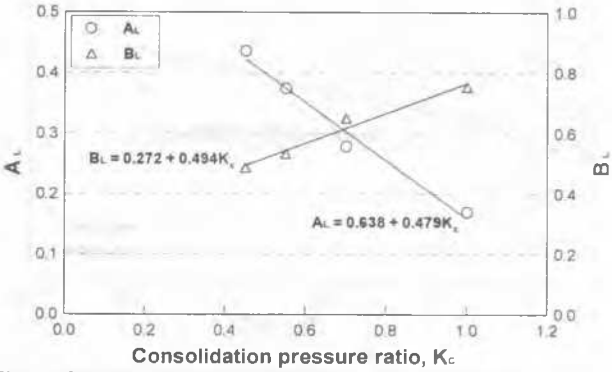


Figure 9. Relationship between consolidation pressure ratio and parameters A_L and B_L

also a straight line passing through the origin, of which slope (p_p'/p_c') is different for each consolidation pressure ratio as shown in Fig. 7.

According to Ishihara (1993), p_p' / p_c' value is independent of the soil fabric, and each soil has its own constant value. But this ratio is found to be dependent highly on the value of K_c during confining the specimen as indicated in Fig. 8 and Table 1. Figure 8 illustrates that the slope of the collapse line on p'-q plane, M_L, decreases with increasing the value of K_c as well as the value of p_p'/p_c' does, i.e. the collapse line for the anisotropic consolidated sand is steeper than that for the isotropic consolidated sand.

The equation of the relationship between the peak strength and the undrained residual strength in equation (1) can be expressed as a simple form in the following equation (2).

$$\frac{S_p}{p_c'} = A_L + B_L \frac{S_{us}}{p_c'} \qquad (2)$$

where A_L and B_L are coefficients depending on the consolidation pressure ratio. Figure 9 shows that A_L decreases linearly with increasing the consolidation pressure ratio, but B_L increases. The values of A_L and B_L of Toyoura sand for the isotropic consolidation condition were reported as 0.17 and 0.66 respectively (Ishihara, 1993).

Figure 10 shows that the relation expressed in equation (2) agrees quite well with the experimental results for both K_c values of 1.0 and K_o. In cases of K_c values of 0.7, 0.55, the same outcomes as described above are also observed.

In conclusion, the equation for S_p/p_c'-S_{us}/p_c' relation

Table 1. Constant parameters on loose silty sand

	K_c			
	1.0	0.7	0.55	K_o(0.45)
M	1.439			
ϕ_s(degree)	35.5			
M_L	0.557	0.677	0.815	0.870
p_p'/p_c'	0.611	0.823	0.919	1.003
A_L	0.170	0.279	0.374	0.436
B_L	0.753	0.650	0.532	0.486

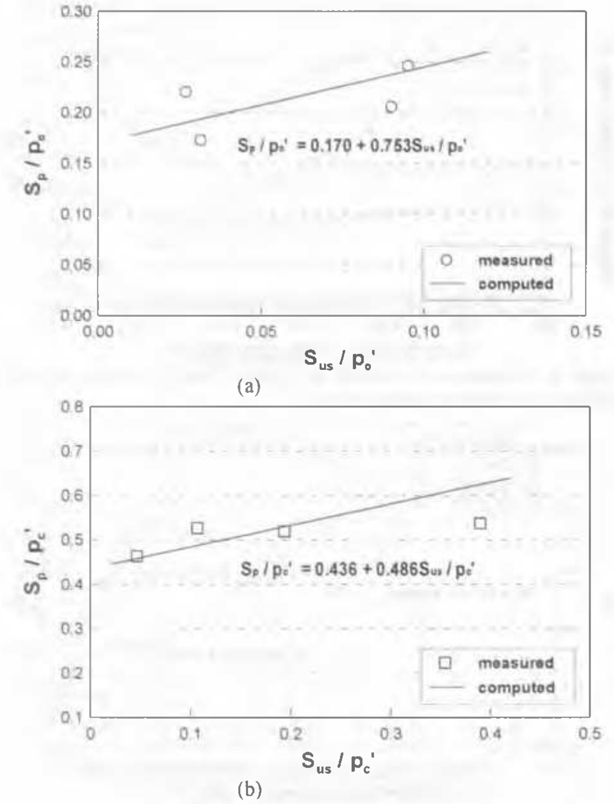


Figure 10. Comparison of the computed and measured values for S_p/p_c' - S_{us}/p_c' relation

suggested by Ishihara(1993) could be used for all consolidation pressure ratios whether the sand is isotropically consolidated or anisotropically consolidated.

4 CONCLUSIONS

Based on the test results presented above, the following conclusions are drawn.

1) The steady state line on p'-q plane shows a unique straight line for all values of the consolidation pressure ratio.

2) The collapse line on p'-q plane is a straight line irrespective of the consolidation pressure ratio, and its slope tends to increase linearly with decreasing the consolidation pressure ratio.

3) The normalized effective mean principal stress at peak with effective mean confining pressure, p_p'/p_c', shows a tendency of decreasing linearly with increasing the consolidation pressure ratio.

4) The relationship between the undrained residual strength (S_{us}) and the peak strength (S_p) for the loose silty sand showing flow failure is expressed as a linear relationship, $S_p / p_c' = A_L + B_L(S_{us} / p_c')$. This equation could be applied not only to the isotropic consolidation case but also to the anisotropic consolidation. And the coefficient A_L decreases linearly with increasing the consolidation pressure ratio, but B_L increases.

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