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Evaluation of the maximum excess pore pressure of normally consolidated cohesive soils during undrained shear

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Abstract

This paper descibes a simple method for evaluating the maximum excess pore pressure of normally consolidated cohesive soils during undrained shear in triaxial tests.

Isotropically consolidated undrained triaxial compression (CIUC), K_0-consolidated undrained triaxial compression (CK_0UC), isotropically consolidated undrained triaxial extension (CIUE), and K_0-consolidated undrained triaxial extension (CK_0UE) tests were carried out on twelve soils to explore the interrelationships between maximum excess pore pressure obtained from these test types and plasticity index.

Different correlation is obtained with variation in either consolidation history (isotropic or K_0-consolidation) and shear under a given stress path (compression or extension loadings). Consistency of data from Kawasaki clay- mixture series and natural clays suggests that the maximum excess pore pressure of natural clays during undrained shear can be extrapolated from results obtained on Kawasaki clay-mixture series only.

Key words: cohesive soil, consolidated undrained shear, earth pressure at rest, laboratory test, pore pressure, plasticity index, stress path.

Introduction

The stresses in field deposits are commonly anisotropic; the major principal effective stress, σ_v', acts in a vertical direction and the minor principal stress, $K_0\sigma_v'$, acts in a horizontal direction, where K_0 is a coefficient of earth pressure at rest. Most commercial laboratories, however, routinely conduct isotropically-consolidated undrained triaxial compression tests (CIUC) because of convenience and the simplicity of the testing procedure. For ease and economy, most of these laboratories perform consolidated undrained triaxial shear tests using a conventional triaxial system under an effective confining pressure equal to the estimated in-situ vertical stress. Consequently, it has become routine practice to consolidate the specimens isotropically ($K_c = 1$) prior to shear testing (Mayne, 1985). As mentioned earlier, the in-situ state of stress for most cohesive soils, however, is anisotropic. How different are the undrained shear strengths measured under in-situ conditions as opposed to routine laboratory conditions?

Anisotropically consolidated tests are more complex and take much longer to run. Furthermore, if K_0-consolidation is desired, ensuring zero lateral strain throughout the consolidation process is not an easy task. In addition, the anisotropic consolidation phase of triaxial test specimens is generally time consuming and expensive, especially if K_0 conditions are maintained. Excess pore pressure is one of the most important factors for evaluating the undrained shear behaviour of cohesive soil strata.

The author has carried out an extensive testing programme to study the mechanical characteristics of cohesive soils with a wide range of plasticity index. Twelve soils were used in two series of experiments. Based on the test data, Kamei (1985 MS), Nakase and Kamei (1988) and Nakase et al. (1988) proposed linear correlations between some soil parameters and plasticity index. Based on these studies, the greatest benefits of sophisticated new analytical methods are to be derived from techniques in which the analysis has been reduced to a simple convenient form (Kamei and Sakajo, 1995a and b; Kamei, 1996). It is of interest to investigate possible correlation of the maximum excess pore pressures of these soils with differing plasticity index for a practical design. The soils investigated have a wide range of plasticity index, from 10 to 55. Plasticity index (PI) is considered here to be a key parameter, as described in detail elesewhere (Kamei, 1996).

The purpose of this paper is to quantitatively investigate the effects of consolidation and shear conditions on the maximum excess pore pressure ($\triangle u_{max}$) of normally consolidated cohesive soils with different plasticity index during undrained shear. The test data comprises a series of consolidated undrained triaxial compression and extension loadings for each soil. An attempt is made to find possible correlation between the normalized $\triangle u_{max}$ during undrained shear and plasticity index. In addition, data are compared to assess the interrelationships for maximum excess pore pressure during undrained shear amongst the CIUC, CK_0UC, CIUE, and CK_0UE tests. The resulting correlations provide a useful procedure to predict maximum excess pore pressure in a more meaningful manner to evaluate the undrained shear behaviour of soils with a wide range of plasticity index.

Soils tested and testing programme

Twelve soils were used in two series of experiments: the Kawasaki clay-mixture series and the reconstituted natural marine clay series. The Kawasaki clay-mixture series is composed of five soils, and the reconstituted natural marine clay series is composed of seven soils. The seven soils were obtained from various locations along the coastal areas of Japan. Tests on several reconstituted natural marine clays were carried out mainly for the purpose of verifying the general applicability of the test results obtained on the Kawasaki clay-mixture series. All tests were consolidated undrained triaxial shear tests with pore pressure measurements. The undrained shear tests were performed under strain-controlled conditions during shear to failure. Four types of consolidated undrained triaxial tests were performed, namely CIUC (undrained compression test on an isotropically consolidated specimen), CK_0UC (undrained compression test on a one-dimensionally K_0-consolidated specimen), CIUE (undrained extension test on an isotropically consolidated specimen), and CK_0UE (undrained extension test on a one-dimensionally K_0-consolidated specimen). Two different values of vertical effective consolidation pressure were used in the consolidation process: 196 kPa and 392 kPa for compression loadings, and 392 kPa and 588 kPa for extension loadings respectively. A back pressure of 196 kPa was applied to all the test specimens throughout the consolidation and undrained shear. For each soil sample, triaxial compression and extension loadings were performed, with a constant rate of axial strain of 0.07%/min. (Kimura and Saitoh, 1983; Nakase and Kamei, 1986). Details of the test conditions and the test appartus used in the present study are given elsewhere (Nakase and Kamei, 1983). Consistency of data from the Kawasaki clay-mixture series and natural clays suggests that the undrained shear characteristics of natural clays can be extrapolated from results obtained on the Kawasaki clay-mixture series only (Kamei, 1985 MS and 1989; Nakase and Kamei, 1988; Nakase et al, 1988).

Test results and discussions

It is well known that the principal stress differences obtained from K_0-consolidated samples are smaller than those obtained from isotropically consolidated samples, irrespective of compression or extension loadings (Nakase and Kamei, 1983 and 1988; Mayne, 1985). Consolidation and shear conditions clearly affect the stress-strain curves of the four different types of triaxial tests. Once a sample has been consolidated under a given state of stresses, the question now arises if the type of stress system applied during undrained shear has an effect on the excess pore pressure. Marked change in the shape of the stress path appears between the tests for isotropically consolidated samples and K_0-consolidated samples (Nakase and Kamei, 1983), due to the change in excess pore pressure response. The shapes of the effective stress paths are almost identical, with a distinct symmetry about the principal stress difference q $(=\sigma_a-\sigma_r)=0$ line for compression and extension loadings for isotropically consolidated samples. The shape of stress paths of K_0-consolidated samples for compression and extension loadings becomes different from those of isotropically samples (Nakase and Kamei, 1983). The effective stress paths are also characterized by sharp reversal as they approach the critical state line, after which they tend to follow a single and unique line of failure points for both drained and undrained tests as defined by the critical state line. Failure will be manifested as a state at which large shear distortions occur, until soils flow as a frictional fluid occur with no change in stress, or in specific volume (v).

Maximum values of excess pore pressure ($\triangle u_{max}/\sigma_{vc}'$) normalized against plasticity index obtained in triaxial tests, with results obtained from four types of triaxial tests, illustrate how the correlation between the values of $\triangle u_{max}/\sigma_{vc}'$ and PI changes with changing consolidation and shear conditions, where $\triangle u_{max}$ is normalized by dividing by the vertical effective consolidation pressure σ_{vc}'. The $\triangle u_{max}/\sigma_{vc}'$ of several other reconstituted natural marine clay is found similar to that of the Kawasaki clay-mixture series, as illustrated in Figures 1 and 2. These results suggest that the maximum excess pore pressure of natural clays during undrained shear can be extrapolated from results obtained on the Kawasaki clay-mixture series only.

Figure 1 shows the relationship between $\triangle u_{max}/\sigma_{vc}'$ and PI in CIU tests. In both the Kawasaki clay-mixture series and natural marine clays data, no distinct trend between the value of

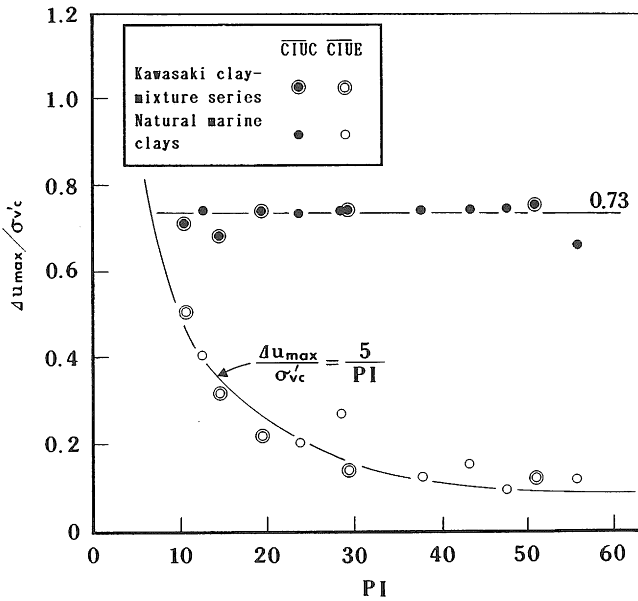

Fig. 1 Variation in $\Delta u_{max}/\sigma_{vc}'$ values with PI for isotropically consolidated samples

$\Delta u_{max}/\sigma_{vc}'$ and PI is seen for the CIUC test. This indicates that the value of $\Delta u_{max}/\sigma_{vc}'$ is essentially constant with PI. It can be expressed by:

$$\Delta u_{max}/\sigma_{vc}'=0.73 \text{ (CIUC)} \tag{1}$$

In extension loading, on the other hand, a distinct trend of decreasing $\Delta u_{max}/\sigma_{vc}'$ with increasing PI is seen. The regression line for the relationship is given by:

$$\Delta u_{max}/\sigma_{vc}'=5/PI \text{ (CIUE)} \tag{2}$$

In addition, it is apparent that the dependence of stress conditions on maximum excess pore pressure in the shear process is more pronounced as the plasticity index of cohesive soils increases.

Figure 2 shows the relationship between Δu_{max} and PI in CK_0U tests. No distinct trend between the value of $\Delta u_{max}/\sigma_{vc}'$ and PI is observed for the CK_0UC test, indicating that the value of $\Delta u_{max}/\sigma_{vc}'$ is essentially constant with PI. It can be expressed by:

$$\Delta u_{max}/\sigma_{vc}'=0.21 \text{ (CK}_0\text{UC)} \tag{3}$$

In extension loading, on the other hand, the value of $\Delta u_{max}/\sigma_{vc}'$ decreases almost linearly with increasing PI. The regression for the relationship is given by:

$$\Delta u_{max}/\sigma_{vc}'=0.29-0.007PI \text{ (CK}_0\text{UE)} \tag{4}$$

It also can be seen from the figures that there is a marked difference in variation between compression and extension loadings for isotropically and K_0-consolidated specimens respectively.

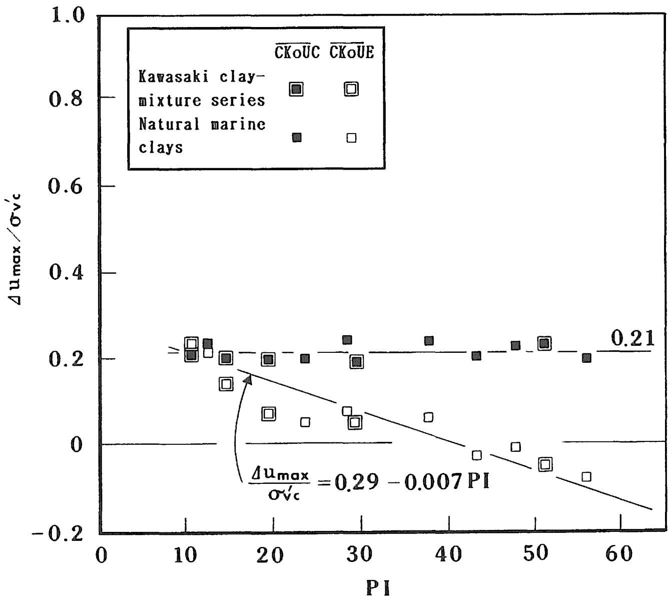

Fig. 2 Variation in $\triangle u_{max}/\sigma_{vc}'$ values with PI for K_0-consolidated samples

Differing correlation is obtained with variation in either consolidation history and stress path during shear. For both isotropically and K_0-consolidated samples, the values of $\triangle u_{max}/\sigma_{vc}'$ decrease with increasing PI irrespective of shear conditions, with the values of $\triangle u_{max}/\sigma_{vc}'$ in compression loading generally larger than those in extension loading. The difference become clear as the plasticity index increases. The same trend is also observed for K_0-consolidated samples. The values of $\triangle u_{max}/\sigma_{vc}'$ in compression loading always show higher excess pore pressure than the extension loading, as would be expected because of the shear process in the triaxial tests. As mentioned earlier, the values of $\triangle u_{max}/\sigma_{vc}'$ in compression loading are approximately constant in the range of PI from 10 to 55. The values are larger for isotropically consolidated samples than for K_0-consolidated samples. The values obtained from K_0-consolidated sample is about 0.29 times larger that from isotropically consolidated samples.

The maximum normalized excess pore pressure decreases in order from the CIUC, CIUE, CK_0UC, and CK_0UE tests, irrespective of PI of the soil samples. The differences in the maximum normalized excess pore pressures are due to differences in the test conditions. The development of excess pore pressure in the foundation, therefore, should be taken into account when the mechanical behaviour of foundation is evaluated accurately. Effect of stress conditions in the consolidation process and shear conditions on the value of the values of $\triangle u_{max}/\sigma_{vc}'$ is more pronounced as the PI of the soil samples decreases. In light of the test results, it is apparent that for a given sample the difference in $\triangle u_{max}/\sigma_{vc}'$ value due to differing test condition is more marked than that due to difference in the PI. This is consistent with general supposition on undrained shear strength (Nakase and Kamei 1983; Mayne 1985).

To this end, values of $\triangle u_{max}/\sigma_{vc}'$ depend significantly on a number of factors, such as consolidation history, stress history, stress paths, grain size, plasticity index and other variables.

When the plasticity index of a soil is known, the maximum values of excess pore pressure of normally consolidated cohesive soils which have been subjected to undrained shear corresponding to different stress conditions, either in consolidation or shear process, can be evaluated from Figures 1 and 2. The proposed equations provide an extremely rapid, easy, reliable and economic means of evaluating $\triangle u_{max}/\sigma_{vc}'$ corresponding to other stress conditions, either in consolidation and shear process. Limitations do exist in the proposed testing procedure, and it should be regarded only as a first approximation. This study provides, however, a basis for quantitative evaluation of maximum excess pore pressure of normally consolidated cohesive soils subjected to undrained shear.

Conclusions

Comparison of data obtained from four different types of triaxial test shows significant differences in undrained shear behaviour evaluations. Different correlation is obtained with variation in either consolidation history (isotropic or K_0-consolidation) and shear under a given stress path (compression or extension loadings). Consistency of data from Kawasaki clay- mixture series and natural clays suggests that the maximum excess pore pressure of natural clays during undrained shear can be extrapolated from results obtained on Kawasaki clay-mixture series only.

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