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LAREAL STRESS CHANGE IN SATURATED SAND AFTER LIQUEFACTION UNDER DIFFERENT STRAIN CONSTRAINT CONDITIONS

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ABSTRACT

Specific drained triaxial tests were performed in order to investigate the influence of strain constraint conditions on lateral stress changes in liquefied sand due to excess pore pressure dissipation. Based on a formulation of the test results, a simplified method is proposed to estimate post-liquefaction lateral stress changes in saturated sand deposits under different constraint conditions of zero and non-zero lateral strains. Its effectiveness is then checked by comparing the predicted results with experimental observations.

KEYWORDS

post-liquefaction; lateral stress change; saturated sand; non-zero lateral strain.

INTRODUCTION

The lateral stresses in saturated sandy soil deposits may change due to excess pore pressure generation and dissipation during and after earthquakes. To trace their changes with sufficient accuracy is of much benefit to 1) evaluating the dynamic stability of various retaining walls, quay-type caissons and infrastructures; 2) determining the change in mean effective principal stress related to the change in soil stiffness; and 3) estimating the change in coefficient of horizontal subgrade reaction for a soil-piles system during an earthquake. However, it is difficult to obtain a satisfactory evaluation because the lateral stress in soils is not a statically determinate variable as the vertical stress. The authors (1995) suggested a simplified method to predict the value of lateral stress under zero lateral strain conditions. For non-zero lateral strain conditions that could occur in actual deposits, however, studies concerning estimation of lateral stress seem quite few.

The object of this study is to investigate experimentally the post-liquefaction lateral stress changes in saturated sand under different strain constraint conditions. A simplified method of estimation is proposed and its effectiveness is confirmed preliminarily.

EXPERIMENTAL PROCEDURE ESTIMATING CHANGE IN LATERAL STRESS

Specific drained consolidation tests were performed on triaxial samples of saturated sand that had been subjected to cyclic undrained loading. During the drained testing, the ratio of lateral to axial strain increments, $\Delta\varepsilon_{lateral}/\Delta\varepsilon_{axial}$, hereby defined as R_ε, was maintained constant. A pneumatic cyclic triaxial test apparatus improved by Shamoto et al.(1995) was used in the tests.

The test operation consists of the following steps: 1) A saturated sand sample was consolidated isotropically or anisotropically subjected to an application of initial effective axial and lateral consolidation stresses, $\sigma'_{A,C}$ and $\sigma'_{L,C}$;

2) A cyclic axial stress $\Delta\sigma_{axial}$ was then slowly applied on the sample under undrained condition until the specified maximum excess pore pressure $(\Delta u)_{max}$ was obtained. In such a conventional cyclic undrained triaxial test process, no change in total lateral stress occurred; 3) A back pressure was adjusted to the same value as $(\Delta u)_{max}$, and then the drainage valve was opened; 4) The back pressure was reduced step by step until the excess pore pressure Δu dissipated to zero. In this step, a prescribed R_ε-value was maintained using a servo-control system. The total lateral stress $\sigma_{lateral}$ decreased from $\sigma'_{L.C}$ to $\sigma'_{L.0}$ during this step, while the total axial stress σ_{axial} remained constant, i.e., $\sigma'_{A.C}$.

The Toyoura sand ($\rho_s = 2.65\ g/cm^3$, $D_{50} = 0.18\ mm$, $e_{max} = 0.973$ and $e_{min} = 0.635$) was used in the tests. All the samples were prepared by pluviating dry sand through air, and saturated by circulating CO_2 gas, percolating de-aired water and then by applying a back pressure of $100\ kPa$. B-values of more than 0.96 were obtained for all the samples. The prescribed R_ε ranged from -0.42 to 0.22. It should be noted that $R_\varepsilon = 0$ corresponds to zero lateral strain condition. Fig.1 shows time histories of $\Delta\sigma_{axial}$, Δu, and $\sigma_{lateral}$ measured in a typical test at $R_\varepsilon = -0.42$.

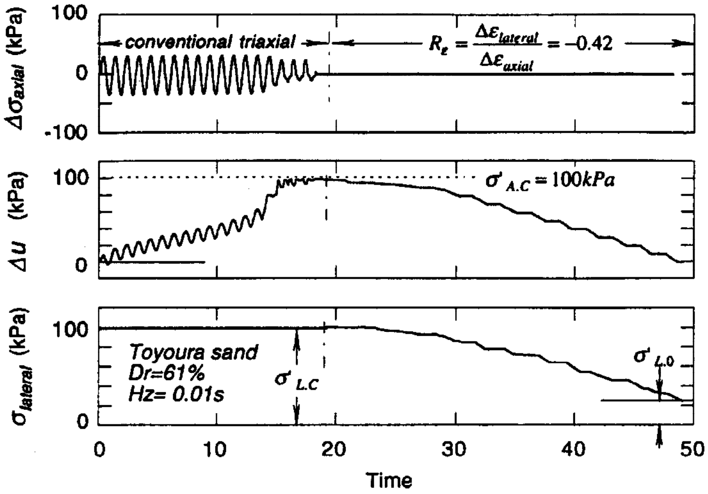

Fig.1 Time history observed in a typical conventional cyclic undrained test followed by drained consolidation with a constant strain increment ratio (R_ε = - 0.42)

CHANGE IN LATERAL STRESS DURING POST-LIQUEFACTION CONSOLIDATION

Change in Post-liquefaction Lateral Pressure Dependent on Excess Pore Pressure Ratio

In Fig. 2, coefficient of lateral pressure, K, coefficient of effective lateral pressure, K', and excess pore pressure ratio, r_u, are, respectively, defined for the convenience of description. Fig. 3(a) shows the experimental relationships between K and r_u in test step 4 with R_ε = - 0.43, 0 and 0.22. K is found to maintain nearly constant or K =1 with decreasing r_u in a very small range after initial liquefaction, and then reduce linearly with further decreasing r_u, irrespective of the value of R_ε. The relationship between K and r_u can therefore be approximately expressed as

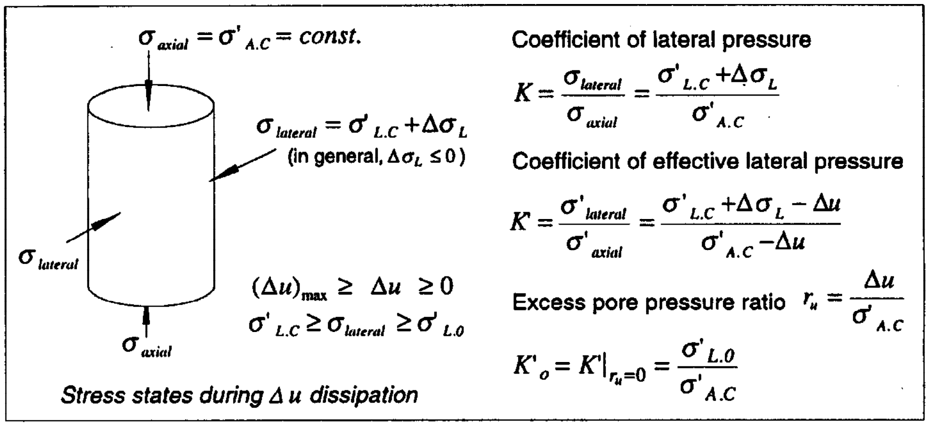

Fig.2 Several definitions with respect to stress states during post-liquefaction consolidation following cyclic undrained loading

$$\left.\begin{aligned} K &= 1.0 & (r_{cr} < r_u \le 1) \\ K &= K'_o + m \cdot r_u & (0 \le r_u \le r_{cr}) \end{aligned}\right\} \tag{1}$$

in which K'_o is the coefficient of effective lateral pressure at $\Delta u = 0$ and m is the slope of the K'-r_u relationship corresponding to $r_u < r_{cr}$, illustrated in Fig. 2, and r_{cr} is a parameter as shown in Fig. 3(a). Because $K = 1$ at $r_u = r_{cr}$ in the second expression of Eq. (1), r_{cr} may be written as

$$r_{cr} = (1 - K'_o)/m \tag{2}$$

In addition, according to the definitions of K' and K shown in Fig. 2, their relation may be obtained as

$$K' = (K - r_u)/(1 - r_u) \tag{3}$$

Based on the data in Fig. 3(a), the relationship between K' and r_u was calculated by Eq. (3) and shown in Fig. 3(b).

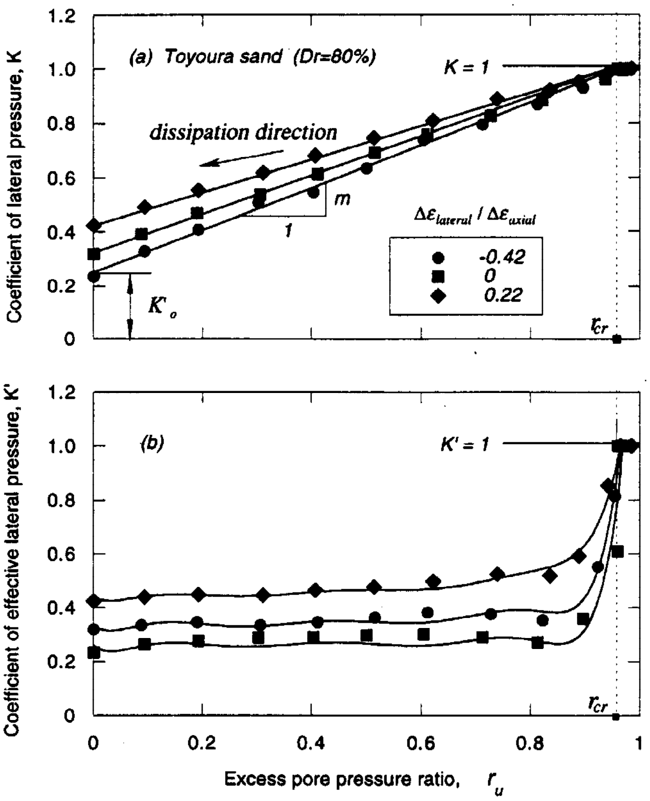

Fig.3 Changes in total and effective lateral stresses during post-liquefaction consolidation under constant strain increment ratios specified

The Slope of K- r_u Relationship Dependent on K'_o

Fig. 3(a) also shows that with increasing R_ε-value, K'_o increases while m decreases. Fig. 4 shows the relationship

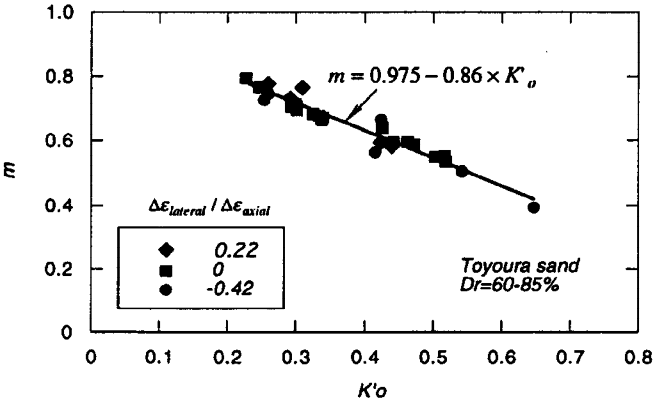

Fig.4 The K'_o-m relationship independent of change in R_ε

between K'_o and m obtained from the tests. A nearly linear correlation exists between the two, which is independent of the differences in relative densities D_r from 60% to 85% and $R\varepsilon$ from -0.42 to 0.22. The curve fitting for this relation gives

$$m = \alpha - \beta \cdot K'_o \tag{4}$$

in which $\alpha = 0.976$ and $\beta = 0.86$ for the Toyoura sand.

DETERMINATION OF COEFFICIENT OF EFFECTIVE LATERAL PRESSURE AT $\Delta u = 0$

Relation of Post-Liquefaction K'_o with K'_{min} Mobilized in Triaxial Compression Tests with Constant $R\varepsilon$-Values

The changes in total and effective lateral stresses with dissipating Δu can be traced by using Eqs. (1) - (4) if K'_o is determined. Obviously, to determine K'_o becomes a key issue.

The effective stress path of a sand during the test step 4 stated above for the case of complete liquefaction is essentially the same with that obtained in a constant $R\varepsilon$ triaxial compression test started from zero effective stress state. Based on such a reason, the available data, obtained from triaxial compression tests with constant $R\varepsilon$-values for saturated Toyoura sand conducted by Shamoto et al. (1995), were used in order to determine the K'_o-value.

Fig. 5(a) shows the relationship between $\sigma'_{lateral}$ and σ'_{axial} observed from triaxial compression tests with $R\varepsilon = 0.22$, 0 and -0.42. Fig. 5(b) shows the relation of stress ratio ($\sigma'_{lateral}/\sigma'_{axial}$) against σ'_{axial}. It is found that the stress ratio approaches asymptotically a constant value as σ'_{axial} increases. Obviously, this constant value represents the minimum stress ratio that can be mobilized under $R\varepsilon$-constant triaxial compression test condition, denoted as K'_{min}.

Note that all the triaxial compression tests as shown in Fig. 5 were started from an initial effective isotropic stress of 20 kPa, and therefore, the corresponding effective stress paths differ from those in post-liquefaction drained triaxial tests started from zero effective stress state. However, comparing the K'_o - and K'_{min}-values, there is a good agreement between the two stress ratios for the same $R\varepsilon$-value, as shown in Fig. 6. This means:

$$K'_o \approx K'_{\min} \tag{5}$$

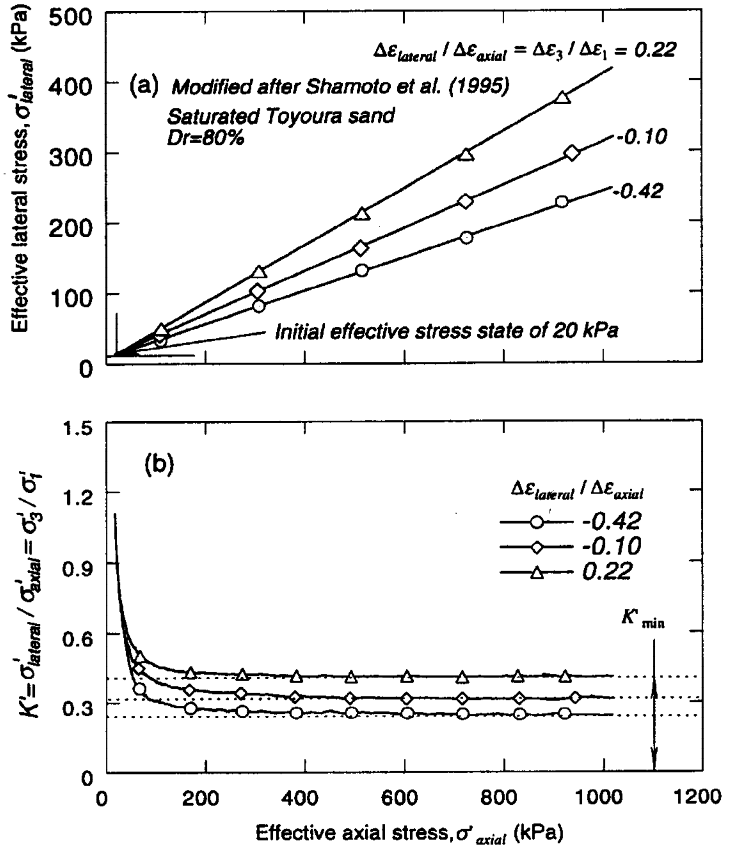

Fig.5 Drained triaxial loading tests at three constant strain increment ratio specified

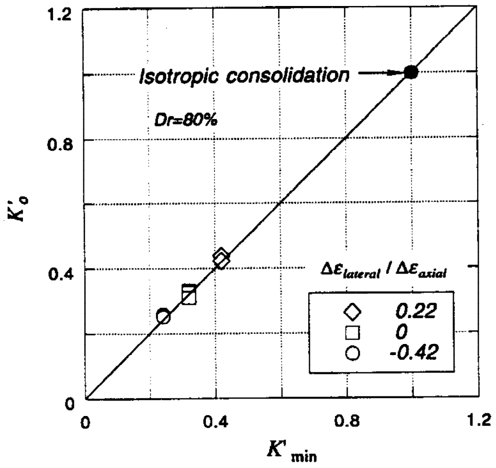

Fig.6 Comparison of K'_o with K'_{min}

A Formulation for K'_{min} Mobilized in Triaxial Compression Tests with Constant $R\varepsilon$-Values

Fig. 7 shows the relationship between $R\varepsilon$ and K'_{min} obtained from all the triaxial compression tests for the samples with Dr =80%. There is a good correlation between the two, defined as:

$$K'_{\min} = \left(\frac{\sigma'_{lateral}}{\sigma'_{axial}}\right)_{\min} = \left(\frac{\sigma'_3}{\sigma'_1}\right)_{\min} = \frac{1}{C-(C-1)R_\varepsilon} \tag{6}$$

in which $C = 3$ at Dr =80% for Toyoura sand.

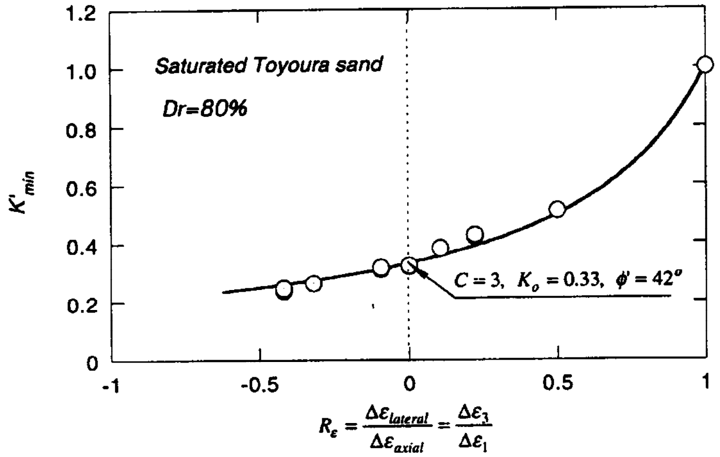

Fig.7 Minimum coefficients of effective lateral pressure mobilized in triaxial compression tests with constant strain increment ratios

Note that the K'_{min}-value at zero lateral strain ($R\varepsilon$ = 0) is usually called "coefficient of earth pressure at rest" and denoted as K_o. Thus, $K'_{min} = K_o = 1/C$ or $C = 1/K_o$ at $R\varepsilon = 0$. Substituting $C = 1/K_o$ into Eq. (6) gives:

$$K'_{\min} = \frac{K_o}{1-(1-K_o)R_\varepsilon} \tag{7}$$

in which $K_o = 1/C = 0.33$ which is the same with the measured K_o-value.

The K_o-value is often estimated by Jaky's equation defined as

$$K_o = 1 - \sin\phi' \tag{8}$$

Substituting Eq. (8) into Eq. (7) leads to

$$K'_{\min} = \frac{1-\sin\phi'}{1-\sin\phi' \cdot R_\varepsilon} \tag{9}$$

in which ϕ' is angle of frictional resistance in terms of effective stress, determined by the following equation based on Mohr-Coulomb's criterion.

$$\phi' = \sin^{-1}[(\sigma'_1 - \sigma'_3)/(\sigma'_1 + \sigma'_3)]_f \qquad (10)$$

For Toyoura sand with $Dr = 80\%$, $\phi' = 42^o$ and thus, $K_o = 1 - \sin 42^o = 0.33$. The relation thus defined by Eq. (9) is shown in Fig. 7 in a solid line. The good agreement in the measured and calculated K'_{min}-$R\varepsilon$ relations shown in Fig. 7 suggests that Eqs. (6) and (8) can provide an empirical estimation of K'_{min}-value to be mobilized under constant $R\varepsilon$-drained tests.

Fig.8 shows the data of the K'_{mi}-values resulted from similar triaxial loading tests by Chu et al (1993) for Sidney sand ($\rho_s = 2.65\ g/cm^3$, $D_{50} = 0.3\ mm$, $e_{max} = 0.855$, $e_{min} = 0.565$ and $\phi' = 39.8^o$). The curve calculated by Eq. (9) at $\phi' = 39.8^o$ is also shown in the same figure. It is seen that those data can be fitted well with the curve, showing the effectiveness of Eq. (9) for other sands.

Fig. 9 shows the effects of ϕ' on K'_o or K'_{min}-values.

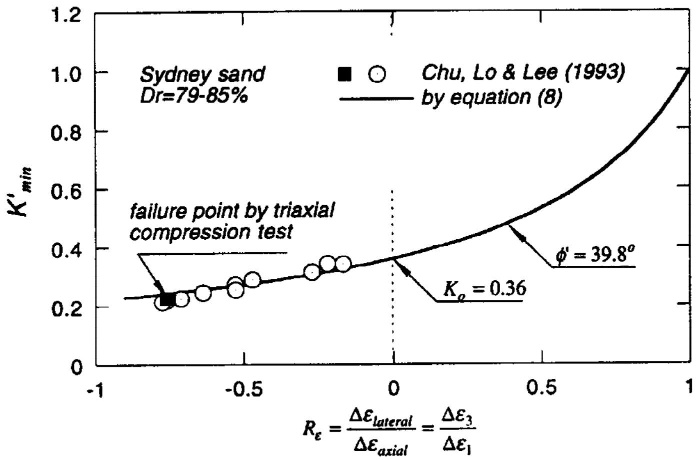

Fig.8 Effectiveness of equation (9) verified by triaxial compression tests with constant strain increment ratios for Sidney sand

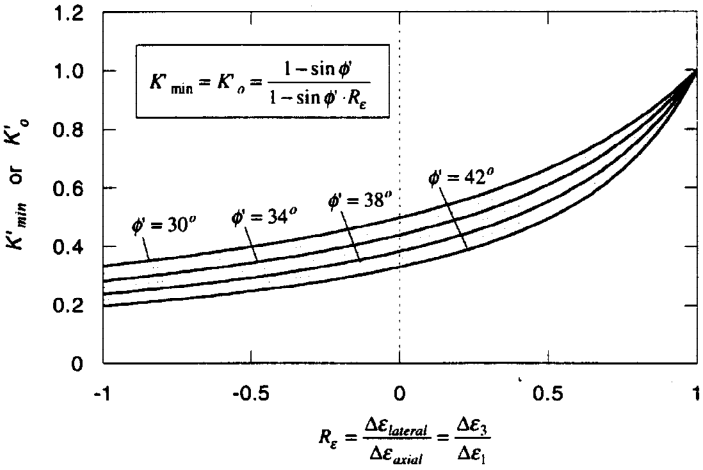

Fig.9 Effects of ϕ' on K'_{min} and K'_o

A SIMPLIFIED METHOD OF ESTIMATION AND ITS PRELIMINARY VERIFICATION

As a consequence of the above experimental analysis, the lateral stress changes in liquefied sand due to excess pore pressure dissipation may be evaluated using the following steps: a) Determine $R\varepsilon$ and ϕ', and then calculate K'_o using Eqs. (5) and (9); b) Calculate m and r_{cr}, using Eq. (4) and then Eq. (3); c) Determine ΔK, an incremental change in K, for Δr_u, an incremental change in r_u, using Eq.(1). Note that both K and r_u of liquefied sands are unity; d) Determine, $\Delta K'$, an incremental change in K' by substituting the known (K, r_u) and ($K+\Delta K$, $r_u+\Delta r_u$) into Eq. (3), respectively, and further determine changes in $\sigma_{lateral}$ and $\sigma'_{lateral}$ according to the definitions shown in Fig. 2; e) Repeat the above steps until r_u becomes zero.

The solid lines shown in Fig. 10 are the experimental facts that $\sigma_{lateral}$ decreases while $\sigma'_{lateral}$ increases as Δu dissipates or σ'_{axial} increases, which were observed during post-liquefaction consolidation with specified constant $R\varepsilon$-values for Toyoura sand (Dr=60% and ϕ' =38°). If the measured Δu was regarded to be known, then the changes in $\sigma_{lateral}$ and $\sigma'_{lateral}$ could be estimated using the proposed method, as shown in Fig.10 with the dotted line. It can be seen that the measured and estimated results show a good agreement. This indicates that the proposed method is effective as a first approximation for estimating post-liquefaction lateral stress changes in saturated sand.

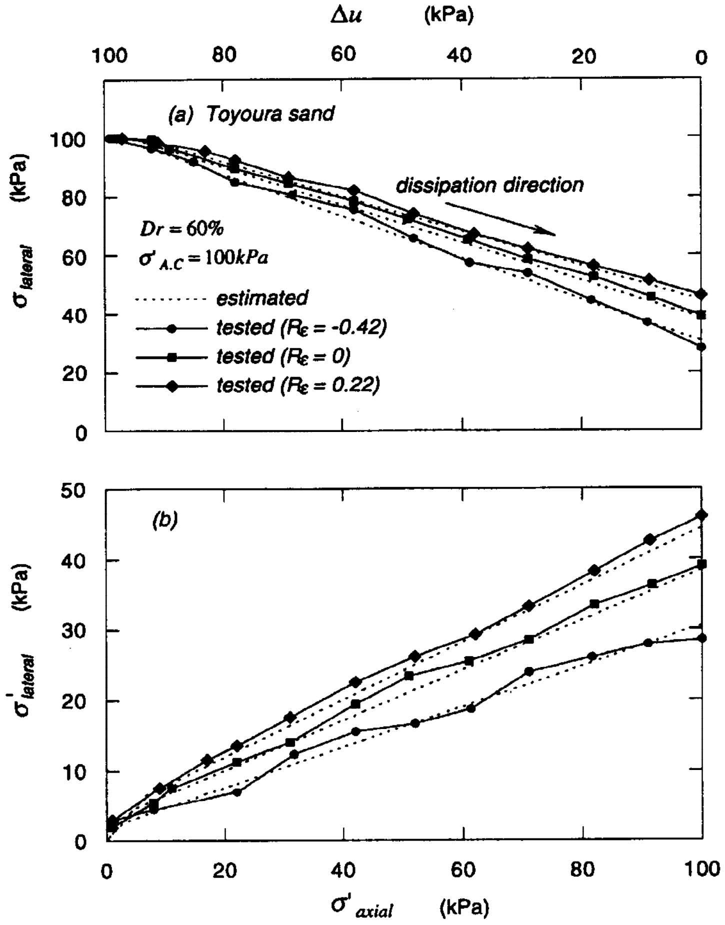

Fig.10 The tested and estimated changes in lateral stresses with increasing effective axial stresses during post-liquefaction consolidation

In general, the strain increment ratio $R\varepsilon$ may change during the entire dissipation process of Δu, and therefore, the increment algorithm has been suggested in the proposed method. In addition, in two- and three-dimensional boundary-value problems involving lateral stress changes in soils, $R\varepsilon$ is unknown variable. The most rational way to determine $R\varepsilon$ should be based on effective stress response analysis.

CONCLUSIONS

The following conclusions may be drawn based on experimental analysis: (1) The post-liquefaction total lateral stress in saturated sand deceases linearly with deceasing excess pore pressure ratio r_u when the value of $R\varepsilon$ is maintained constant; (2) A nearly linear relation exists between the slope of the K-r_u relation m, and the coefficient of effective lateral pressure at $r_u = 0$, K'_o, and this relation is independent of $R\varepsilon$; (3) The post-liquefaction K'_o-value can be determined as a function of $R\varepsilon$ and angle of frictional resistance, ϕ'. Based on these, a simplified methodology has been proposed to predict the changes in post-liquefaction lateral stresses in saturated sand under non-zero lateral strain constraint conditions. As a result, the changes in mean effective principal stresses in liquefied sand deposits due to excess pore pressure dissipation can be rationally evaluated.

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