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SYNOPSIS The state paramater, which describes the initial state of sand before shearing, combining with the concepts of critical stress ratio line and phase transform line are used to assess the characteristics of sand during shearing. The state parameter of each tested sample is determined after the steady state line is contructed, and then relations of characteristics of the cyclic deformation behavior and the state parameter of sand are discussed. The value of the lowest point, S_{upl} on the CSR line in the $p' - q$ plot is related to e_c for a specific sand. Once the stress path of monotonic or cyclic tests crosses the CSR line, strain softening may quickly occur. On the contrary, the stress path bends sharply upwards and to the right along the PT line if it touches the PT line. Liquefaction resistance may decrease with increasing the value of α for sand having $\psi > 0$. Oppositly, it may increase with increasing the value it of α for sand having $\psi < 0$. In the case of sand having $\Psi \cong 0$, nearly keeps no change with increasing the value of α.

INTRODUCTION

Liquefaction during earthquake has been of primary concern and of considerable disscusions by engineers. The SPT-based liquefaction analysis developed by Seed(1984) is most popular for engineers' practice. Seed's Liquefaction Assessment Chart (SLAC) correlates the equivalent cyclic stress ratio required to cause liquefaction to the strength of the soil element depicted by the corrected SPT blow count $(N_1)_{60}$. This corelation was developed for clean sand at an effective confining pressure of 1tsf and in a level ground condition. However, for soil element in the slopes or near buildings there exist initial static shear stresses on the horizontal plane which can significantly affect the liquefaction resistance of the soil. To correct this discrepancy with a given α value, Rollins and Seed proposed a correlation between K_α and α. Here α is defined as the ratio of initial static shear stress on the horizontal plane, τ_s divided by the vertical stress, σ_o. Correction factor, K_α, is defined as the ratio of the liquefaction resistance of the soil at a given initial static shear $(\alpha > 0)$ to the liquefaction resistance under level condition $(\alpha = 0)$. Seed's suggested correlation is interrelated with relative density (D_r) of sand.

Effects of initial static shear have been investigated in the laboratory by several research workers. The researchers based their studies only on D_r and failed to identify the fundamental parameter that govern these effects. Therefore, the conflicting and confusing results are found.

The relative density approach assumes the existence of reference densities and attemped to normalize behavior in terms of these reference density. However, the relative density approach does not accommodate the influence of stress level on sand behavior. Confining pressure modifies sand deformation behavior. Even dense sand tested at sufficiently high confining pressure will behave similarly to loose sand. Therefore, properties of sands cannot be expressed in terms of D_r alone; a description of stress level must also be included. In general, mean stress is a suitable stress measure. The void ratio or density on steady state which has a unique structure and is not influenced by the original test conditions may be selected as a reference condition. The steady state point is defined as that a soil mass deforms under conditions of constant effective stress, void ratio and velocity. The steady state line (SSL) is defined as the locus of all steady state points in void ratio-mean stress space (Been & Jefferies).

A series of CIU test can be carried out on samples at different void ratios and stress levels to define a number of steady state points. These points then define the SSL. The difference between the initial state and the steady state in $e - logp'$ plot at the same mean stress level characterizes the sand's state and is called the state parameter, Ψ. Pillai(1991) correlates K_α to state parameter, Ψ, that govern the strength-deforation of soils using steady state concept.

In this paper experimental investigations are reported. The monotonic behaviors of sand with CU and CD tests are first examined, and then, the SSL is defined and the state parameters of tested samples are determined as well. A series of stress-controlled cyclic triaxial tests were performed. The specimens were first anisotropically consolidated under principal stress σ_1 and σ_{3c}, with different K_c $(K_c = \sigma_1/\sigma_{3c})$; these induce static shear stress in the sample, represented by the maximum value $\tau_s = 0.5(\sigma_1 - \sigma_{3c})$ acting on 45 deg planes. Afterwards the specimens were cyclically loaded until liquefaction occurring. Evaluation of the initial static shear stress affecting the resistance of liquefaction is interpreted with the state parameter.

TEST PROCEDURE

Two series of triaxial tests on Likan Sand were performed in this paper. (1) Monotonic strain controlled drained and undrained triaxial tests for Likan Sand having diffenent Ψ

values. (2)Anisotroically consolidated stress-controlled cyclic triaxial tests with different combinations of α and Ψ.

Likan Sand is a uniformly graded, fine grain sand. The mineralogy of the material is mainly quartz and mica. The particles are mostly flaky and friable. The index properties of Likan Sand are as follows: D_{50}=0.24mm ; C_u=1.87 ; e_{max} = 1.239 and e_{min} = 0.756.

The tests were conducted on specimens of 71mm diameter and 152 mm height. The specimens were placed between enlarged (76mm diameter) end platens to accommodate the large strains associated with liquefaction. The end platens were lubricated by rubber membranes with silicone grease in between to reduce the effects of end restraint, that is to preserve uniform conditions of stress and strain.

Test samples were prepared using the moist tamping method. The sand was mixed with 8% of water by weight before being placed in the mold and tamped to the desired height and density. Saturation was ensured by CO_2 purging, percolation of deaired water and back pressure. A B value greater than 0.97 was obtained. During this process an effective stress of approximately 20 kPa was maintained on the sample. In some cases, high back pressure were used to avoid cavitation of the pore fluid during the test due to large negative pore pressures.

BEHAVIOR OF MONOTONIC SHEARING

The steady state of deformation for any mass of particles is the state in which the mass is continuously deforming at constant volume, constant normal effective stress, constant shear stress, and constant velocity. The critical state has been defined as the state at which the soil continue to deform at constant stress and constant void ratio. The steady or critical state is thus an ultimate state to which the sample will go after large strains under monotonic loading. The steady state has traditionally been measured using undrained tests on loose sand samples, while the critical state is generally inferred from drained tests on dense sand.

The consolidated undrained triaxial compression and extension tests were performed on Likan Sand . The point on the stress-strain curve at which the specimen is continuously deforming at consatant deviatoric stress is chosen as the steady state point. The locus of those points actually reach a steady state defines the SSL on the $e - logp'$ plot. The consolidated drained triaxial compression and extension tests were also performed and then using the same criterion as described in undrained cases to define the critical state line (CSL) on the $e - logp'$ plot. In some cases, end points of tests which have not reached the steady or critical state yet are plotted with arrows indicating the direction of possible state change.

Figs. 1-a and 1-b show the comparison of SSL from triaxial compression and extension tests for Likan sand, respectively. Solid symbols represent steady states and critical states. Hollow symbols represent initial states before shearing. Solid line represents the best fitting line for all the steady state points and critical state points. The figures suggest that, for Likan Sand, the critical and steady state are the same. However, these two states are dependent of stress path as shown in Fig.2-a. Fig.2-a and Fig.2-b also show that the equations of the best fitting lines for SSL calculated from triaxia; compression and extension tests in $e - logp'$ or $e - logq$ plots, respectively.

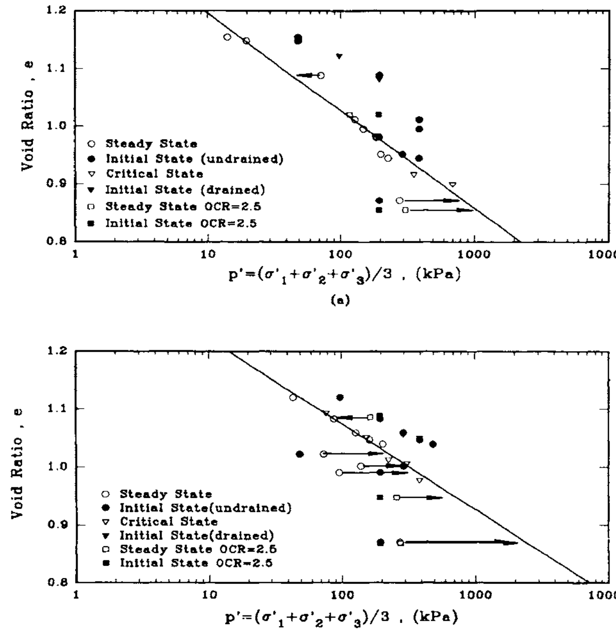

Fig.1 Comparison of SSL and CSL (a) from triaxial compression tests (b) from triaxial extension tests

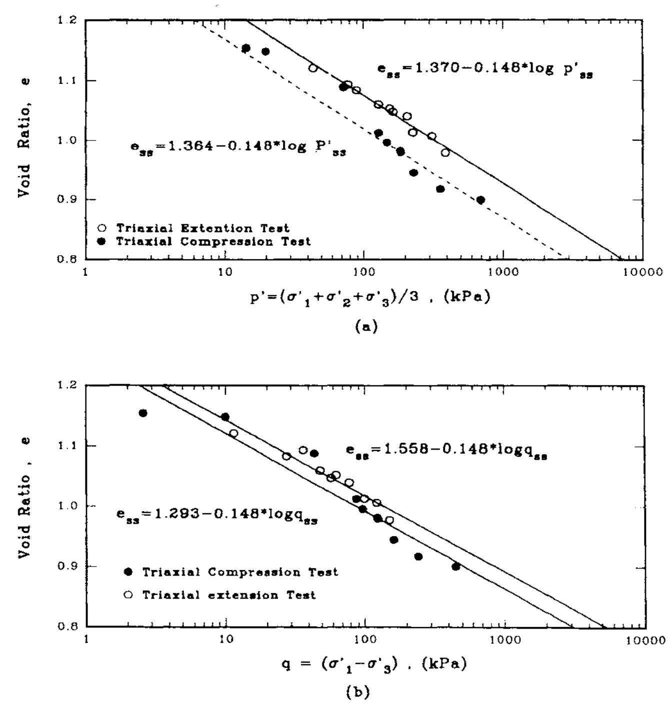

Fig.2 Comparison of steady state in triaxial extension and compression tests (a) void ratio versus $logp'$ (b) Void ratio versus $logq$

SSL for compression tests on $e - logp'$ plot is:

$$e_{ss} = 1.364 - 0.148 * logp'_{ss} \qquad (1-a)$$

SSL for extension tests on $e - logp'$ plot is:

$$e_{ss} = 1.37 - 0.148 * logp'_{ss} \qquad (1-b)$$

SSL for compression tests on $e - logq$ plot is:

$$e_{ss} = 1.293 - 0.148 * logq_{ss} \qquad (1-c)$$

SSL for extension tests on $e - logq$ plot:

$$e_{ss} = 1.558 - 0.148 * logq_{ss} \qquad (1-d)$$

The values of q_{ss} on the $e_{ss} - logq_{ss}$ plot represent the residual strength for the specific void raio of sand.

Fig. 3 is the stress path ($p' - q$) plot under monotonic undrained loading. The shear deformation behaviors are quite different for sands having different values of Ψ. There is a large shear stress drop accompanied by high pore pressure changes for samples with high positive Ψ during undrained tests. The locus of points at which strain softening is initiated defines a curve in stress space that has been termed the "critical stress ratio (CSR) line" (Vaid and Chern). On the contrary, for the samples with negative Ψ there is no peak shear stress due to dilation strongly occurring. The higher positive Ψ the state of sands, the larger volume contraction under drained shearing or the much sharper increase in pore water pressure under undrained shearing tend to be. Fig. 4 shows that the equations of the best fitting lines for CSR line in $e - logp'$ and $e - logq$ plots, respectively.
CSR line in $e - logp'$ plot is:

$$e_{csr} = 1.399 - 0.148 * logp_{csr} \qquad (2-a)$$

CSR line in $e - logq$ plot is:

$$e_{csr} = 1.293 - 0.148 * logq_{csr} \qquad (2-b)$$

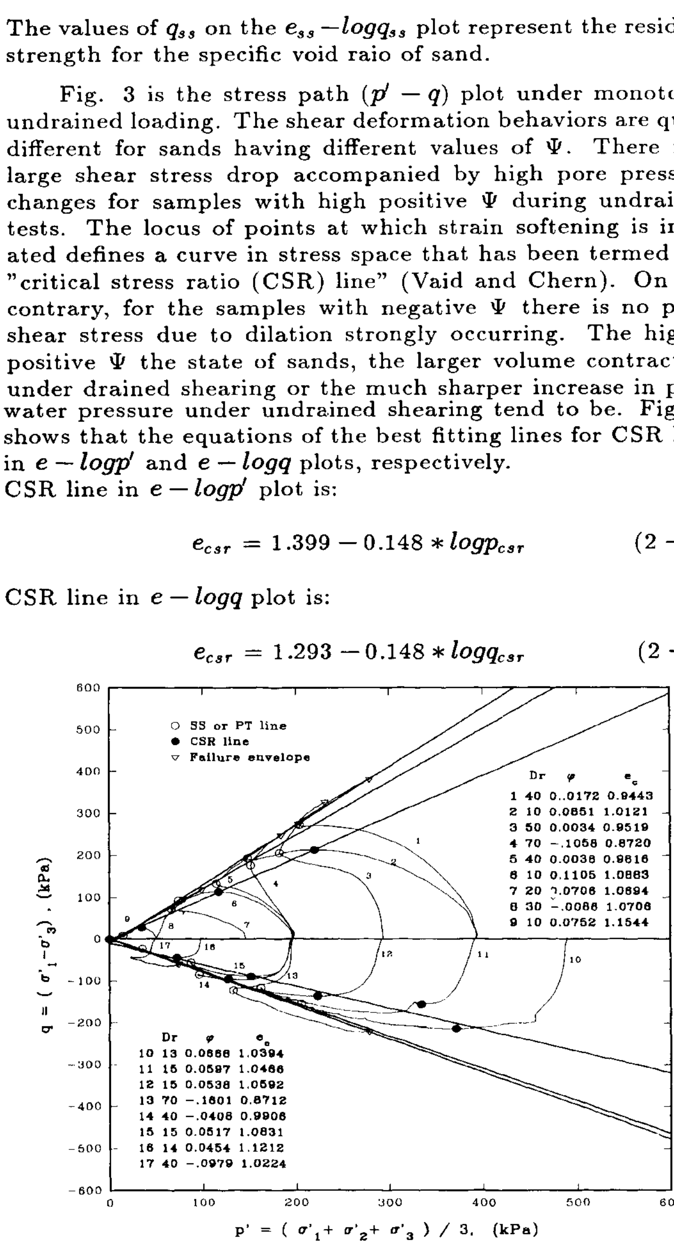

Fig.3 Stress paths of monotonic triaxial tests on Likan Sand

For a given void ratio, there exists a minimun confining pressure to induce strain softening under later undrained shearing. The higher the density of sands, the higher the minimun confining pressure needs. Consequently, the value of the lowest point, S_{upl} on the CSR line in the $p' - q$ plot is strongly related to e_c for a given sand. Sample consolidated less than this minimun confining pressure will develop dilative behav-

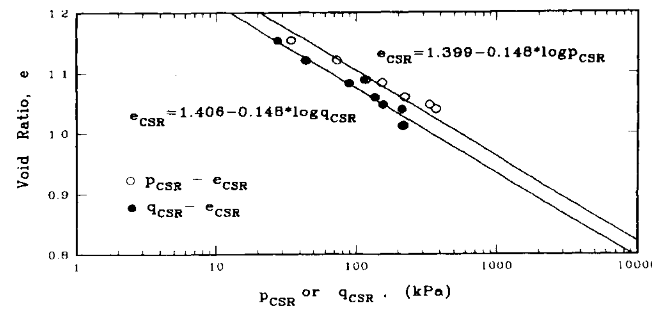

Fig.4 Relations of void ratio versus $logp_{csr}$ and q_{csr}

ior during shearing. The corresponding stress path shows a turnaround or elbow and moves back along the failure line. The turnaround point in the stress path is called the phase transformation point. The locus of these points defines the so-called " phase transformation line" (PT line). That is the pore water in theses tests decreased after an initial increase, and the shear stress increase monotonically until the end of the test. Fig. 5 shows that the necessary and sufficient condition for Likan sand to be contractive and develop unlimited strain in undrained loading is state parameter $\Psi > 0.05$ at the end of consolidation. Likan Sand having the state parameter greater than 0.05 will develop strain softening behavior. Therefore CSR line on Fig. 3 comes out not from the origin of $p' - q$ stress space but from the point where p' is larger enough to suppress the dilation during shear for a given sand.

From the discussions above the conclusions can be drawn. Once the stress path of monotonic loading crosses the CSR line, strain softening may quickly occur. On the contrary , the stress path bends sharply upwards and turns to the right along the PT line if it touches the PT line. Therefore it is reasonably inferred that PT line would come out from origin of $p' - q$ stress space and end at the point where p' is larger enough to suppress the dilation for a given sand. The CSR line, PT line, SS line and failure line on Likan sand are clearly shown in Fig. 3. Eq. 1 and 2 can help us to image the shape of the boundary surface in the $e - p' - q$ three dimensions plot.

BEHAVIOR OF CYCLIC UNDRAINED LOADING

The specimen is consolidated with an axial stress, $\sigma_1 \geq \sigma_{3c}$, i.e. with a ratio $K_c = \sigma_1/\sigma_{3c} \geq 1$. After consolidation, a cyclic deviatoric stress $\pm\sigma_{cy}$ is applied undrained in axial direction. This induces a cyclic shear stress $\tau_{cy} = \pm 1/2\sigma_{cy}$ and static shear stress, $\tau_s = 1/2(\sigma_1 \text{-} \sigma_{3c})$ on 45 deg planes. The initial static shear stress ratio is defined as $\alpha = \tau_s/\sigma_{3c}$. When $\tau_s \leq \tau_{cy}$, there is shear stress reversal, i.e., the radial stress becomes the major principal stress and the specimen goes into extension during part of the cycle. If $\tau_s \geq \tau_{cy}$, there is no shear stress reversal and the sample always in compression. The degree of stress reversal can be defined with $R = (\tau_{cy} - \tau_s)/\tau_{cy} + \tau_s) \times 100\%$. The deformation of the sand is the result of the movement and rearrangement of the grains, i.e., the change of the fabric of the sand resulting from the stress conditions. Many researchers have shown that the existed fabric of sand collapses and causes larger pore water generation after the stress reversal ($R < 0$).

Three series of cyclic triaxial tests subjected different initial static shear for four different state of sand are performed. Accumulated strain is defined as the maximun axial strain measured from the beginning of cyclic loading. Liquefaction resistance is defined that the cyclic shear stress ratio τ_{cy}/σ_{3c} needs to reach the four different values of the accumulated strains in ten uniform stress cycles. The values of 2%, 5%, 10% and 15% of accumulated strain are chosen as the failure criterion in this paper, respectively.

In order to relate liquefaction resistance with initial static shear, it is necessary to establish the figures of the cyclic stress ratio versus number of cycles required to cause 2%, 5%, 10% and 15% of accumulated strain , respectively. Afterwards liquefaction resistance, i.e., the required cyclic stress ratio to cause a speccific value of accumulated strain in ten cycles, is easily determined. The relations of cyclic stress ratio (τ_{cy}/σ_{3c}) to cause different values of accumulated strain and initial static shear stress ratio (α) on Likan Sand are shown in Fig. 5-a. Fig. 5-b shows the relation of K_α versus α. The results of these two figures show: (1) liquefaction resistance decreases with increasing α value for the contractive soil($\Psi > 0$). (2) liquefaction resistance increases with increasing α value for the dilative soil ($\Psi < 0$). (3) In the case of medium dense sand having $\Psi \cong 0$, liquefaction resistance keep nearly no change with increasing α value. Whatever the state parameter Likan Sand has, the potential of liquefaction resistance will be less influenced by the α value if the larger accumulated strains are chosen as failure strains.

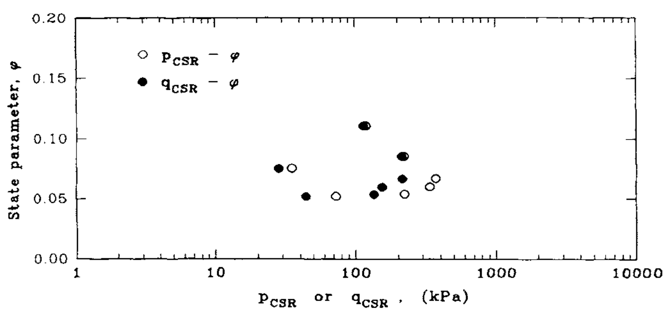

Fig.5 Relations of state parameter versus $logp'_{csr}$ and $logq_{csr}$

SUMMARY AND CONCLUSIONS

The state paramater, which describes the initial state of sand before shearing, combining with the concepts of CSR line and PT line are used to assess the characteristics of sand during both monotonic and cyclic shearing. The following conclusions may be made:

(1). The critical state and steady state are the same states for Likan Sand.

(2). S_{up1} on the CSR line in the $p' - q$ plot is strongly related to e_c for a given sand. CSR Line comes out not from the origin of $p' - q$ plot but from the point where p' is larger enough to suppress the dilation during shearing. However, PT line comes out from the origin of $p' - q$ stress space but ends at the point where p' is larger enough to suppress the dilation. The value of S_{up1} and PT line position strongly dominate the deformation behavior both monotonic shearing and cyclic shearing.

(3). Liquefaction resistance may decrease with increasing α value for the contractive soil($\Psi > 0$). On the contrary, liquefaction resistance may increase with increasing α value for the dilative soil ($\Psi < 0$). However, there may be nearly the same liquefaction resistance for the sand having $\Psi \cong 0$.

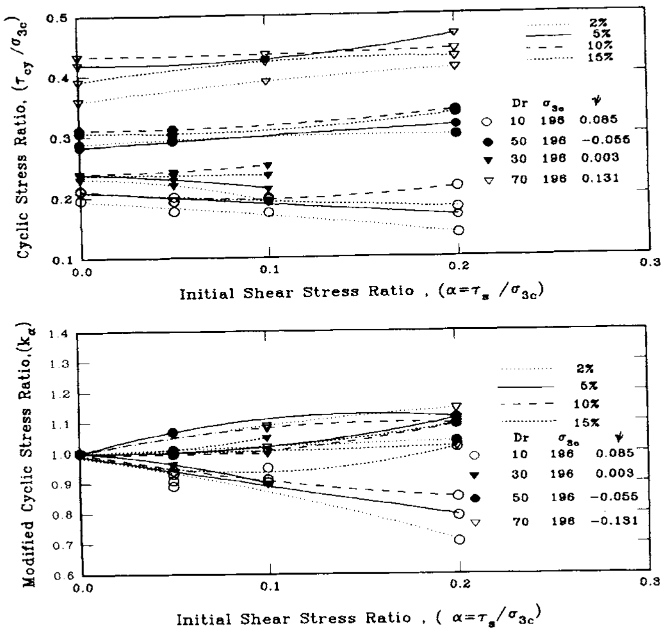

Fig.6 (a)Relations of cyclic stress ratio and initial static shear ratio at different accumulated strains (b) Relations of modified cyclic stress ratio and intial static shear stress ratio

(4). Liquefaction resistance is less influenced by the initial static shear if the larger accumulated strains are chosen as failure strains.

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REFERENCE

Been, K and Jefferies, M.G. (1985). "A State Parameter for Sands" Geotechnique, 35(2):99-112.

Pillai, V.S. (1991). "Liquefaction Analysis of Sands: Some Interpretation of Seed's K_α (Sloping Ground) and K_σ (Depth) Correction Factors Using Steady State Concept", Proc. 2nd Conf. on Recent Advances in Geotech. Earthquake Engrg. and Soil Dynamics, Vol. 1:579-587.

Rollins, K.M. and Seed, H.B. (1990). "Influence of Building on Potential Liquefaction Damage", J. Geotech. Engrg. Div., ASCE, 116(2):165-185.

Seed, H.B., Idriss, I.M. and Arango, I. (1983). "Evaluation of Liquefaction Potential Using Field Performance Data", J. Geotech. Engrg, Div., ASCE, 109(3):458-482.

Vaid, Y.P. and Chern. J.C. (1985). "Cyclic and Monotonic Undrained Response of Sturated Sand", Advances in the art of testing soils under cyclic conditions, ASCE Annual Convention :120-147.