EVALUATION OF ENGINEERING PROPERTIES AND LIQUEFACTION RESISTANCE OF A SILTY SAND BY ITS STATE PARAMETER

by

Y. C. Chen and C. T. Chin

Reprinted from

Proceedings, 7th International Conference on Behaviour of Offshore Structures, Vol.3, 1994, pp.295-304

EVALUATION OF ENGINEERING PROPERTIES AND LIQUEFACTION RESISTANCE OF A SILTY SAND BY ITS STATE PARAMETER

Y.-C. CHEN

Department of Construction Engineering, National Taiwan Institute of Technology
P.O. Box 90-130, Taipei, Taiwan 106, R.O.C.

C.-T. CHIN

Moh and Associates, Inc., 35, L.11, Kwangfu N. Rd., Taipei, Taiwan 105, R.O.C.

ABSTRACT

The engineering properties and liquefaction resistance of a silty sand were evaluated by its state parameter in this paper. Triaxial compression tests and torsional simple shear tests were performed on remolded samples of a silty sand to study the effects of several factors on the steady state line, such as the fines content, sample preparation, stress path, and loading rate. Test results of undrained cyclic torsional simple shear test showed that more or less linear relationship exists between state parameter and liquefaction resistance.

KEYWORDS

State parameter; liquefaction; steady state line; fines content; stress path; sample preparation.

INTRODUCTION

Behavior of sand is controlled by its density and confining stress. Relative density is the commonly used index to describe the state of sand. However, it is well known that relative density cannot fully describe the mechanical behavior of sand. Therefore a parameter, which can incorporate the density and stress state of soil, is needed to reflect the engineering behavior of sand. To establish a rational engineering approach to constructing structures using undensified hydraulic sand fill, Been and Jefferies (1985) developed a state parameter concept to characterize the sand behavior. They found that significant engineering design parameters are dependent on the state parameter. Recently, quite a few hydraulic sand fill islands will be constructed on the west coast of Taiwan to be used as industrial parks. Therefore, it would be economic and safe to apply the state parameter concept in designing these islands.

Been and Jefferies (1985) propose to use the steady state line (SSL) on the e-log Γ' plane as the reference line. State parameter, Ψ, is defined as the difference between initial void ratio and the corresponding void ratio at the same stress level on the steady state line (Fig.1). State parameter combines the influence of density and stress so that it can reasonably characterize many important engineering behaviors of sand, as well as liquefaction resistance.

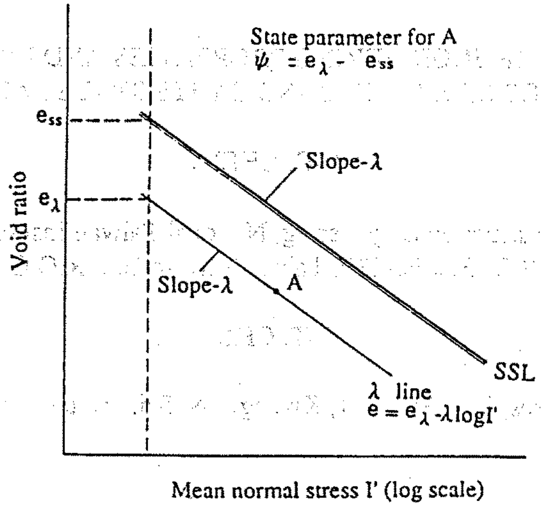

Fig. 1. Definition of State Parameter

LITERATURE REVIEW

Steady state of sand refers to the state that sand continuously deform at constant volume, constant effective stress, constant shear stress, and constant strain rate (Been and Jefferies, 1985, Been et al., 1991). Only until fabric is totally restructured, all influence of particle orientation is stable, and all crushing of particles is completed, a steady state can be achieved. Steady state line is the loci where soils reach steady state from various void ratios and stress states. The original structure of specimen only has minor effect on the stress-strain behavior during the beginning stage of shearing. But 'flow' structure and its corresponding strength are independent of its initial structure. Major factors influencing steady state line of sand include fines content, particle shape, stress path, and magnitude of effective stresses. Some of the major previous research results are summarized in the following paragraphs.

Fines content affects the location and slope of steady state line on e-log I' plane. With increasing percentage of fines, steady state line moves leftward with changing slopes (Been and Jefferies, 1985, Dobry et al., 1985, Konard, 1990). It is also noted that well rounded sand has falter slope of steady state line than sand of angular shape (Konard, 1990, Poulos et al., 1985). Some researches indicate that steady state line is independent of the stress path that soil specimens experienced during shearing (Been et al., 1991, Castro et al., 1992). However, there are other studies showing that different steady state lines can be obtained from different stress paths (Kuerbis et al., 1988, Vaid et al., 1990). It is generally agreed that either it is a stress-controlled or a strain-controlled test that steady state line is approximately the same (Castro et al., 1982). Rate of shearing also does not have any obvious influence on steady state line (Negussey et al., 1988).

Magnitude of effective stress affects the shape of steady state line (Been et al., 1991, Castro et al., 1992). With effective stress less than 5 ksc, steady state line is a straight line. Steady state line will curve downward when effective stress exceeds 10 ksc. The reason is that the sand particles crush at higher confining stress state and the fines content increases. Anisotropic consolidation does not significantly influence the steady state line (Castro et al., 1992). When soil specimen reaches its steady state, initial fabric of sand is totally restructured. Thus method of sample preparation does not have significant influence of steady state line (Been et al., 1991, Poulos, 1981, Poulos et al., 1985).

There are three major categories of saturated sand behaviors under cyclic undrained shearing, namely flow liquefaction, limited liquefaction and cyclic mobility (Vaid et al., 1985). These three types of liquefaction behaviors are closely related to the initial state of sand. If the initial state of sand is located on the right hand side of the steady state line (contraction side), flow liquefaction may occur. If the initial state of sand is located on the left hand side of the steady state line (dilation side), cyclic mobility may occur. If the initial state is very close to the steady state line, limited liquefaction may occur.

SAMPLE PREPARATION AND TESTING PROCEDURES

Testing material used in this study is Taipei silty sand with fines contents of 2%, 14%, and 57%. Table 1 presents the physical properties of test specimens. Both dry tamping (DT) and moist tamping (MT) methods were used to prepare samples. Each sample was divide into five layers with equal weight. Each layer of soil was poured into the mold and then compacted to its specified height. Specimens with various relative density can be obtained by controlling the height of specimen. Water content of specimen was controlled to be within 5% when moist tamping method was used.

Table 1. The physical properties of test specimens.

F.C. (%)	D_{100} (mm)	D_{60} (mm)	D_{50} (mm)	D_{30} (mm)	D_{10} (mm)	G_s (mm)	e_{max}	e_{min}	L.L. (%)	P.L. (%)
2	0.60	0.18	0.17	0.15	0.10	2.72	1.17	0.70	--	--
14	0.60	0.16	0.15	0.12	0.06	2.72	1.04	0.45	--	--
57	0.60	0.08	0.06	0.03	0.007	2.70	1.34	0.74	24.5	21.9

Triaxial tests and torsional shear tests were used in this study. The major purpose of carrying out triaxial test is to investigate the influence of various factors on the determination of steady state line. It is also used to establish relationships between state parameter and engineering properties. After the specimens were consolidated, they were sheared by strain-controlled drained or undrained loading. Strain rates used in this study are 0.025%/min and 0.00625%/min. Monotonic and cyclic torsional shear tests were conducted. The purpose of running torsional tests is to study the influence of stress path on steady state line. Torsional test results were also used to establish the relationship between state parameter and liquefaction resistance.

TEST RESULTS AND DISCUSSIONS

Steady State Line

Undrained Test Results. For undrained triaxial tests on test specimens with 2 % fines content initially located on the contraction side, Figures 2a, 2b, and 2c present results of stress-strain curves, pore pressure responses, and effective stress paths, respectively. Figure 2a shows that 3 sets of tests have strain-softening behavior . Deviator stress of these 3 tests does not change when strain level reaches 20%. On the other hand, the rest of the tests do not show a constant deviator stress even when vertical

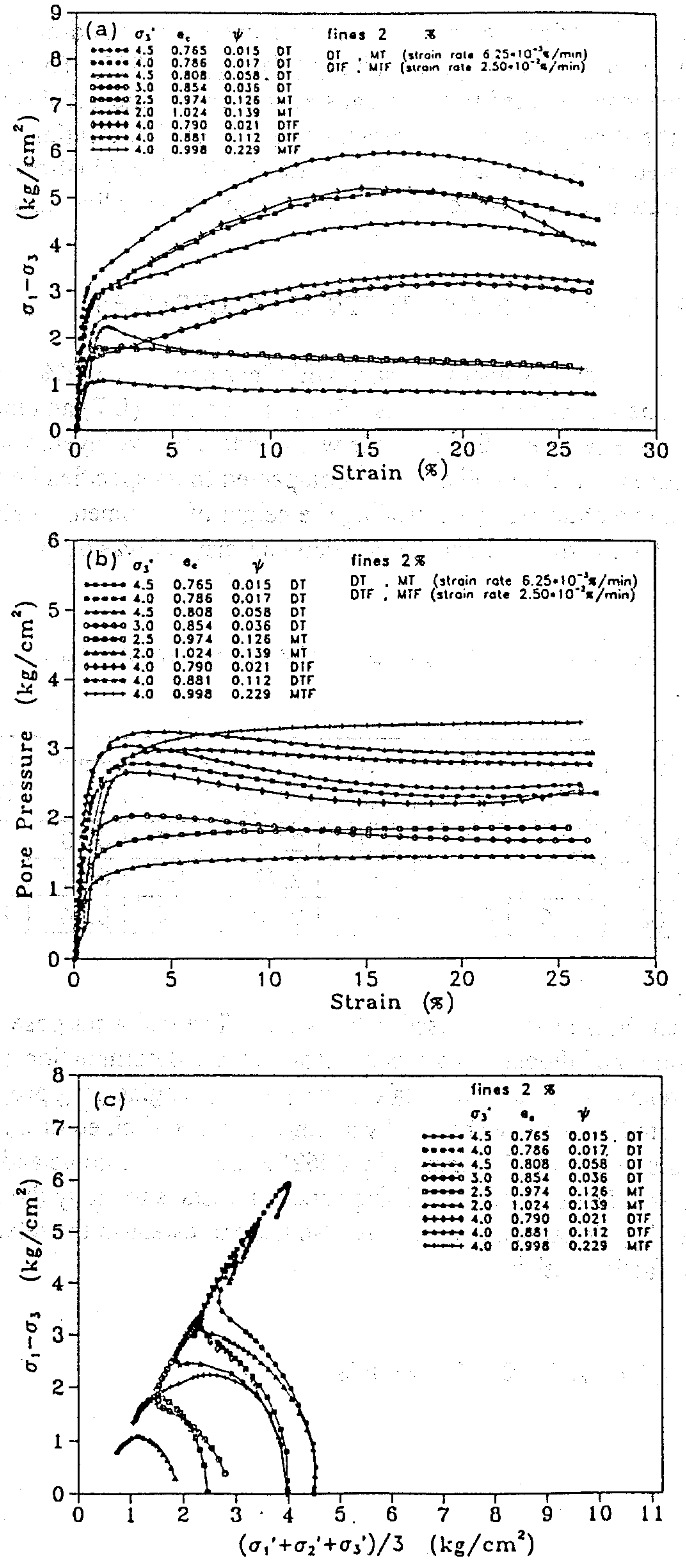

Fig. 2. Results of stress-strain curves, pore pressure responses, and effective stress paths for undrained triaxial tests (2 % fines, contraction side).

strain exceeds 25%. But Fig. 2b shows that pore pressures of most of the tests do not change when strain reaches 25%. Therefore steady state is determined at the stage where pore pressure achieves a stable state. Figure 2c indicates that 3 specimens with state parameter larger than 0.126 have contraction behavior whereas the other specimens with state parameter less than 0.112 have contraction behavior at beginning but dilation behavior later on. For undrained triaxial tests on specimens with 2 % fines content initially located on the dilation side, test results show that pore pressure has generally approached a stable state at 25% strain but deviator stress has not. Based on the undrained test results, Fig. 3 indicate that specimens reach an unique steady state line independent of their initial state.

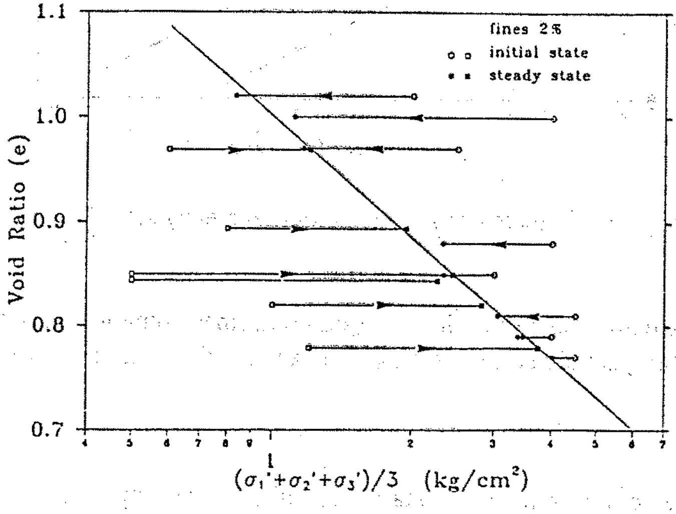

Fig. 3. Steady state line obtained by undrained triaxial tests for specimens with 2% fines.

Drained Test Results. Drained test results indicate that test specimens can hardly reach steady state even at very large strain level, especially for specimens at dilation side. It suggests that steady state line can be more easily reached by undrained test than drained test.

Factors Affecting the Determination of Steady State Line

Sample Preparation Method. Different sample preparation methods can cause different fabrics of the specimens. Dry tamping and moist tamping methods were used to prepare the specimens for undrained triaxial compression tests. Figure 4 indicates that for samples with fines contents of 2 % and 14 % sample preparation method does not have significant influence on steady state line.

Strain Rate. Rates of 0.025%/min and 0.00625%/min were used in conducting undrained triaxial compression tests. Figure 4 indicates that rate effect is insignificant.

Anisotropic Consolidation. Figure 4 also presents the results of anisotropically consolidated undrained traxial compression tests (indicated as CAU). Anisotropic consolidation does not have any major effect on the determination of steady state line.

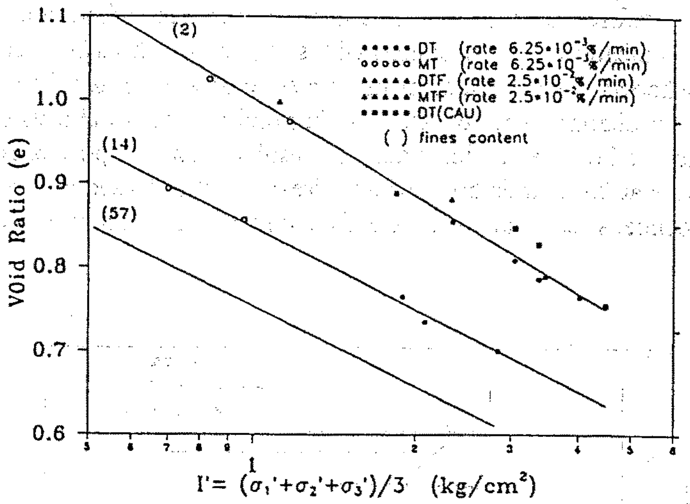

Fig. 4. Effects of various factors on steady state line.

Fines Content. Steady state lines corresponding to 3 different fines contents are presented in Fig. 4. With increasing fines content, steady state line moves leftward and the slope of steady state line becomes flatter.

Stress Path. Based on the definition of steady state that soil continuously deforms at constant volume, effective stress, shear stress and strain rate, it is still possible that different steady state lines may be obtained by different tests , e.g. triaxial compression test, triaxial extension test, and simple shear test. This study used undrained triaxial compression test and undrained torsional shear test on remolded specimens with 2 % fines content to investigate the effect of stress path on steady state line. Test results (Fig. 5) show that the steady state line determined by torsional shear test is located left to the steady state line determined by triaxial test. It indicates that steady state line of sand is dependent on the stress path reaching steady state.

Engineering Properties

Undrained Shear Strength At Steady State. This study used undrained triaxial compression test and undrained torsional shear test on remolded specimens with 2 % fines content to investigate the effect of stress path on undrained shear strength at steady state. Test results in Fig. 6 indicate that the undrained shear strength is a function of void ratio. It does not have an obvious relationship with stress path.

Maximum Undrained Shear Strength. Figure 7 presents the relationship between state parameter (Ψ) and normalized undrained shear strength (q_{max}/σ_c'). Normalized undrained shear strength decreases with increasing state parameter. Figure 7 also indicates that both triaxial and torsional test results lie on the same curve describing the relationship between state parameter and normalized undrained shear strength.

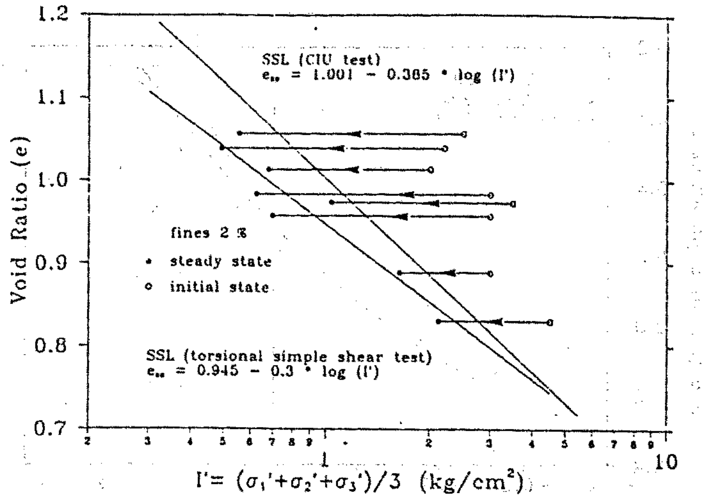

Fig. 5. Effect of stress path on steady state line.

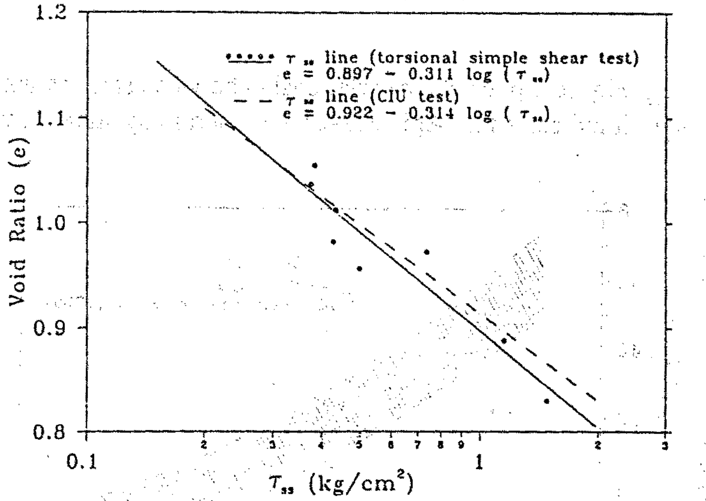

Fig. 6. Undrained shear strength at steady state by triaxial test and torsional shear test.

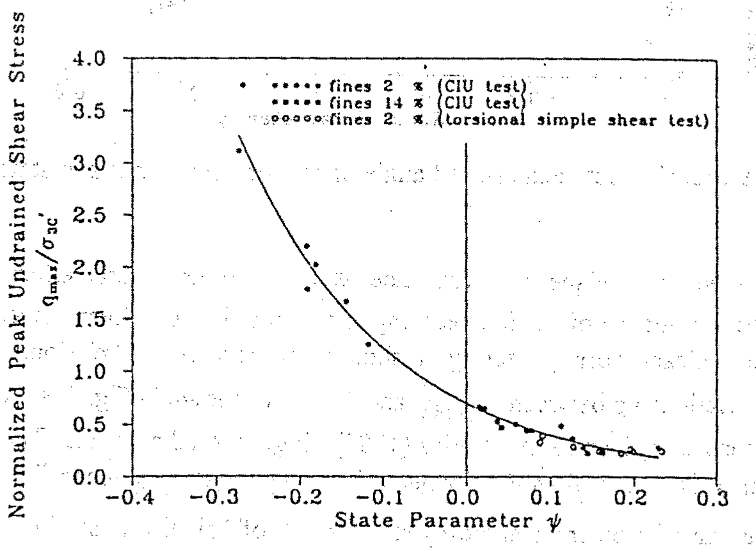

Fig. 7. Relationship between normalized undrained shear strength and state parameter.

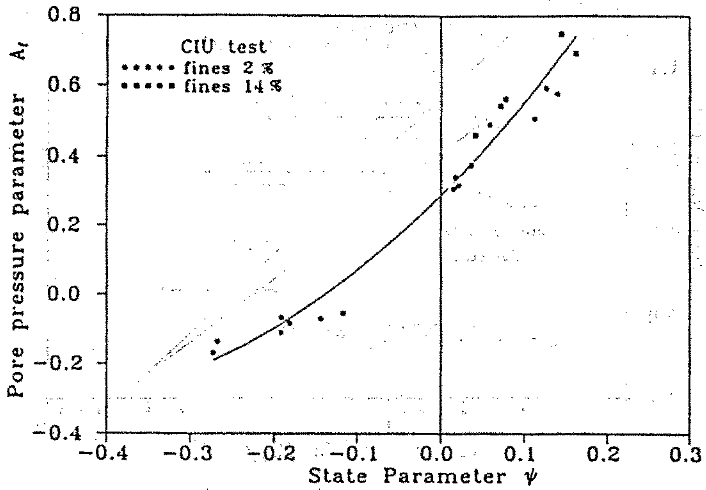

Fig. 8. Relationship between pore pressure parameter at failure and state parameter.

Pore Pressure Parameter. Figure 8 presents the relationship between state parameter and pore pressure parameter at failure (A_f). It indicates that A_f increases with increasing state parameter of sand.

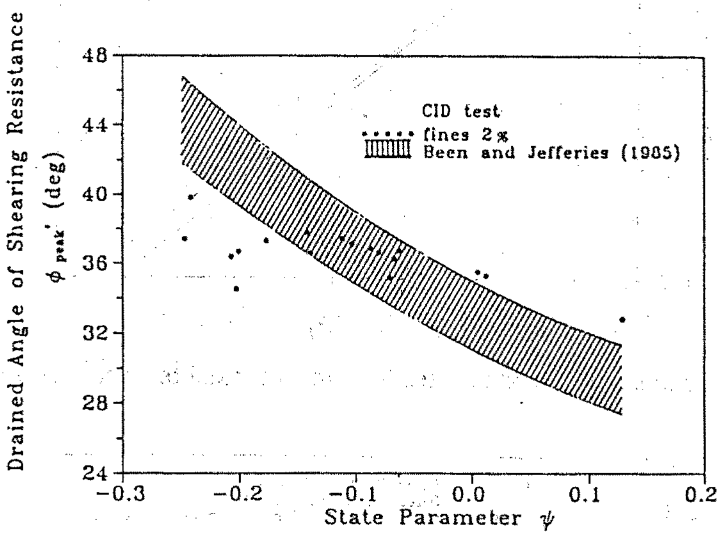

Fig. 9. Relationship between drained angle of shearing resistance and state parameter.

Friction Angle. Drained angle of shearing resistance, ϕ_{peak}', reflects overall effect of the friction angle of material itself, influence of particle rearrangement, and dilation effect. Since state parameter reflects dilation effect of sand during shearing, it should also have certain relationship with ϕ_{peak}'. Figure 9 shows the relationship between ϕ_{peak}' and Ψ. Also shown in Fig. 9 is the typical range of various sands summarized by Been and Jefferies (1985). Figure 9 indicates that Taipei silty sand has a lower ϕ_{peak}' when Ψ is smaller than -0.15 while it has a higher ϕ_{peak}' when Ψ has a positive value. Test results indicate that friction angle at steady state (ϕ_{ss}') of Taipei silty sand is between 24^o and

37° with an average value of 35°. It is noted that ϕ_{ss}' is not a constant but a function of void ratio. It decreases with increasing void ratio.

Liquefaction Resistance. Liquefaction resistance refers to the stress ratio between cyclic shear stress and effective confining stress (τ / σ_{mc}') needed to cause initial liquefaction in 10 or 20 cycles. In order to evaluate relationship between state parameter and liquefaction resistance, specimens of varying densities have been consolidated with effective confining stresses of 0.5 and 1.0 ksc. Specimens were sheared by undrained torsional cyclic loading until initial liquefaction occurred. Figure 10 shows a linear relationship between state parameter and liquefaction resistance. Liquefaction resistance decreases with increasing state parameter.

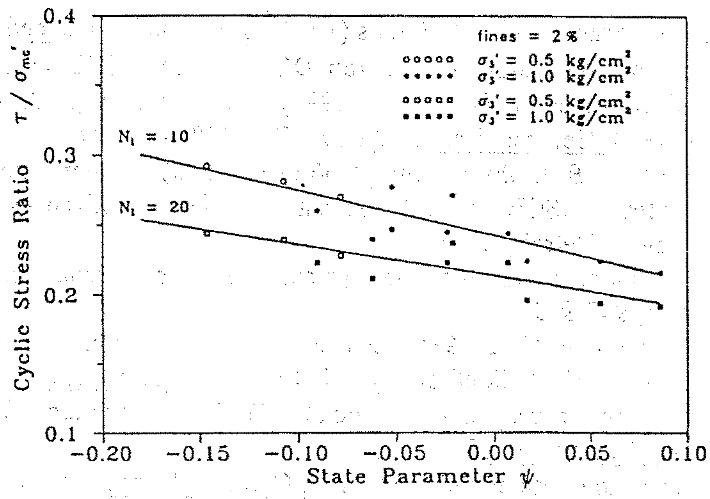

Fig. 10. Relationship between liquefaction resistance and state parameter.

CONCLUSIONS

Based on the results of triaxial compression test, monotonic torsional shear test and cyclic torsional shear test on remolded samples of Taipei silty sand, conclusions on steady state line and its associated engineering properties can be summarized as below:

(1) Factors such as sample preparation method, strain rate, and anisotropic consolidation do not have major influence on the determination of steady state line of sand.

(2) Fines content of sand will affect both the location and slope of the steady state line. Slope of the steady state line becomes flatter as fines content increases.

(3) Monotonic torsional shear test and triaxial compression test give different steady state lines. The steady state line determined by torsional test is located to the left of that of triaxial test. However, both tests give approximately the same undrained shear strength at steady state.

(4) State parameter can reflect many major engineering properties during drained and undrained loading, such as the normalized undrained shear strength and pore pressure parameter at failure during undrained loading, and angle of shearing resistance during drained loading.

(5) State parameter and liquefaction resistance has a linear relationship. Liquefaction resistance decreases with increasing state parameter.

REFERENCES

Been, K. and M. G. Jefferies (1985). A state parameter for sands. Geotechnique, 35, 99-112.

Been, K., M. G. Jefferies and J. Hachey (1991). The critical state of sands. Geotechnique, 41, 365-381.

Castro, G., J. L. Enos, J. W. France and S. J. Poulos (1982). Liquefaction induced by cyclic loading. Report to National Science Foundation, Washington, DC, No. NSF/CEE-82018.

Castro, G., R. B. Seed, T. O. Keller and H. B. Seed (1992). Steady-state strength analysis of Lower San Fernando Dam Slide. J. Geotech. Engng. Div., ASCE, 118, 406-427.

Dobry, R., A. Vasquez-Herrera, R. Mohamad and M. Vucetic (1985). Liquefaction flow failure of silty sand by torsional cyclic tests. ASCE National Convention Session on Advances in the Art of Testing Soils under Cyclic Loading, Detroit, 29-50.

Konard, J. M. (1990). Minimum undrained strength versus steady-state strength of sands. J. Geotech. Engng. Div. ASCE, 116, 948-963.

Kuerbis, R., D. Negussey and Y. P. Vaid (1988). Effect of gradation and fines content on the undrained response of sand. ASCE Conf. on Hydr. Fill Struc., Geotech. Special Pub. 21, 330-345.

Negussey, D., W. K. D. Wijewickreme and Y. P. Vaid (1988). Constant-volume friction angle of granular materials. Can. Geotech. J., 25, 50-55.

Poulos, S. J. (1981). The steady state of deformation. J. Geotech. Engng. Div., ASCE, 107, 553-562.

Poulos, S.J., G. Castro and J. W. France (1985). Liquefaction evaluation procedure. J. Geotech. Engng. Div. ASCE, 111, 772-792.

Vaid, Y. P. and J. C. Chern (1985). Cyclic and monotonic undrained response of saturated sands. ASCE National Convention Session on Advances in the Art of Testing Soils under Cyclic Loading, Detroit, 120-147.

Vaid, Y. P., E. K. F. Chung and R. H. Kuerbis (1990). Stress path and steady state. Can. Geotech. J., 27, 1-7.