The effects of anisotropy on static and dynamic behaviour of soil

Prasanna Rousseau
School of Engineering
Indian Institute of Technology. Mandi
Mandi, Himachal Pradesh, India
prasanna@iitmandi.ac.in

Siva Sivathayalan
Civil and Environmental Engineering
Carleton University
Ottawa, ON, Canada
Siva.Sivathayalan@carleton.ca

***Abstract* - The undrained behaviour of sands is affected by many factors including the initial state and loading path. If laboratory studies are to be meaningful in the context of in-situ problems, both the initial state and subsequent loading path in-situ have to be appropriately simulated in the laboratory. This is critical since most natural soils have an anisotropic (or technically a transversely isotropic) fabric and their response is direction dependent. The term initial state encompasses the density, fabric of the soil, and the stress conditions which are characterized by the three principal stresses and their directions. This paper summarizes the impact of anisotropic fabric on both monotonic and cyclic undrained behaviour of sands.**

The anisotropic response that is manifested in simpler triaxial compression and extension tests and is systematically studied using a relatively complex hollow cylinder torsional shear device. It is shown that the tendency for strain softening, which could lead to catastrophic consequences under monotonic loading, is very much dependent of fabric and loading path. It is demonstrated that current cyclic liquefaction design practice that depends on the cyclic resistance ratio, CRR is rather simplistic, but the available data suggests that cyclic simple shear resistance is possibly a lower bound for the actual resistance.

The data and experience presented in this paper suggest that the difficulties encountered in using laboratory test results in field problems are possibly a result of inappropriate laboratory characterization without regard to the initial fabric and the subsequent loading paths in-situ.

Keywords - Soil anisotropy, Liquefaction, Cyclic resistance, Hollow cylinder torsional shear test

Nomenclature:

R_e, R_i	External and internal radius of soil specimen
H	Height of the soil specimen
D_{50}	Mean particle size
F_z	Vertical force
T_h	Torque
P_e, P_i	External and internal pressure
α_σ	$tan^{-1}(\tau_{z\theta}/\{\sigma_z - \sigma_3\})$, Inclination of major principal stress axis with respect to vertical axis of deposition
$\sigma_z, \sigma_r, \sigma_\theta$	Axial, radial, and circumferential stress
$\sigma_1, \sigma_2, \sigma_3$	Total major, intermediate, and minor principal stress
$\sigma'_1, \sigma'_2, \sigma'_3$	Effective major, intermediate, and minor principal stress
σ'_m	$(\sigma'_1 + \sigma'_2 + \sigma'_3)/3$, Effective mean normal stress
σ_m	$(\sigma_1 + \sigma_2 + \sigma_3)/3$, Total mean normal stress
σ_d	$(\sigma_1 - \sigma_3)$, Deviatoric stress
σ'_{vc}	Effective confining stress
$\tau_{z\theta}$	Torsional shear stress
$\varepsilon_z,\ \varepsilon_r,\ \varepsilon_\theta$	Axial, radial, and circumferential strain
$\gamma_{z\theta}$	Torsional shear strain
b_σ	$(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ Intermediate principal stress parameter
$\tau_{cy,max}$	Maximum cyclic shear stress
K_0	At-rest earth pressure coefficient
K_α	Correction factor for initial static shear stress
K_σ	Correction factor for confining stress

I. INTRODUCTION

The inherent cross-anisotropic fabric of granular soil deposits arising from the natural sedimentation process gives rise to its stress path dependent behaviour; i.e., the strength and deformation characteristics of soils depend on both the magnitude and direction of principal stresses. Several laboratory studies were carried out in the past to study the influence of cross-anisotropy on the shear strength characteristics of soils under triaxial condition by preparing the soil specimens deposited at different inclination of bedding planes [2, 6, 17]. However, it is reported that the test results obtained from the specimens prepared at different inclination of bedding planes are unreliable and such experiments require complex interpretations [1, 10]. Presently, with the help of advanced laboratory testing devices such as true triaxial, directional shear cell and hollow cylinder torsional shear apparatus, the effect of cross-anisotropy is investigated by rotating the direction of principal stresses with respect to the deposition axis [5, 9, 13-15, 18].

In laboratory testing of soils, the major objective is to simulate the in-situ behaviour of the material as closely as possible under possible loading and drainage conditions. The first step towards realizing this goal is to replicate the in-situ soil fabric in the laboratory. Several specimen reconstitution methods have been developed to mimic the in-situ soil fabric resulting from different natural deposition processes. The most prominent methods are Air pluviation (AP), Water pluviation (WP) and Moist tamping (MT). These reconstitution methods result in different soil fabric which in turn affects the stress-strain behaviour of soils [6, 11, 16, 21, 22, 24]. Water pluviation duplicates the soil fabric resulting from the deposition in an alluvial environment whereas moist tamping duplicates the soil fabric in compacted hydraulic fills. Fig. 1 shows the undrained response of Syncrude sand reconstituted to similar initial stress states and density by WP, AP, and MT methods [22]. It can be noted that WP specimens exhibited a strong dilative response whereas MT specimens exhibited a weak softening response. This clearly shows the influence of soil fabric resulting from each reconstitution technique on the shear strength of soil. Prasanna and Sivathayalan [7] demonstrated that within a particular reconstitution technique, even procedural variations yield different soil fabric which in turn affects the shear strength.

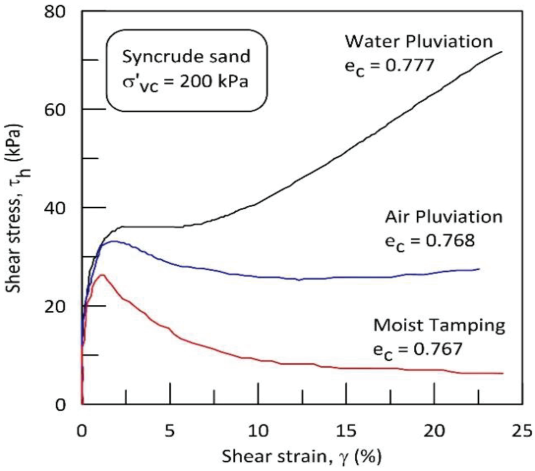

Fig. 1. Effect of specimen reconstitution method on the undrained response of Syncrude sand (after Vaid et al. 1999 [22]).

Pluviation in water or air under the action of gravity results in a cross-anisotropic soil fabric which causes the behaviour of soil to be dependent on both the magnitude of principal stresses and the inclination of major principal stress axis with respect to the vertical axis of deposition (α_σ). Vaid and Thomas [23] demonstrated the loading mode dependent behaviour of water pluviated Fraser River sand specimens through a series of undrained triaxial tests. The soil specimen exhibited weak contractive response under triaxial extension mode and strong dilative response under triaxial compression mode. The conventional laboratory testing devices such as triaxial and simple shear, have either a fixed directions of principal stresses or offer limited control over the directions. So, to fully evaluate the effect of soil anisotropy on the static and dynamic response of soil, it is very essential to have a device which allow direct and independent control over the magnitude of three principal stresses ($\sigma_1, \sigma_2, \sigma_3$) and α_σ. The advance testing devices such as true triaxial, directional shear cell (DSC) and hollow cylinder torsional shear apparatus were developed for this purpose. In a true triaxial apparatus, the intermediate principal stress (σ_2) can be varied between major (σ_1) and minor principal stress (σ_3) continuously but α_σ varies abruptly from 0° to 90°. The DSC which is a plane strain apparatus can control the direction of principal stresses, but it is inefficient in controlling the effective mean normal stress (σ'_m) and intermediate principal stress parameter (b_σ) independently. DSC also has limitations in strain measurement, pore pressure measurements and drainage control [4]. A hollow cylinder torsional shear apparatus [13, 15, 18, 19] is a versatile apparatus which can control parameters α_σ, b_σ, σ'_m, and deviatoric stress (σ_d) independently along with full drainage control.

This paper summarizes the influence of cross-anisotropic soil fabric on the undrained monotonic and cyclic behaviour of sands. The data and experience gained from extensive research on hollow cylinder torsional shear tests on water pluviated Fraser River sand is presented. A detailed discussion on the effect of initial stress state and loading paths on the static and cyclic liquefaction characteristics of the sand is provided.

II. HOLLOW CYLINDER TORSIONAL SHEAR APPARATUS

The influence of anisotropic soil fabric on its mechanical response can be well characterized using a hollow cylinder torsional shear device [13, 15,18,19] which allows independent control of the three principal stresses and their direction in one plane. This permits the simulation of various in-situ loading cases, be it axisymmetric, plane strain, or general 3D loading, and systematic studies that can provide insights into the nature of anisotropy and its influence on the undrained response.

The Carleton University Hollow cylinder device (CU-HCT) is custom made to facilitate consolidation to the desired generalized state, and shear loading along complex stress/strain paths. It uses a relatively larger size specimen, with nominal internal radius (R_i) of 50 mm, external radius (R_e) of 75 mm, and height (H) of 300 mm. These dimensions were chosen to minimize the degree of stress non-uniformity across the wall of the hollow cylindrical specimen when subjected to different external, internal pressure, and/or torque [19, 25], and to permit better repeatability during reconstitution. Fig. 2 shows a photograph of the CU-HCT device. The four surface tractions vertical force F_z, Torque T_h, and internal pressure (P_i) and external pressure (P_e) induce axial stress σ_z, radial stress σ_r, circumferential stress σ_θ, and torsional shear stress $\tau_{z\theta}$ and respective strain components ε_z, ε_r, ε_θ, and $\gamma_{z\theta}$ in the wall of the specimen. The independent control of the surface tractions enables the independent control of total mean normal stress σ_m, σ_d, b_σ, and α_σ. A data acquisition and control program developed in-house is used to follow the desired loading paths. Further details of the apparatus and its capabilities can be found in Logeswaran and Sivathayalan [3] and Prasanna and Sivathayalan [8], and all void ratios reported were computed using volume measurements [20] to improve the reliability of void ratio calculations.

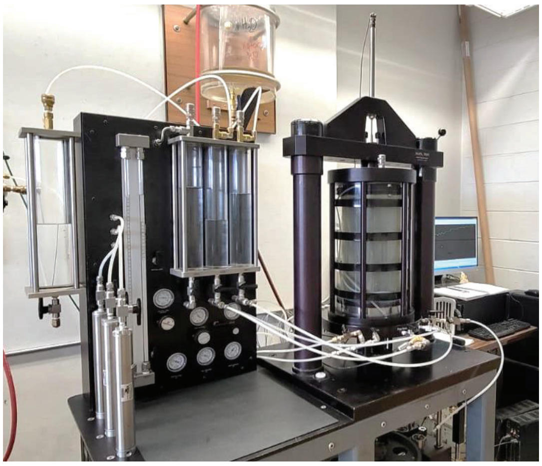

Fig. 2. The CU-HCT Device

All tests reported herein were conducted on Fraser Delta sand, which underlies the heavily populated regions of the lower mainland in British Columbia. Fraser Delta sand is a medium grained and uniformly graded sand with average particle size D_{50} of 0.27 mm. The detailed properties of Fraser River sand used in this study are provided in Prasanna et al. [9] The undrained response of this material is of significant interest in the Canadian context since the lower mainland is potentially susceptible to significant seismic shaking (on account of a mega-thrust earthquake occurring in the nearby Cascadia Subduction Zone). The natural deposits in this region are formed in an alluvial environment, and thus water pluviation was chosen as the preferred reconstitution method for preparing the test specimens in the laboratory. Prior studies using undisturbed (in-situ frozen) sand specimens have demonstrated that response of water pluviated specimens are representative of the response of in-situ sands [12, 22].

III. MONOTONIC INSTABILITY AND FLOW POTENTIAL

Fig. 3 shows the range of monotonic response of fully saturated Fraser River sand (Skempton's pore pressure parameter B ≈ 0.99) consolidated to essentially identical initial fabric, density and principal stress states, and sheared undrained along fixed principal stress directions. At the initial state prior to undrained shear, the specimen was

ISBN: 978-624-6150-05-1

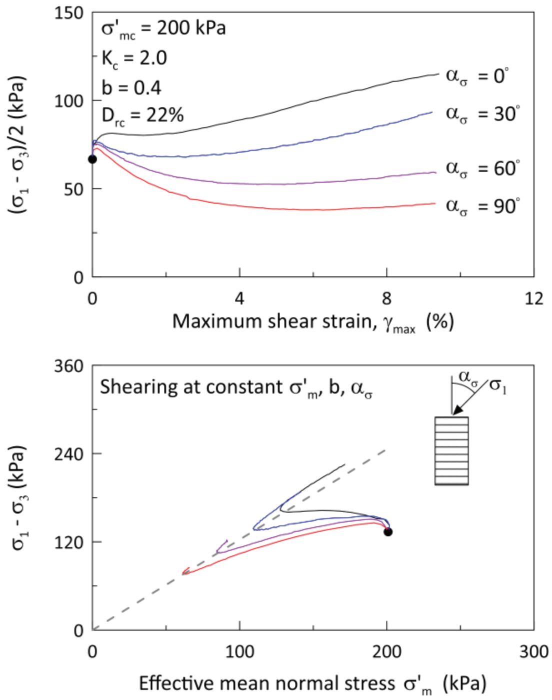

Fig. 3. Influence of loading path on the stability of Fraser River sand

consolidated to typical at-rest earth pressure (K_o) stress conditions, and has effective principal stresses of $\sigma_1' \approx 273\,kPa$, & $\sigma_2' \approx 191\,kPa$ and & $\sigma_3' = 136\,kPa$, and thus an initial static shear stress of about 68 kPa. It can sustain the stresses under this state while drained, and this stress state might represent a stable slope. However, a small undrained perturbation, depending on the direction of major principal stress with respect to the direction of deposition, may trigger a sudden flow deformation.

As seen in Fig. 3, at this initial state, the material marginally strain softens at $\alpha_\sigma = 0°$ and strain softens to a larger extent when sheared along $\alpha_\sigma = 30°$ but in both cases upon reaching a quasi-steady state, it subsequently strain hardens, and thus the deformation is limited and depends on the applied stress increment. However, when sheared along $\alpha_\sigma = 60°$ or $\alpha_\sigma = 90°$ the sand strain softens significantly and realizes a minimum undrained strength that is much smaller than the initial static shear stress. Such loading therefore will result in catastrophic consequences. Notwithstanding the significantly different stress-stain curves as a function of α_σ the friction angle mobilized at the instant of phase transformation (the state of maximum excess pore water pressure) is essentially a constant. Similar behaviour of sands consolidated to different initial states have been reported in the literature [13].

IV. CYCLIC RESISTANCE RATIO

The capacity of a soil to resist liquefaction during earthquake shaking is generally characterized by the parameter cyclic resistance ratio, CRR_N, which is defined as the ratio of an equivalent uniform cyclic shear stress ($\tau_{cy,max}$) required to cause liquefaction in a specified number of loading cycles (*N*) to the effective confining stress (σ_{vc}'). The number of cycles is characteristic of the intensity of the earthquake, and N varies from about 2 for a magnitude M=5 earthquake to about 25 for M=8.5 earthquake [26]. In practice, CRR_N is usually obtained from empirical correlations, or cyclic resistance curves that establish a relationship between the cyclic stress ratio, *CSR* and the number of cycles of liquefaction, *N*.

The dependence of CRR_N on confining stress level, and initial static shear stress has been recognized for many years, and the former is routinely corrected by using the correction factor K_σ, which depends on both density and confining stress level. This correction factor K_σ, is known to decrease with increasing effective confining stress level. While a correction factor K_α has been proposed to account for initial static shear stress effects but quantifying K_α for practical applications has been difficult as the presence of static shear stresses may increase or decrease the cyclic resistance depending on the density, level of static shear and the potential for strain softening.

The effect of loading mode on CRR_N has been recognized based on cyclic triaxial and simple shear tests, and cyclic simple shear is generally deemed to be representative of the in-situ resistance due to the presumed analogue between in-situ loading and cyclic simple shear. While simple shear is a good representation of vertically propagating shear waves (SH-wave), the actual cyclic loading in-situ need not be necessarily due to SH-waves alone. This is especially the case, if the site is near the epicenter of a shallow earthquake, or if the bedrock-soil interface is not horizontal. In such cases the actual earthquake shaking is rather complex and can only be simulated properly using cyclic HCT tests [22].

Further, cyclic triaxial is limited to axisymmetric loading condition and cyclic simple shear to plane strain loading condition. Also, the principal stress directions remain fixed (or jump between 0°& 90°) in cyclic triaxial and it rotates between $\pm 45°$ in cyclic simple shear. While cyclic triaxial tests cannot simulate the initial stress conditions on a slope at all, these can be closely represented in a cyclic simple shear test. However, under generalized cyclic loading condition the nature of principal stress rotation could be complex, and is dependent on the initial stress state conditions, and the relative magnitudes of the cyclic shear stress and normal stress increments during the earthquake. Such loading cannot be simulated in a simple shear test [8].

Fig. 4 shows the variation in cyclic resistance in essentially identical specimens (i.e., same initial fabric, density, and same magnitude and direction of principal stresses during consolidation) on level ground subjected to the same magnitude of cyclic shear stress ratio (i.e., same $\tau_{cy,max}$) but with different levels of stress rotation. The specimens subjected to larger 45° principal stress rotation exhibit weaker cyclic resistance compared to those subjected to 30° principal stress rotation. The CRR_{15} of this sand is only about 0.17 when the principal stresses rotate between $\pm 45°$ and it is about 0.20 when the principal stresses rotate between $\pm 30°$. This clearly demonstrates the influence of degree of stress rotation on the cyclic resistance of sand which is not considered in current design practice.

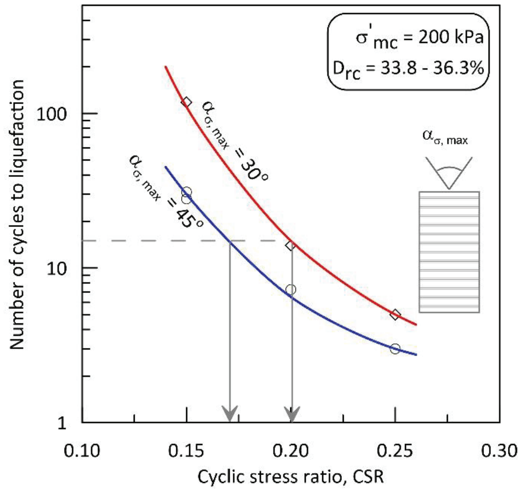

Fig. 4. Dependence of cyclic resistance on the degree of stress rotation (after Sivathayalan et al. 2015 [14]).

The data presented in Fig. 4 represent the response of sands on level ground where there is no initial static shear stresses on the horizontal plane. The test data presented in Fig. 5 shows the influence of generalized initial static shear on otherwise identical specimens subjected to identical cyclic loading both in terms of the magnitude of cyclic shear stress and degree of principal stress rotation. These specimens were prepared at the same initial fabric, density, and consolidated to the same magnitude of principal stresses, but the major and minor principal stress directions varied. The cyclic loading imposed to represent the earthquake shaking was identical. The data shows that the initial inclination of principal stress axes influences the CRR_{15} to a lesser extent when compared to the degree of stress rotation.

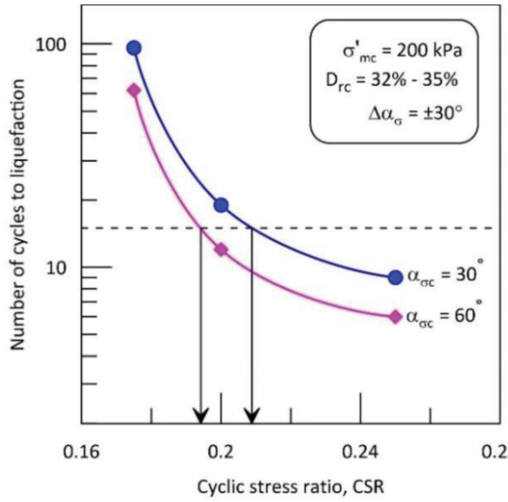

Fig. 5. Influence of initial principal stress directions on cyclic resistance (after Prasanna et al. 2020 [9]).

V. SUMMARY & CONCLUSIONS

Laboratory experimental data from different series of experiments are presented to illustrate the influence of anisotropy on the undrained response of soils. These results demonstrate that deformation characteristics under monotonic loading are highly dependent on the initial stress state and the relative inclination of the major principal stress to the deposition direction during undrained shear. A sand may be dilative and stable under a given loading path but may strain soften and flow under a different path. This can lead to drastically different stability implications in slopes that are stable under drained loading, but might flow due to a small undrained perturbation.

ISBN: 978-624-6150-05-1

In addition to the initial principal stress magnitudes and directions, the magnitude of cyclic principal stress changes, and the resulting directional changes in the principal stress directions affect the cyclic deformation characteristics. The CRR is dependent on the degree of principal stress rotation. Our experience to date shows that the weakest cyclic resistance is obtained if the principal stresses rotate by ±45° during cyclic loading. This suggests that relying on cyclic simple shear tests to characterize CRR is appropriate at this time as it would yield a conservative estimate compared to loading that involves different levels of stress rotation.

ACKNOWLEDGMENTS

The intellectual contributions of many graduate students over the years have helped to gradually improve the capabilities of the test equipment, and enhance the experimental geotechnical research conducted at Carleton University. This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada, Canada Foundation for Innovation, and the Ontario Innovation Trust. The financial support provided by the Ontario Trillium Scholarship and Carleton University to the first author, and the technical assistance of Stanley Conley, Pierre Trudel and Jason Arnott are also gratefully acknowledged.

REFERENCES

[1] Lade, P. V., and Kirkgard, M. M. (2000). "Effects of stress rotation and changes of b-values on cross-anisotripic behavior of natural, K0-consolidated soft clay." Soils and Foundations, 40(6), 93–105.

[2] Lade, P. V., and Wasif, U. (1988). "Effects of height-to-diameter ratio in triaxial specimens on the behavior of cross-anisotropic sand." Advanced triaxial testing of soil and rock, STP977, R. T. Donaghe, R. C. Chaney, and M. L. Silver, eds., ASTM, West Conshohocken, PA, 706–714.

[3] Logeswaran, P. and Sivathayalan, S. (2014), "A new hollow cylinder torsional shear device for stress/strain path controlled loading", ASTM Geotechnical Testing Journal, 37(1): 1-12, doi:10.1520/GTJ20120202

[4] Menkiti, C.O. (1995). "Behaviour of clay and clayey-sand, with particular reference to principal stress rotation." Msc. thesis, Imperial College London.

[5] Ochiai, H., and Lade, P. V. (1983). "Three-Dimensional Behavior of Sand with Anistropic Fabric." Journal of Geotechnical Engineering, 109(10), 1313–1328.

[6] Oda, M. (1972). "Initial Fabrics and Their Relations to Mechanical Properties of Granular Material." Soils and Foundations, 12(1), 17–36.

[7] Prasanna, R., and Sivathayalan, S. (2017). "Efect of moist tamping water content on the shear strength of soil" GeoOttawa 2017, Ottawa, Canada. Paper No: 346

[8] Prasanna, R. and Sivathayalan, S. (2022), Liquefaction of sands subjected to principal stresds rotation caused b generalized seismic loading, Canadian Geotechnical Journal, Can. Geotech. J. (in press). dx.doi.org /10.1139/cgj-2021-0035

[9] Prasanna, R., Sinthujan, N., and Sivathayalan, S. (2020). "Effects of Initial Direction and Subsequent Rotation of Principal Stresses on Liquefaction Potential of Loose Sand." Journal of Geotechnical and Geoenvironmental Engineering, 141(3), 1–13.

[10] Saada, A. S. (1970). "Testing of anisotropic clay soils." J. Soil Mech. and Found. Div., 96(5), 1847–1852.

[11] Sadrekarimi, A. & Olson, S.M., 2012. Effect of sample-preparation method on critical-state behavior of sands. Geotechnical Testing Journal, 35(4), pp.548–562.

[12] Sivathayalan, S. & Vaid, Y.P. (2004), "Cyclic resistance and post liquefaction response of undisturbed in-situ sands", in proc. Of the 13th world conference on Earthquake engineering, Vancouver, BC. August 1-6. #2940.

[13] Sivathayalan, S., and Vaid, Y. P. (2002). "Influence of generalized initial state and principal stress rotation on the undrained response of sands." Canadian Geotechnical Journal, 39(1), 63–76.

[14] Sivathayalan, S., Logeswaran, P., and Manmatharajan, V. (2015). "Cyclic Resistance of a Loose Sand Subjected to Rotation of Principal Stresses." Journal of Geotechnical and Geoenvironmental Engineering, 141(3), 1–13.

[15] Symes, M.., Gens, A., and Hight, D. W. (1984). "Undrained anisotropy and principal in saturated sand." Geotechnique, 34(1), 11–27.

[16] Sze, H.Y. & Yang, J., 2014. Failure Modes of Sand in Undrained Cyclic Loading : Impact of Sample Preparation. Journal of Geotechnical and Geoenvironmental Engineering, 140(1), pp.152–169.

[17] Tatsuoka, F., Sonoda, S., Hara, K., Fukushima, S., and Pradhan, T. B. . (1986). "Failure and deformation of sand in torsional shear." Soils and Foundations, 26(4), 79–97.

[18] Uthayakumar, M., and Vaid, Y. P. (1998). "Static liquefaction of sands under multiaxial loading." Canadian Geotechnical Journal, 35(2), 273–283.

[19] Vaid, Y.,P., Sayao, A., Hou, E., and Negussey, D., (1990), Generalized stress-path-dependent soil behaviour with a new hollow cylinder torsional apparatus, Canadian Geotechnical Journal, 27(5): 601-616

[20] Vaid, Y. P. and Sivathayalan, S. (1996), "Errors in the estimates of void ratio", Canadian Geotechnical Journal 33(6):1017-1020. dx.doi.org /10.1139/t96-128

[21] Vaid, Y. P., and Sivathayalan, S. (2000). “Fundamental factors affecting liquefaction susceptibility of sands.” Canadian Geotechnical Journal, 37, 592–606.

[22] Vaid, Y. P., Sivathayalan, S., and Stedman, D. (1999). “Influence of Specimen-Reconstituting Method on the Undrained Response of Sand.” Geotechnical Testing Journal, 22(3), 187–195.

[23] Vaid, Y. P., and Thomas, J. (1995). “Liquefaction and Postliquefaction Behavior of Sand.” Journal of Geotechnical Engineering, American Society of Civil Engineers, 121(2), 163–173.

[24] Wanatowski, D. & Chu, J., 2008. Effect of Specimen Preparation Method on the Stress-Strain Behavior of Sand in Plane-Strain Compression Tests.

[25] Wijewickreme, D., and Vaid, Y.P. (1991). Stress nonuniformities in hollow cylinder torsional specimens. Geotechnical Testing Journal, 14: 349–362

[26] Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dobry, R., Finn, W.D.L., Harder Jr, L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.C., Marcuson III, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power,M.S., Robertson, P.K., Seed, R.B., and Stokoe II, K.H. 2001. Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils, Journal of Geotechnical and Geoenvironmental Engineering, 127(10): 817 833.

ISBN: 978-624-6150-05-1