Flow liquefaction potential of loose sand: stress path envelope and energy-based evaluation

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Title

Flow liquefaction potential of loose sand: stress path envelope and energy-based evaluation

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Abstract

Flow liquefaction, which is characterized by sudden collapse following the unstable behavior of saturated loose sand, may lead to the most catastrophic consequence of all liquefaction-related phenomena. This note presents a systematic experimental investigation into the flow liquefaction potential of sand under various initial and cyclic shear conditions. The cyclic flow liquefaction responses are compared to the monotonic shear results under an identical initial testing condition. It is found that the effective stress path of a monotonic test appears to envelop that of its corresponding cyclic test. The energy-based liquefaction potential evaluation indicates that the accumulative dissipated energy is uniquely correlated not only with the pore pressure and axial strain induced in sand, but also with the degraded stiffness during cyclic loading. Furthermore, the energy capacity for triggering the flow liquefaction appears to be intimately related to the cyclic resistance of sand; this signifies the potential applicability of energy-based liquefaction potential evaluation using strength data available in conventional analysis.

Keywords: flow liquefaction; stress path; dissipated energy; stiffness; cyclic resistance

41 Introduction

42 Flow liquefaction is a phenomenon that results from collapse deformation following
43 the unstable behavior of saturated loose or contractive sand at the state of low mean
44 effective stress and shear strength. The flow liquefaction type behavior, which may produce
45 the most devastating effects of all liquefaction-related catastrophic damage (e.g., the
46 spreading of embankments and dams), can be induced under either monotonic or cyclic
47 loading conditions (Ishihara 1996; Yang 2002; Andrade et al. 2013; Yang and Pan 2017).
48 Flow liquefaction under undrained monotonic shear depends on both the state of the
49 sample and the mode of shearing. For very loose sand, flow liquefaction that triggers the
50 instability state (IS, Lade 1992) may emerge in both the triaxial compression (TC) and
51 extension (TE). However, at a dense state, the sand may exhibit flow liquefaction in TE but
52 dilate after the phase-transformation state (PTS, Ishihara et al. 1975) in TC. Such distinctly
53 different behaviour in TC and TE has been widely reported; see Riemer and Seed (1997), De
54 Gennaro et al. (2004), and Pan et al. (2018), among others. This scenario is related to the
55 interplay between the loading direction and the fabric anisotropy of the sand formed during
56 sample preparation or natural deposition (Sivathayalan and Vaid 2002; Yang et al. 2008;
57 Yang et al. 2018). Recent numerical studies by Nguyen et al. (2017) and Rahman et al. (2018)
58 further indicated that the instability stress ratio of granular materials, which depends on
59 both the state parameter and consolidation stress path, is closely related to the contact
60 orientation of particles. Furthermore, during a cyclic triaxial loading test, such an anisotropic
61 nature of pluviated or deposited sands leads to the following observation: in response to an
62 applied symmetrical cyclic stress, the flow liquefaction of isotropically consolidated samples
63 is typically initiated on the extension side of the stress space.

Numerous studies have been conducted to assess the monotonic and cyclic shear resistance of sand to liquefaction using the state-dependent concept in the framework of critical state soil mechanics (Chu and Leong 2002; Lo et al. 2010; Yang and Sze 2011; Mizanur and Lo 2012; Baki et al. 2014; Rahman et al. 2014; and Pan and Yang 2018). It is recognized that the flow liquefaction behavior under monotonic and cyclic loadings are intimately related; however, no consensus has been made regarding the triggering condition of cyclic flow liquefaction that is determined based on the monotonic shear response of sand. De Gennaro et al. (2004), Georgiannou et al. (2008), and Baki et al. (2012) reported that under cyclic loading, flow liquefaction occurs when the effective stress path touches or crosses the instability line defined from the monotonic test, indicating that the initiation of cyclic flow liquefaction relies on the monotonic instability behavior. But on the other hand, some studies by Yamamuro and Covert (2001), Mao and Fahey (2003), and Li et al. (2017) suggested that the effective stress path of a monotonic test has an envelope effect on that of a cyclic test; this implies that flow liquefaction is triggered when the cyclic stress path approaches or goes beyond the stress path of the corresponding monotonic test. Further exploration is required to investigate whether the linkage between monotonic and cyclic shear responses is influenced by the stress history of the geological activity and adjacent construction processes. For example, sand deposits in the natural or manmade slopes and embankments may often experience a driving shear force prior to cyclic loading (Mohamad and Dobry 1986; Vaid et al. 2001; Sze and Yang 2014). Yoshimine and Hosono (2000) and Andersen (2015) further indicated that the sustained static stress associated with subsoil under a gravity structure would emerge on either the compression or extension side. Furthermore, soils in the field that have undergone repetitive erosion and excavation may involve an unloading stress path in addition to the initial sustained shear stress. Such

in-situ stress conditions can be mimicked by imposing an initial static stress cycle prior to subsequent shear tests (Oda et al. 2001; Toyota and Takada 2016).

Since the pioneering work of Seed and Idriss (1971), the “equivalent” stress-based approach has been widely adopted in liquefaction analysis, in which the effect of actual irregular loading with varying waveforms can be approximately equivalent to the application of a uniform cyclic loading with a reduced magnitude (Andersen 2015). However, the quantitative analysis based on the “equivalent” approach is seemingly not definitive and probably varies with specific irregular loading patterns. An alternative method is the use of the dissipated energy concept. It was first introduced by David and Berrill (1982) following the assumption of Nemat-Nasser and Shokooh (1979) that the dissipated energy per unit volume resulting from the breakdown of soil skeleton is directly related to the pore pressure buildup. This could be an efficient way in evaluating the pore pressure increments of sand under both uniform and irregular cyclic stress conditions (e.g., Baziar and Jafarian 2007; Polito et al. 2013; Azeiteiro et al. 2017). As such, Kokusho (2013) and Pan and Yang (2020) further indicated that the energy dissipation correlates well not only with the generated pore pressure but also with the induced strain. Although these previous studies have afforded valuable data for the energy-based evaluation of liquefaction potential, the validity of this method remains uncertain when it is applied to evaluate the strain development, stiffness degradation, and cyclic resistance of sand under various initial and cyclic stress conditions. A comprehensive analysis of this subject requires a more sophisticated experimental program, which forms the primary objective of this study.

In this research, a series of undrained monotonic and cyclic triaxial tests are performed on loose sand; the interpretation of results is composed of two parts. In the first part, through a comparison between the cyclic and monotonic shear responses under the same

initial condition, the stress path envelope determined from the monotonic test on the occurrence of cyclic flow liquefaction is investigated. In the second part, it is shown through the energy-based liquefaction analysis that the dissipated energy can be uniquely correlated with pore pressure, strain, stiffness, and cyclic resistance, irrespective of the initial stress histories and cyclic shear conditions.

Experimental procedures

The test material used in this study, Toyoura sand, is a standard sand that has been extensively characterized in literature. All experiments were conducted using an automated triaxial system as described by Pan and Yang (2020) and the sample preparation procedure was similar to that used in Yang and Pan (2017). The obtained saturated samples were isotropically consolidated (IC) to a mean effective stress of $p'_0 = 100$ kPa, and the void ratios, e_0 , of these samples at the end of consolidation were controlled at 0.861–0.876 (relative density $D_r = 26\%$ – 29%). The undrained loading waveforms including one uniform cyclic (abbreviated as “UCyc”) and two irregular cyclic (“ICyc1” and “ICyc2”) patterns were then imposed on the specimens at a frequency of 1 Hz. In comparison to the pattern “UCyc” that consists of ten cycles of equal amplitude, the patterns “ICyc1” and “ICyc2” are composed of different components of stress pulses. In particular, the former is composed of four cycles with a maximum amplitude (q_{peak}) followed by four cycles of $0.8q_{\text{peak}}$ and two cycles of $0.4q_{\text{peak}}$, whereas the latter contains only one single maximum spike (q_{peak}) along with other relatively small amplitudes ($0.5q_{\text{peak}}$ and $0.2q_{\text{peak}}$).

Four types of initial stress histories along a drained and constant p' stress path were considered in the following uniform cyclic tests: compressional sustained stress (q_0) with magnitudes of 20 and 80 kPa, extensional q_0 with magnitudes of –20 and –40 kPa,

compressional and extensional stress cycle with amplitudes of 80 and -40 kPa, respectively. The change in the density of specimens during the stress history was not considered because its variation is only slight, which was not expected to produce discernable discrepancies in the undrained results during the subsequent uniform cyclic loading. To aid in explaining the cyclic responses of sand, several undrained TC and TE tests on samples having the same initial condition as those for cyclic tests were conducted. All the series of monotonic and cyclic triaxial tests with varying initial stress histories and undrained shearing conditions are listed in Table 1.

Flow liquefaction under monotonic and cyclic loadings

Fig. 1(a) and (b) shows the effective stress paths and stress–strain curves of IC sand in TE_0 ($e_0 = 0.872$) and UCyc_0_25 ($e_0 = 0.861$) tests, respectively. Clearly, the typical flow liquefaction behavior can be observed in both cases. Under the monotonic TE condition, the instability state (IS) is attained at the peak deviatoric stress, $q_{IS} = 30$ kPa; it is followed by continuous contraction and unstable response. Cyclic flow liquefaction occurs in the UCyc_0_25 test, which is accompanied by a complete loss of effective stress and a sharp increase in axial strain. In particular, it is noteworthy in Fig. 1(a) that the effective stress path of the TE_0 test forms a boundary that envelops the cyclic stress path. This implies that when the stress state of the cyclic test approaches and then crosses the stress path envelope determined from the corresponding monotonic test, the cyclic stress path will evolve rapidly and reduce to the near-zero stress state.

Fig. 2 illustrates a comparison between effective stress paths obtained from the monotonic (TE_0) and irregular cyclic (ICyc1_0_25 and ICyc2_0_25) tests. Both “ICyc1” (Fig. 2(a)) and “ICyc2” (Fig. 2(b)) type waveforms were imposed on samples ($e_0 = 0.866$ and 0.874 ,

respectively) at $q_{\text{peak}} = 25$ kPa, which is the same as the amplitude of the uniform cyclic stress considered in Fig. 1. The general trends of the cyclic stress path observed in Fig. 2 appear similar to those shown in Fig. 1, i.e., the continuous reduction in mean effective stress and a sudden loss of shear resistance at the beginning of cyclic flow. Compared to the effective stress path obtained from the TE_0 test, it is evident that the stress path envelope defined from the monotonic test still applies to irregular cyclic loadings.

Fig. 3(a) and (b) illustrates the typical cyclic and monotonic behavior of sand underwent compressional $q_0 (= 80$ kPa) and extensional $q_0 (= -40$ kPa), respectively. The first case (UCyc_80_35 test) shown in Fig. 3(a) is related to the sample ($e_0 = 0.870$) subjected to the cyclic deviatoric stress, $q_{\text{cyc}} = 35$ kPa; it exhibits a response that is considerably different from that shown in Fig. 1. The cyclic stress path shows a considerable reduction in effective stress during the incipient cycling, and appears to be stabilized in the subsequent cycles. Accordingly, the typical plastic strain accumulation (Yang and Sze 2011) type behavior can be observed with a gradual accumulation of axial strain on the compression side. Similar to Fig. 1, Fig. 3(a) shows that the specimen in TE_80 test ($e_0 = 0.864$) exhibits an instability response and thereafter fail in flow liquefaction. To further inspect the link between monotonic and cyclic responses, the effective stress paths obtained from the TC_80 test ($e_0 = 0.875$) have been superimposed in Fig. 3(a). Clearly, the shear resistance increases monotonically, accompanied by a significant dilation in the post PTS stage. Compared to the UCyc_80_35 test, it is found that the cyclic stress path initially follows or crosses the monotonic TC stress path, but the cyclic flow liquefaction is not triggered in this case. This implies that only when the monotonic test, which defines the stress path envelope for the corresponding cyclic test, exhibits flow liquefaction with a complete loss of strength and effective stress, the cyclic flow liquefaction could occur in the sand.

Comparison is presented in Fig. 3 (b) between the results of TE₋₄₀ and UCyc_{-40_8} tests for samples ($e_0 = 0.876$ and 0.871 , respectively) subjected to an extensional q_0 . In this figure, the typical flow liquefaction type behavior is observed under either the monotonic or cyclic loading condition. Regarding the monotonic stress path envelope associated with cyclic flow liquefaction, a key point of observation that differs from the aforementioned results could be highlighted. As shown in Fig. 3(b), during the UCyc_{-40_8} test, the stress valleys formed by the superimposition of cyclic and sustained shear stresses are always lower than the q_{ls} values obtained from the TE₋₄₀ tests. In this case, the occurrence of cyclic flow liquefaction is inevitable; more specifically, it tends to be triggered slightly behind the instant the cyclic stress path crosses the corresponding monotonic stress path for the last time.

The influence of an initial stress cycle on the monotonic and cyclic responses and their correlations is presented in Fig. 4. The samples in Fig. 4(a) ($e_0 = 0.861$ for TE_{0⁽⁸⁰⁾} test and $e_0 = 0.870$ for UCyc_{0⁽⁸⁰⁾_25} test) and Fig. 4(b) ($e_0 = 0.869$ for TE_{0⁽⁻⁴⁰⁾} test and $e_0 = 0.876$ for UCyc_{0⁽⁻⁴⁰⁾_25} test) were subjected to a compressional and extensional stress cycle, respectively. It is evident that the samples under both monotonic TE and cyclic loading fall in the typical flow liquefaction behavior. Similar to the IC sand, the monotonic stress paths observed in Fig. 4 envelop the corresponding cyclic response; the triggering of cyclic flow liquefaction can be regarded as the instant when the stress state during cyclic loading crosses the effective stress path in the TE test.

Energy-based liquefaction potential evaluation

According to Kokusho (2013) and Pan and Yang (2020), the dissipated energy per unit volume, W , during cyclic loading is represented by the stress-strain loop and can be

calculated by summing up the hysteretic area of each individual stress cycle, as follows:

$$W = \sum_{i=1}^{n-1} \frac{1}{2} (q_{i+1} + q_i) (\varepsilon_{a,i+1} - \varepsilon_{a,i}) \quad (1)$$

where n is the total number of calculated increments, and q_i and $\varepsilon_{a,i}$ are the deviatoric stress and axial strain in the i^{th} increment, respectively. Fig. 5(a) and (b) shows the variation of residual pore pressure ratio, u_r (the ratio of residual pore pressure to the initial mean effective stress, p_0'), and permanent axial strain, ε_a , versus the cumulative dissipated energy for the sand exhibiting flow liquefaction, respectively. The dimensionless energy dissipation, W_n , is obtained by normalizing it to p_0' . Note that the data for the sand subjected to compressional q_0 (UCyc_20 and UCyc_80 tests series) are excluded in this diagram and the following analysis because there is no cyclic flow liquefaction observed in these two cases. As shown in Fig. 5(a), the test data for various testing conditions fall within a narrow convex strip. In the strain versus energy correlation in Fig. 5(b), although the data points are somewhat scattered, the ε_a – W_n relationships follow a general concave tendency, that is, the strain development initially appears to be indistinct but thereafter accelerates when the energy starts to rapidly dissipate. This demonstrates that the difference in either the pore pressure or strain versus energy relationship under different testing conditions is marginal.

Fig. 6(a) presents the variation of the equivalent Young's modulus, E_{eq} , which is defined in a hysteretic stress–strain loop by calculating the backbone curve slope, with the associated axial strain for each loading cycle until flow liquefaction triggering. The test data on a semilogarithmic scale for the sand under various initial and cyclic stress conditions indicate a clear dependence of degraded stiffness on the sustained shear stress level. In Fig. 6(b), E_{eq} for each individual stress cycle is plotted against W_n , which is calculated through the associated stress–strain loop. All the data points fall within a narrow band with the

dashed lines forming the upper and lower bounds, as shown in this figure. It can be observed that an increase in W_n would reduce E_{eq} . This may be attributed to the assumption that the increasing energy dissipation resulting from the breakdown of soil skeleton is mathematically related to the stiffness degradation because of plastic deformation. As compared to the interpretation shown in Fig. 6(a) from the strain perspective, Fig. 6(b) demonstrates that the concept of dissipated energy is more promising in evaluating the stiffness characteristics of sand under cyclic loading.

Given the clear correspondence between monotonic and cyclic flow liquefaction described previously, Fig. 7(a) presents the relationship of the shear resistance between the monotonic and cyclic tests. In this figure, the cyclic shear stress ratio ($CSR = q_{cyc}/(2p'_0)$) is normalized by the monotonic shear strength S_{IS} as follows and is plotted against the number of cycles required to flow liquefaction (N_f).

$$S_{IS} = |q_{IS} - q_0| / (2p'_0) \quad (2)$$

As shown in Fig. 7(a), the data for the sands under various testing conditions collapse on a narrow region. Despite the data scatter, the mean trend interpreted in this diagram indicates that the normalized version of the CSR versus N_f relationship is insusceptible to the cyclic stress waveform, sustained shear stress, and initial stress cycle. Therefore, for the sand that exhibits a flow liquefaction type behavior under monotonic loading, the shear resistance to cyclic flow liquefaction can be predicted from the shear strength at IS in the corresponding monotonic tests. Fig. 7(b) further presents the relationship between N_f and the normalization of CSR to instability stress ratio $\eta_{IS} (= q_{IS}/p'_{IS})$ during monotonic loading. It is shown that the trend of $CSR/(\eta_{IS}/2)$ for the sand sheared from an isotropic static stress state is seemingly independent on the cyclic stress waveform or the presence of an initial stress cycle. However, the data points for the sand subjected to an initial sustained q_0

(UCyc_–20 and UCyc_–40 tests series) are scattered and deviate significantly from the main trend, suggesting that the stress state of the sand prior to cyclic loading should be taken into account when correlating the cyclic resistance with the stress ratio at IS in monotonic tests. In Fig. 7(c), the energy capacity for triggering flow liquefaction, $W_{n,flow}$, is directly correlated with the liquefaction resistance, $CSR_{N=10}$, which represents the CSR required for liquefaction at $N_f = 10$. Note that the $W_{n,flow}$ values represent the means of the energy capacity for a given test series with varying cyclic stress amplitudes. As seen in Fig. 7(c), $W_{n,flow}$ appears to be uniquely correlated with $CSR_{N=10}$, with the dashed line indicating a linearly increasing tendency. This scenario indicates that the energy-based method has the potential applicability for flow liquefaction evaluation of sand under various initial and cyclic stress conditions, through relating soil strength to the standard penetration test values, which have been widely adopted and verified in engineering practice by using the conventional stress-based approach.

Conclusions

A series of monotonic and cyclic triaxial tests were performed to investigate the linkage between monotonic shear response and cyclic flow liquefaction of loose Toyoura sand under various initial and cyclic shear conditions. The concept of dissipated energy was introduced and employed in evaluating the flow liquefaction potential. The major findings are as follows:

1. The flow liquefaction type monotonic response for loose or contractive sand is the precondition of the occurrence of cyclic flow; in such case, the monotonic stress path constitutes an envelope for the stress state during the cyclic loading. Remarkably, cyclic flow liquefaction is triggered at the instant or shortly after the cyclic stress drives the

stress state across the monotonic effective stress path, depending on the relative magnitude of the trough of the cyclic stress and the monotonic deviatoric stress at the instability state.

2. The residual pore pressure and axial strain induced in sand are closely related to the accumulative dissipated energy in a convex or concave trend, respectively. There exist practically unique correlation of degraded stiffness and dissipated energy determined in a given stress cycle, which is barely affected by the cyclic stress amplitude and waveform, and is also independent of the sustained shear stress level and the presence of an initial stress cycle.

3. A unified relationship is obtained between the cyclic resistance and the corresponding monotonic strength at the instability state. This finding can facilitate the prediction of the flow liquefaction susceptibility of sand under cyclic loading. Furthermore, the energy capacity for triggering cyclic flow appears to be uniquely correlated with the liquefaction resistance, irrespective of the cyclic stress waveform and initial stress history.

Last but not least, some new proposals and quantitative findings obtained from this study provide in-depth insights into the cyclic liquefaction and flow behavior of relatively loose sand. However, further investigation by conducting laboratory tests considering a variety of initial states and stress conditions should be undertaken to further verify the proposed approach.

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299 References

- 300 Andersen, K.H. 2015. Cyclic soil parameters for offshore foundation design. *Frontiers in*
301 *Offshore Geotechnics III*, London, Vol. 1: 5–84.
- 302 Andrade, J.E., Ramos, A.M., and Lizcano, A. 2013. Criterion for flow liquefaction instability.
303 *Acta Geotechnica*, 8(5): 525–535.
- 304 Azeiteiro, R.J., Coelho, P.A., Taborda, D.M., and Grazina, J.C. 2017. Energy-based evaluation
305 of liquefaction potential under non-uniform cyclic loading. *Soil Dynamics and*
306 *Earthquake Engineering*, 92: 650–665.
- 307 Baki, M.A.L., Rahman, M.M., Lo, S.R., and Gnanendran, C.T. 2012. Linkage between static
308 and cyclic liquefaction of loose sand with a range of fines contents. *Canadian*
309 *Geotechnical Journal*, 49(8): 891–906.
- 310 Baki, M.A.L., Rahman, M.M., and Lo, S.R. 2014. Predicting onset of cyclic instability of loose
311 sand with fines using instability curves. *Soil Dynamics and Earthquake Engineering*,
312 61–62: 140–151.
- 313 Baziar, M.H. and Jafarian, Y. 2007. Assessment of liquefaction triggering using strain energy
314 concept and ANN model: capacity energy. *Soil Dynamics and Earthquake Engineering*,
315 27(12): 1056–1072.
- 316 Chu, J., and Leong, W.K. 2002. Effect of fines on instability behaviour of loose sand.
317 *Géotechnique*, 52(10): 751–755.
- 318 David, R.O., and Berrill, J.B. 1982. Energy dissipation and seismic liquefaction in sands.
319 *Earthquake Engineering and Structural Dynamics*, 10(1): 59–68.
- 320 De Gennaro, V., Canou, J., Dupla, J.C., and Benahmed, N. 2004. Influence of loading path on

- 321 the undrained behaviour of a medium loose. Canadian Geotechnical Journal, 41(1):
322 166–180.
- 323 Georgiannou, V.N., Tsomokos, A., and Stavrou, K. 2008. Monotonic and cyclic behaviour of
324 sand under torsional loading. Géotechnique, 58(2): 113-124.
- 325 Ishihara, K. 1996. Soil behavior in earthquake geotechnics. Clarendon Press, Oxford.
- 326 Ishihara, K., Tatsuoka, F., and Yasuda, S. 1975. Undrained deformation and liquefaction of
327 sand under cyclic stresses. Soils and Foundations, 15(1): 29–44.
- 328 Kokusho, T. 2013. Liquefaction potential evaluations: Energy-based method versus
329 stress-based method. Canadian Geotechnical Journal, 50(10): 1088–1099.
- 330 Lade, P.V. 1992. Static instability and liquefaction of loose fine sandy slopes. Journal of
331 Geotechnical Engineering, ASCE, 118(1): 51–71.
- 332 Li, Y., Yang, Y.M., Yu, H.S., and Roberts, G. 2017. Correlations between the stress paths of a
333 monotonic test and a cyclic test under the same initial conditions. Soil Dynamics and
334 Earthquake Engineering, 101: 153–156.
- 335 Lo, S.R., Rahman, M.M., and Bobei, D.C. 2010. Limited flow behaviour of sand with fines
336 under monotonic and cyclic loading. Geomechanics and Geoengineering, 5(1): 15–25.
- 337 Mao, X., and Fahey, M. 2003. Behaviour of calcareous soils in undrained cyclic simple shear.
338 Géotechnique, 53(8): 715–727.
- 339 Mizanur, R.M., and Lo, S.R. 2012. Predicting the Onset of Static Liquefaction of Loose Sand
340 with Fines. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 138(8):
341 1037–1041.
- 342 Mohamad, R., and Dobry, R. 1986. Undrained monotonic and cyclic triaxial strength of sand.
343 Journal of Geotechnical Engineering, ASCE, 112(10): 941–958.
- 344 Nemat-Nasser, S., and Shokooh, A.A. 1979. Unified approach to densification and

liquefaction of cohesionless sand in cyclic shearing. Canadian Geotechnical Journal, 16(4): 659–678.

Nguyen, H.B.K., Rahman, M.M., and Fourie, A.B. 2017. Undrained behaviour of granular material and the role of fabric in isotropic and K_0 consolidations: DEM approach. Géotechnique, 67(2): 153–167.

Oda, M., Kawamoto, K., Suzuki, K., Fujimori, H., and Sato, M. 2001. Microstructural interpretation on liquefaction of saturated granular soils under cyclic loading. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 127(5): 416–423.

Pan, K., and Yang, Z.X. 2018. Effects of initial static shear on cyclic resistance and pore pressure generation of saturated sand. Acta Geotechnica, 13(2): 473–487.

Pan, K., Yang, Z.X., and Xu, T.T. 2018. Impact of static preshearing on undrained anisotropy and shear characteristics of sand. International Journal of Geomechanics, ASCE, 18(12): 04018162.

Pan, K., and Yang, Z.X. 2020. Evaluation of liquefaction potential of sand under random loading conditions: Equivalent approach versus energy-based method. Journal of Earthquake Engineering, 24(1): 59–83.

Polito, C., Green, R.A., Dillon, E., and Sohn, C. 2013. Effect of load shape on relationship between dissipated energy and residual excess pore pressure generation in cyclic triaxial tests. Canadian Geotechnical Journal, 50(11): 1118–1128.

Rahman, M., Mal, B., and Lo, S.R. 2014. Prediction of undrained monotonic and cyclic liquefaction behavior of sand with fines based on the equivalent granular state parameter. International Journal of Geomechanics, ASCE, 14(2): 254–266.

Rahman, M.M., Nguyen, H.B.K., and Rabbi, A.T.M.Z. 2018. The effect of consolidation on undrained behaviour of granular materials: experiment and DEM simulation.

- 369 Geotechnical Research, 5(4): 199–217.
- 370 Riemer, M.F., and Seed, R.B. 1997. Factors affecting apparent position of steady state line.
- 371 Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 123(3): 281–288.
- 372 Seed, H.B., and Idriss, I.M. 1971. Simplified procedure for evaluating soil liquefaction
- 373 potential. Journal of Soil Mechanics and Foundations Division, ASCE, 97(9): 1249–1273.
- 374 Sivathayalan, S., and Vaid, Y.P. 2002. Influence of generalized initial state and principal
- 375 stress rotation on the undrained response of sands. Canadian Geotechnical Journal,
- 376 39(1): 63–76.
- 377 Sze, H.Y., and Yang, J. 2014. Failure modes of sand in undrained cyclic loading: impact of
- 378 sample preparation. Journal of Geotechnical and Geoenvironmental Engineering, ASCE,
- 379 140(1): 152–169.
- 380 Toyota, H., and Takada, S. 2016. Variation of liquefaction strength induced by monotonic
- 381 and cyclic loading histories. Journal of Geotechnical and Geoenvironmental Engineering,
- 382 ASCE, 143(4): 04016120.
- 383 Vaid, Y.P., Stedman, J.D., and Sivathayalan, S. 2001. Confining stress and static shear effects
- 384 in cyclic liquefaction. Canadian Geotechnical Journal, 38(3): 580–591.
- 385 Yamamuro, J.A., and Covert, K.M. 2001. Monotonic and cyclic liquefaction of very loose
- 386 sands with high silt content. Journal of Geotechnical and Geoenvironmental Engineering,
- 387 ASCE, 127(4): 314–324.
- 388 Yang, J. 2002. Non-uniqueness of flow liquefaction line for loose sand. Géotechnique, 52(10):
- 389 757–760.
- 390 Yang, J., and Sze, H.Y. 2011. Cyclic Strength of Sand under Sustained Shear Stress. Journal of
- 391 Geotechnical and Geoenvironmental Engineering, ASCE, 137(12): 1275–1285.
- 392 Yang, Z.X., Li, X.S., and Yang, J. 2008. Quantifying and modeling fabric anisotropy of granular

- 393 soils. *Géotechnique*, 58(4): 237–248.
- 394 Yang, Z.X., and Pan, K. 2017. Flow deformation and cyclic resistance of saturated loose sand
395 considering initial static shear effect. *Soil Dynamics and Earthquake Engineering*, 92:
396 68–78.
- 397 Yang, Z.X., Xu, T.T., and Chen, Y.N. 2018. Unified modeling of the influence of consolidation
398 conditions on monotonic soil response considering fabric evolution. *Journal of*
399 *Engineering Mechanics*, ASCE, 144(8): 04018073.
- 400 Yoshimine, M., and Hosono, Y. 2000. Effect of anisotropy of sand on results of undrained
401 triaxial test, *Memoirs of Graduate School of Engineering, Tokyo Metropolitan University*
402 50, 158-169.

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Figure captions

- Fig. 1. (a) Effective stress paths and (b) stress–strain curves of sand under uniform cyclic loading and monotonic triaxial extension
- Fig. 2. Comparison between cyclic and monotonic effective stress paths: (a) case of ICyc1; (b) case of ICyc2
- Fig. 3. Comparison between cyclic and monotonic effective stress paths: (a) case of compressional q_0 ($= 80$ kPa); (b) case of extensional q_0 ($= -40$ kPa)
- Fig. 4. Comparison between cyclic and monotonic effective stress paths in the case of (a) compressional and (b) extensional stress cycle
- Fig. 5. (a) Pore pressure ratio and (b) axial strain against accumulative dissipated energy
- Fig. 6. Equivalent Young's modulus varying with (a) axial strain and (b) dissipated energy
- Fig. 7. (a) Relationship between N_f and the normalization of cyclic resistance to monotonic shear strength; (b) relationship between N_f and the normalization of cyclic resistance to instability stress ratio; (c) correlation of liquefaction resistance to energy capacity for triggering flow liquefaction

Table 1. Summary of monotonic and cyclic triaxial tests ($p_0' = 100$ kPa)

Series	Shearing mode	e_0	q_0 (kPa)	q_{cyc} (kPa)	S_{IS} or CSR^a	Test ID ^b
I (Isotropic consolidation)	TE	0.872	0	/	0.15	TE_0
	UCyc	0.862	0	15	0.075	UCyc_0_15
		0.865	0	20	0.1	UCyc_0_20
		0.861	0	25	0.125	UCyc_0_25
		0.874	0	30	0.15	UCyc_0_30
	ICyc1	0.870	0	20	0.1	ICyc1_0_20
		0.866	0	25	0.125	ICyc1_0_25
		0.866	0	32	0.16	ICyc1_0_32
		0.861	0	20	0.1	ICyc2_0_20
	ICyc2	0.874	0	25	0.125	ICyc2_0_25
		0.876	0	30	0.15	ICyc2_0_30
II (Compressional sustained stress)	TC	0.865	20	/	/	TC_20
	TE	0.871	20	/	0.25	TE_20
	UCyc	0.867	20	25	0.125	UCyc_20_25
		0.875	20	30	0.15	UCyc_20_30
	TC	0.875	80	/	/	TC_80
	TE	0.864	80	/	0.53	TE_80
	UCyc	0.862	80	17	0.085	UCyc_80_17
		0.870	80	35	0.175	UCyc_80_35
III (Extensional sustained stress)	TE	0.876	-20	/	0.06	TE_-20
	UCyc	0.875	-20	8	0.04	UCyc_-20_8
		0.870	-20	15	0.075	UCyc_-20_15
	TE	0.876	-40	/	0.02	TE_-40
	UCyc	0.871	-40	8	0.04	UCyc_-40_8
IV (Compressional stress cycle)	TE	0.861	0	/	0.14	TE_0 ⁽⁸⁰⁾
	UCyc	0.876	0	20	0.1	UCyc_0 ⁽⁸⁰⁾ _20
		0.872	0	23	0.115	UCyc_0 ⁽⁸⁰⁾ _23
		0.870	0	25	0.125	UCyc_0 ⁽⁸⁰⁾ _25
		0.868	0	32	0.16	UCyc_0 ⁽⁸⁰⁾ _32
V (Extensional stress cycle)	TE	0.869	0	/	0.21	TE_0 ⁽⁻⁴⁰⁾
	UCyc	0.874	0	20	0.1	UCyc_0 ⁽⁻⁴⁰⁾ _20
		0.864	0	23	0.115	UCyc_0 ⁽⁻⁴⁰⁾ _23
		0.876	0	25	0.125	UCyc_0 ⁽⁻⁴⁰⁾ _25

Note: ^a S_{IS} (shear strength at the instability state) for monotonic tests and CSR (cyclic stress ratio) for cyclic tests. ^b

The designation identifies: 1) the undrained shearing mode—TC for triaxial compression, TE for triaxial extension, UCyc and ICyc for uniform and irregular cyclic loading, respectively; 2) initial deviatoric stress prior to undrained shearing, q_0 , and ⁽¹⁾ for the amplitude of initial stress cycle; 3) cyclic deviatoric stress, q_{cyc} .

Fig. 1 (a) Effective stress paths and (b) stress–strain curves of sand under uniform cyclic loading and monotonic triaxial extension

Fig. 2 Comparison between cyclic and monotonic effective stress paths: (a) case of ICyc1; (b) case of ICyc2

Fig. 3 Comparison between cyclic and monotonic effective stress paths: (a) case of compressional q_0 ($= 80 \text{ kPa}$); (b) case of extensional q_0 ($= -40 \text{ kPa}$)

Fig. 4 Comparison between cyclic and monotonic effective stress paths in the case of (a) compressional and (b) extensional stress cycle

Fig. 5 (a) Pore pressure ratio and (b) axial strain against accumulative dissipated energy

Fig. 6 Equivalent Young's modulus varying with (a) axial strain and (b) dissipated energy

Fig. 7 (a) Relationship between N_f and the normalization of cyclic resistance to monotonic shear strength; (b) relationship between N_f and the normalization of cyclic resistance to instability stress ratio; (c) correlation of liquefaction resistance to energy capacity for triggering flow liquefaction