A direct simple shear device for static liquefaction triggering under constant shear drained loading

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The development of a direct simple shear device to carry out constant shear drained (CSD) tests is outlined. The purpose of the device is to study static liquefaction instability triggered by a rising phreatic surface under principal stress directions representative of conditions below a slope. A series of tests on a laboratory-standard sand are outlined, indicating (a) brittle instability under a drained increasing phreatic surface, (b) a reasonable trend between the instability stress conditions and the sample density and (c) a general agreement between the qualitative behaviour seen in the new device and the previous CSD testing carried out on saturated samples under dead weight. The sensitivity of the instability stress conditions to sample density is emphasised.

KEYWORDS: anisotropy; laboratory equipment; liquefaction

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INTRODUCTION

Static liquefaction is increasingly recognised as a common failure mechanism for tailings storage facilities and other large hydraulic fill deposits (Davies *et al.*, 2002; AECOM, 2009; Morgenstern *et al.*, 2016). While static liquefaction can be triggered by a variety of drained or undrained stress paths, it is arguably an increasing phreatic surface that is the most dangerous mechanism as (a) it is difficult to obviate the potential for this occurrence within most hydraulic fill structures and (b) minimal pre-instability deformation may occur.

The potential for a slow phreatic surface rise triggering static liquefaction was first established through model tests (Eckersley, 1990) and stress-controlled triaxial compression testing (Sasitharan *et al.*, 1993). The testing approach of Sasitharan *et al.*, later referred to as the constant shear drained (CSD) test (Anderson & Riemer, 1995), has since been adopted by many researchers (Junaideen *et al.*, 2010; Monkul *et al.*, 2011; Chu *et al.*, 2012), with deviator stress applied using either dead weights or a servo control. CSD testing has also been carried out under triaxial extension (Dong *et al.*, 2016) and plane strain compression conditions (Wanatowski *et al.*, 2010).

One aspect of the CSD-type triggering of static liquefaction that has not been thoroughly investigated is the initiation of instability in an element of soil under principal stress directions (α) other than 0 and 90° – that is, the conditions likely to exist below much of a slope. For example, the numerical modelling of embankment construction with undrained load increments suggests ranges of α from 15 to 60° (Jardine & Smith, 1991), while a drained simple shear loading of sands carried out in a hollow cylinder device (Shibuya & Hight, 1987) suggests α of

approximately 20° under mobilised shear strength ratios ($\tau_{\alpha 0}/\sigma'_z$), typical of the pre-triggering condition of many static liquefaction failures (e.g. Sadrekarimi, 2016).

The triggering of static liquefaction under α values similar to those likely to exist below a slope is important as clear evidence indicates that the instability stress ratio ($n_{IL} = q/p'$) of loose sandy soils exhibits anisotropy. For example, Fig. 1 presents a summary of two hollow cylinder test programmes (Uthayakumar & Vaid, 1998; Sivathayalan & Vaid, 2002) where n_{IL} at different α values are normalised against n_{IL} under compression ($\alpha = 0^\circ$) conditions. These data clearly indicate that the rotation of α results in significant reductions to n_{IL} .

This paper outlines the development of a stress-controlled direct simple shear (DSS) apparatus that enables CSD testing. This device was developed to enable the investigation of static liquefaction instability under α values more representative of below slope conditions. It is noted that CSD testing has previously been carried out within a stacked ring-type (Kjellman, 1951) DSS through the ‘wetting’ of an initially unsaturated sample (Cuomo *et al.*, 2017). However, the strengths obtained at failure and the stress–strain behaviour observed in this work indicate that the samples were not brittle and/or contractive, and hence are not directly applicable to the form of brittle static liquefaction instability from the rising phreatic surface that is considered herein.

DESCRIPTION OF THE DEVICE

Drawings of the new device are presented in Fig. 2, and annotated images are presented in Fig. 3. The device comprises a top platen fixed by means of a horizontal restraint of the vertical loading shaft. The base platen is free to move in the direction of the horizontal loading, comprising a wheeled ‘cart’ containing the bottom platen and drainage channels and accommodates the connection to the horizontal loading shaft. Vertical loads are applied to the sample through the top platen by means of a water tank positioned below the device. A steel cross bar and steel wires connect the water tank to the vertical load ram and top platen. Horizontal (shear) loading is applied through dead weights or a bucket of water suspended from a steel cable that is connected to the horizontal load shaft through a

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Fig. 1. Summary of the observed effects of α on η_L

pulley. Stress-controlled loading is thus achieved in both the horizontal and vertical directions.

Samples are enveloped using a 0.4 mm thick membrane and restrained laterally by a series of Teflon rings with an internal diameter of 71 mm. Horizontal and vertical loads are measured using 1 and 2 kN load cells, respectively, fixed on the relevant shaft connected to the specimen. Similarly, horizontal and vertical displacement is tracked by means of two linear variable differential transformers (LVDTs) connected to each shaft. All load cells and LVDTs used were supplied by GDS Instruments.

The device fits within a sealable tank to enable the future studies of CSD behaviour either under elevated back pressures (e.g. Dyvik *et al.*, 1987), or for tests without Teflon rings, where known horizontal stresses are applied to the sample, as done in the 'Berkeley-type' simple shear devices (e.g. Boulanger *et al.*, 1993).

MATERIALS AND METHODS

Soil and preparation methods

Tests were carried out using silica fine sand, a commercial sand produced by Sibelco Australia Limited. The material is

a fine sand, with a $D_{90}/D_{50}/D_{10}$ of 0.38/0.21/0.13 mm, respectively, $0.3\% < 75 \mu\text{m}$ and G_s of 2.64. Samples were prepared using the moist-tamping technique. The sand was prepared at 5% water content and tamped in two layers of equal volume and mass into the membrane-lined Teflon rings. The surface of the first layer was lightly scarified prior to the placement and the compaction of the second layer. Samples were approximately 20 mm high.

Test procedure

After specimen preparation, the base cart was inserted into the tank, the top platen was lowered into contact with the specimen and the membrane was folded back over the top platen and secured with two O-rings. The top and bottom drainage lines were then connected to the platens. The vertical loading tank was first filled with water to apply an approximate total vertical stress of 20 kPa for the saturation procedures. Saturation involved first flushing the specimen with carbon dioxide for 30 min, followed by flushing a minimum of five pore volumes of de-aired water. After the completion of flushing, the sample was connected to a de-aired water reservoir located approximately 1 m above the specimen, providing a back pressure of 10 kPa. The magnitude of back pressure was accounted for during the calculation of vertical effective stresses acting on the samples tested.

After saturation, the vertical effective stress on the specimen was increased to approximately 185 kPa and held constant for 30 min. The horizontal loading shaft was then connected to the base cart and the horizontal load was applied by means of a slow placement of weights or the filling of a bucket with water. Once the target horizontal load was achieved, the sample was kept under the target vertical and horizontal load conditions for 30 min prior to the commencement of CSD loading which was applied by siphoning water from the vertical loading tank at a flow rate such that the vertical effective stress reduced at approximately 2 kPa/min. This was continued until the initiation of instability – which was clearly indicated by a loud 'bang' as the horizontal load of the dead weights hit the floor. A video of the initiation of instability in a commissioning test on the device is included in Supplementary Information to this paper.

Fig. 2. Schematic sections of CSD DSS

Fig. 3. Photographs of CSD device: (a) overview, (b) side view, (c) sample prepared for the CSD stage

Nine tests at a range of preparation void ratios were carried out, as summarised in Table 1.

Saturation procedure considerations

Typical DSS testing was carried out under constant volume conditions, a method that has been shown to provide comparable results to undrained tests (Finn, 1985; Dyvik *et al.*, 1987). Constant volume testing is convenient as it does not require saturation with a back pressure – although samples are typically still saturated to eliminate matric suction (e.g. Al-Tarhouni *et al.*, 2011). However, the tests carried out in this study were under a reducing vertical effective stress, with the sample free to change the height and drain throughout the test. Therefore, additional saturation procedures (compared to constant volume DSS testing) were adopted in the form of carbon dioxide flushing, de-aired water flushing, and a provision of 10 kPa back pressure through an elevated de-aired water reservoir.

RESULTS AND DISCUSSION

The results of four of the tests carried out (CSD-01, -02, -04 and -09) are presented in Fig. 4. These tests provide a range of densities from the testing programme. The initiation of instability is indicated by the open diamond markers. These instability points represent the final recording of data prior to the initiation of significant and essentially instantaneous horizontal displacement.

The pre-instability behaviour of each test presented is broadly similar. For most tests, although the rate of the shear strain is seen to increase with the approaching instability, these pre-instability shear strains are typically small (i.e. <1.5%). Only test CSD-01, the densest sample tested in this programme, exhibited a higher shear strain prior to the instability. Initial pre-instability vertical strains are slightly dilative, as a consequence of the reduction in vertical effective stress. With the approaching instability, vertical strains generally become contractive.

It is noted that the shear strain responses of the four tests are slightly inconsistent with respect to the strain occurring

Table 1. Summary of the CSD DSS tests

Test	Condition after drained shear stress application				Instability condition			
	τ_{xy} : kPa	σ'_v : kPa	τ_{xy}/σ'_v : dimensionless	e_c : dimensionless	τ_{xy} : kPa	σ'_v : kPa	τ_{xy}/σ'_v : dimensionless	e_{IL} : dimensionless
CSD-01	36.3	183.0	0.20	0.634	36.0	74.5	0.48	0.634
CSD-02	37.0	182.9	0.20	0.675	39.7	123.1	0.32	0.674
CSD-03	35.9	176.0	0.20	0.739	Failed prior to CSD stage			
CSD-04	35.8	174.7	0.20	0.687	36.2	122.2	0.30	0.687
CSD-05	34.9	184.2	0.19	0.692	35.5	123.4	0.29	0.693
CSD-06	35.9	179.7	0.20	0.681	36.5	116.5	0.31	0.681
CSD-07	34.0	177.4	0.19	0.688	35.3	124.2	0.28	0.689
CSD-08	36.5	181.8	0.20	0.662	38.7	86.9	0.45	0.660
CSD-09	34.0	174.5	0.19	0.708	34.3	126.1	0.27	0.709

Fig. 4. CSD test results: (a) τ_{xy} against σ'_v , (b) γ against σ'_v , (c) γ against time, (d) ϵ_v against time

under a given reduction of vertical effective stress. For example, CSD-01 exhibits a slightly higher shear strain under the same vertical effective stress reduction as CSD-09, despite CSD-01 being denser and having a higher final instability stress ratio τ_{xy}/σ'_v . However, these differences are seen at relatively low shear strains (<0.5%), which represent a horizontal displacement of about 0.1 mm. It is suggested that given the potential for the development of a slight frictional resistance on the horizontal load shaft, and a possible influence of this friction on the pre-instability deformation pattern, a qualitative comparison of the pre-instability behaviour is speculative. The effects of shaft friction during stress-controlled CSD testing have also been observed in the triaxial tests (e.g. Sasitharan *et al.*, 1993). Alternatively, as noted subsequently, a comparison of the test data at the initiation of instability (where a small shaft friction would be irrelevant) provides a consistent trend.

The results of all tests are summarised in Fig. 5, in terms of the instability strength ratio against the void ratio at instability (e_{IL}). The instability τ_{xy}/σ'_v values ranging from 0.20 to 0.50 were observed in the samples tested, with a clear trend between the void ratio and instability τ_{xy}/σ'_v . It is noted that the most loose test prepared in this programme, CSD-03, failed during the set-up of the siphon lines, prior to the actual commencement of CSD loading. Slightly higher densities were therefore used in the subsequent tests to avoid the creation of such a metastable sample. It is noted that the results presented in Fig. 5 would be essentially identical whether plotted against the void ratio at the start of CSD (e_c) or e_{IL} , given the small volumetric strains seen during the CSD process. What is also clear from Fig. 5 is that

Fig. 5. Summary of the effects of density on the initiation of instability

relatively small changes in the void ratio result in significant changes in the stress ratio that triggers the instability. Given the difficulty in accurately estimating the in situ void ratio of loose sandy fills, the importance of such small changes in the void ratio cannot be overemphasised.

CONCLUSIONS

A DSS test device developed to enable CSD testing was outlined, involving the application of vertical and horizontal (shear) loads by means of dead weights or water-filled tanks.

The reduction in the vertical effective stress during the CSD loading stage was accomplished by slowly siphoning water from the vertical loading tank. The initiation of static liquefaction under these drained loading conditions was observed, with qualitative behaviour similar to that of previous CSD testing under triaxial and plane strain conditions. A reasonable trend between the density and the stress ratio at the initiation of instability was observed.

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REFERENCES

- AECOM (2009). *Root cause analysis of TVA Kingston dredge pond failure on December 22, 2008*. Vernon Hills, IL, USA: AECOM.
- Al-Tarhouni, M., Simms, P. & Sivathayalan, S. (2011). Cyclic behaviour of reconstituted and desiccated–rewet thickened gold tailings in simple shear. *Can. Geotech. J.* **48**, No. 7, 1044–1060.
- Anderson, S. A. & Riemer, M. F. (1995). Collapse of saturated soil due to reduction in confinement. *J. Geotech. Engng* **121**, No. 2, 216–220.
- Boulanger, R., Chan, C. K., Seed, H. B., Seed, R. B. & Sousa, J. B. (1993). A low-compliance bi-directional cyclic simple shear apparatus. *Geotechnical Testing Journal* **16**, No. 1, 36–45, <https://doi.org/10.1520/GTJ10265J>.
- Chu, J., Leong, W. K., Loke, W. L. & Wanatowski, D. (2012). Instability of loose sand under drained conditions. *J. Geotech. Geoenviron. Engng* **138**, No. 2, 207–216.
- Cuomo, S., Moscariello, M. & Foresta, V. (2017). Wetting tests of partially saturated soils under simple shear conditions. *Geotech. Lett.* **7**, No. 2, 197–203, <https://doi.org/10.1680/jgele.17.00019>.
- Davies, M. P., Mcroberts, E. C. & Martin, T. E. (2002). Static liquefaction of tailings – fundamentals and case histories. *Proceedings of Tailings Dam 2002: Proceedings of the Joint ASDSO/USSD Specialty Conference*, Las Vegas, NV, USA, pp. 233–255.
- Dong, Q., Xu, C., Cai, Y., Juang, H., Wang, J., Yang, Z. & Gu, C. (2016). Drained instability in loose granular material. *Int. J. Geomech.* **16**, No. 2, 04015043.
- Dyvik, R., Berre, T., Lacasse, S. & Raadim, B. (1987). Comparison of truly undrained and constant volume direct simple shear tests. *Géotechnique* **37**, No. 1, 3–10, <https://doi.org/10.1680/geot.1987.37.1.3>.
- Eckersley, D. (1990). Instrumented laboratory flowslides. *Géotechnique* **40**, No. 3, 489–502, <https://doi.org/10.1680/geot.1990.40.3.489>.
- Finn, W. (1985). Aspects of constant volume cyclic simple shear. *Proceedings of Advances in the Art of Testing of Soils under Cyclic Conditions*, Detroit, MI, USA (ed. V. Khosla), pp. 74–98. New York, USA: ASCE.
- Jardine, R. J. & Smith, P. R. (1991). Evaluating design parameters for multi-stage construction. *Proceedings of Geo-coast '91 International Conference*. Yokosuka, Japan: Yokohama Port and Harbour Research Institute, vol. 1, pp. 197–202.
- Junaideen, S. M., Tham, L. G., Law, K. T., Dai, F. C. & Lee, C. F. (2010). Behaviour of recompacted residual soils in a constant shear stress path. *Can. Geotech. J.* **47**, No. 6, 648–661.
- Kjellman, W. (1951). Testing the shear strength of clay in Sweden. *Géotechnique* **2**, No. 3, 225–232, <https://doi.org/10.1680/geot.1951.2.3.225>.
- Monkul, M. M., Yamamuro, J. A. & Lade, P. V. (2011). Failure, instability, and the second work increment in loose silty sand. *Can. Geotech. J.* **48**, No. 6, 943–955.
- Morgenstern, N. R., Vick, S. G., Viotti, C. B. & Watts, B. D. (2016). *Fundão tailings dam review panel: report in the immediate causes of the failure of the Fundão Dam*.
- Sadrekarami, A. (2016). Static liquefaction analysis considering principal stress directions and anisotropy. *Geotech. Geol. Engng* **34**, No. 4, 1135–1154.
- Sasitharan, S., Robertson, P. K., Sego, D. C. & Morgenstern, N. R. (1993). Collapse behavior of sand. *Can. Geotech. J.* **30**, No. 4, 569–577.
- Shibuya, S. & Hight, D. W. (1987). On the stress path in simple shear. *Géotechnique* **37**, No. 4, 511–515, <https://doi.org/10.1680/geot.1987.37.4.511>.
- Sivathayalan, S. & Vaid, Y. P. (2002). Influence of generalized initial state and principal stress rotation on the undrained response of sands. *Can. Geotech. J.* **39**, No. 1, 63–76.
- Uthayakumar, M. & Vaid, Y. P. (1998). Static liquefaction of sands under multiaxial loading. *Can. Geotech. J.* **35**, No. 2, 273–283.
- Wanatowski, D., Chu, J. & Loke, W. L. (2010). Drained instability of sand in plane strain. *Can. Geotech. J.* **47**, No. 4, 400–412.

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