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Effect of sample size on the critical state line for two sands

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ABSTRACT: The laboratory measurement of the critical state line (CSL) has become reasonably standardized in geotechnical laboratory practice in the investigation of tailings storage facilities (TSFs). Available data generally supports the view that – for most sandy soils and tailings - there is a single unique CSL regardless of sample preparation method. Alternatively, there is some limited evidence for the effects of sample size on the laboratory-determined CSL – however, this data is somewhat limited, being: (i) a first study using measurement of sample dimensions for samples as small as 38 mm diameter, and assumptions regarding saturation collapse volume change (i.e. not directly measured) and (ii) moderate correlation between sample size and CSL elevation in a recent round robin exercise where other variables were not controlled. As such, further investigation of the potential for sample size to affect CSL elevation would be useful. The current study outlines a series of tests on two laboratory-standard sands in three laboratories, comparing typical (e.g. 72 mm diameter) specimens to much larger specimens of 150 and 300 mm, respectively. Importantly, direct measurement of end-of-test sample void ratio was made in all tests – i.e., no assumptions regarding saturation collapse volume change were required, while other experimental variables were controlled allowing a focus on only sample size. The results suggested no consistent effect of sample size on the inferred CSL within the range of typical void ratio reliability of +/- 0.02 expected for CSL determination. Further, examination of critical state friction ratio and instability stress ratio showed negligible effect of sample size within the range of typically expected experimental variability.

KEYWORDS: laboratory testing, critical state line, liquefaction

1 INTRODUCTION

The laboratory measurement of the critical state line (CSL) has become a reasonably standardized process applied commonly in current characterisation and liquefaction assessments of tailings storage facilities (TSFs) and other hydraulic fills (Morgenstern et al. 2016, Jefferies et al. 2019). Typical sample diameters used in such testing reflect those adopted more generally in current laboratory practice, these being between 50 to 80 mm diameter for reconstituted specimens (e.g. Reid et al. 2021) and 2:1 height to diameter (H/D) ratio with oversized lubricated end platens and implementation of end of test soil freezing (EOTSF) to provide routine and accurate measurement of sample void ratio.

An area that has not been fully explored is the potential effect of sample size on the measured CSL. Jefferies et al. (1990) showed significant effect of sample size on the stress-strain response of dense triaxial tests, yet owing to the dense state of these specimens, the effects on the CSL are difficult to assess. Omar and Sadrekarimi (2014) showed an apparent consistent bias between CSL elevation and sample diameter (38 – 70 mm) – however, initial test measurements combined with an assumption regarding sample volume change during saturation collapse raises important questions about the reliability of the outcomes, particularly when considering the influence of sample size on void ratio accuracy for 38 mm diameter specimens (Vaid and Sivathayalan 1996). Alternatively, Reid and Fourie (2016) showed indistinguishable CSLs for 63 and 72 mm diameter specimens, while Reid et al. (2021) showed a potential slight effect of CSL diameter on CSL elevation, of the opposite direction as Omar and Sadrekarimi. Clearly, the available data is insufficient to draw a firm conclusion.

The current study outlined two programs on reference sands carried out in the laboratories of WSP and BGC, respectively, to investigate the effects of sample size on inferred CSL and, where possible, other aspects of inferred soil behaviour. This testing has leveraged existing test programs by Fanni et al. (2022) and Wightman et al. (2025) on the two sands tested, enabling focus on the results of the larger diameter tests carried out for this study.

2 MATERIALS AND METHODS

2.1 *WSP Testing*

The initial test program at The University of Western Australia (UWA) and WSP was carried out on silica fine sand (SFS), a standard sand used in Australia for research purposes produced by Sibelco Australia. The gradation data is presented in Figure 1. The CSL using typical sample sizes (72 mm diameter, 144 mm high) had previously been measured by Fanni et al. (2022) and serves as the reference for the larger-diameter work in this paper. SFS has a D_{50} of 0.21 mm, Coefficient of Uniformity (C_u) of 4.2 and has no particles passing 0.075 mm.

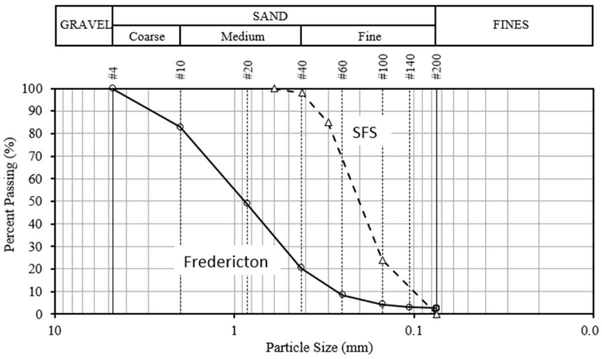

Figure 1. Particle size distribution of SFS and Fredericton sand

The large diameter triaxial device used at WSP allowed specimens of approximate initial diameter and height of 150 mm and 300 mm, respectively and is presented in Figure 2. The triaxial system was manufactured by GDS Instruments, while modified base and top platens were developed by WSP that allowed oversize lubricated ends and end of test soil freezing (EOTSF). It was found in initial tests that the mass of sample was such that upon cell removal and collapse of the specimen, significant leakage occurred owing to stretching of the membrane and o-rings at the base of the sample. Therefore, in the tests reported herein, pipe clamps were used to securely fasten the o-rings at the base and prevent leakage during test disassembly and freezing.

For the current study WSP carried out four tests of 150 mm diameter specimens. After initially moist tamping to a loose condition, the samples were flushed with deaired water, then back pressure saturated to achieve a minimum Skempton's B value of 0.95, consistent with the 72 mm testing previously outlined by Fanni et al. (2022). All tests were isotropically consolidated, and two sheared undrained and two drained.

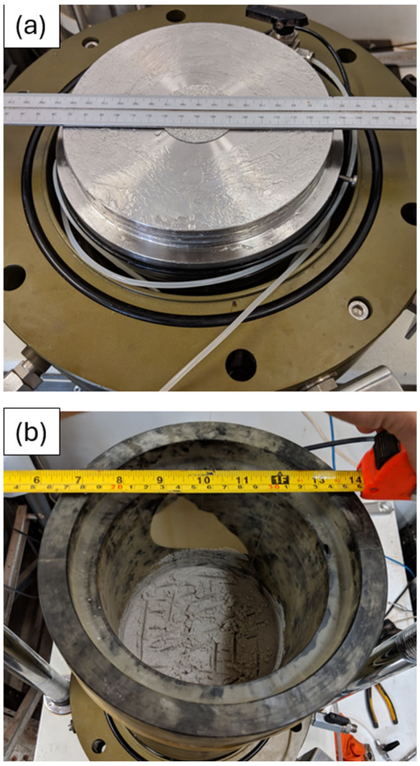

Figure 2. WSP 150 mm diameter triaxial equipment: (a) oversized based platen during preparation, the base is "modular" and can be removed for EOTSF, and (b) preparing a specimen, scarifying layer surface

2.2 *BGC testing*

BGC's testing was carried out on a Fredericton sand, a local quarry sand used by BGC for research and commissioning purposes (Wightman et al., 2025). The material tested is a clean fine to coarse, angular (low roundness) quartz and feldspathic sand with intermediate sphericity. The sand was screened on the no. 4 (4.75 mm) sieve and thoroughly mixed prior to initiating the testing program. Fredericton sand has a D_{50} of approximately 1 mm, a Coefficient of Uniformity (C_u) of 4.2 and a total fines content (<0.075 mm) of 3%.

The 70 mm diameter tests were conducted using an automated triaxial system manufactured by GDS which allows control of fluid pressures and volume changes to within 1 kPa and 0.5 cm^3. The base and top platens were developed by BGC which allowed use of oversized lubricated ends. The platens had total diameters of 85 mm and central porous stone diameters of 25 mm. EOTSF was used for accurate determination of void ratio.

The 300 mm diameter tests were carried out in a large diameter cyclic triaxial system manufactured by GDS Instruments. The base and top platens were developed by BGC and allowed use of oversize lubricated ends with total diameters of 365 mm and porous disc diameters of 100 mm. The platens had sealing bolts that allowed removal of the sample (and platens) from the cell without loss of pore water. Given the large sample volume and the use of sealing bolts, potential errors due to water loss were negligible. For instance, a 100 mL of water would correspond to a void ratio of less than 0.005. Therefore, accurate void ratios could be determined without the need for EOTSF. The BGC large triaxial testing system used in the current study is shown in Figure 3.

All specimens (70 mm and 300 mm) had height (H) to diameter (D) ratios of 2H:1D. After initially moist tamping to a loose condition, the sample were flushed with deaired water, then back pressure saturated to achieve a minimum Skempton's B value of 0.95, consistent with the 70 mm testing previously outlined by Wightman et al. (2025).

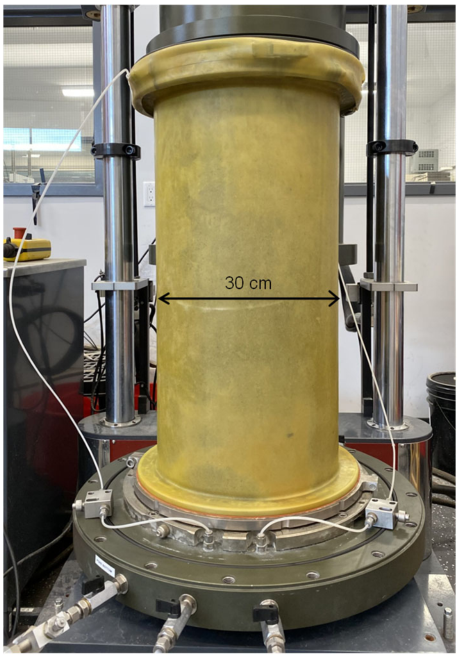

Figure 3. BGC 300 mm diameter triaxial equipment

BGC carried out a series of six tests on 70 mm diameter specimens to define the CSL (previously outlined by Wightman et al. 2025), followed by three tests on the larger 300 mm diameter specimens for the purpose of investigating size effects.

All tests were isotropically consolidated, with drained and undrained shearing adopted to allow investigation of instability and to infer the CSL location at a wide range of mean effective stresses.

3 RESULTS

3.1 *WSP Testing*

The results of the WSP testing on 150 mm diameter samples are summarized as a state diagram in Figure 4, and the drained tests as mobilized friction ratio vs. axial strain in Figure 5.

The drained tests appear to be tending to the same CSL – the CID500 test reaching a critical state (CS) condition indistinguishable from the CSL obtained with 72 mm samples, while the CID100 is within 0.01 void ratio. Further, the critical state friction ratio M_{tc} suggested by the 150 mm diameter CID specimens appears indistinguishable from that previously obtained 72 mm samples by Fanni et al. (2022). Alternatively, as the CIU tests exhibited either liquefaction or a quasi-steady state (QSS) their results were inconclusive in the context of the current study and are not examined here – however, it is noted that the test exhibiting a QSS appears to be tending towards the same CSL.

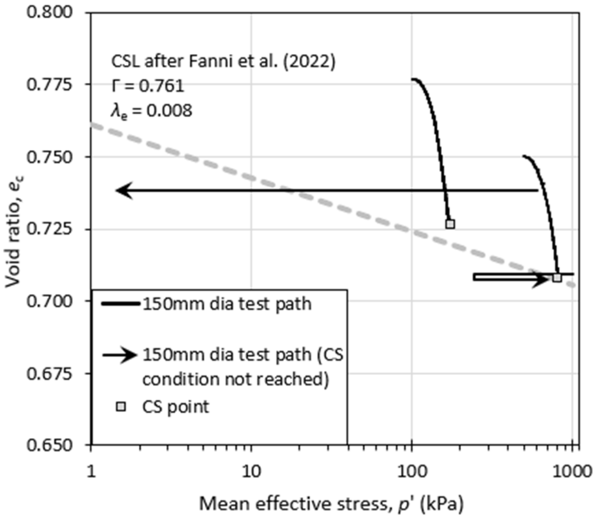

Figure 4. WSP SFS test results – state diagram

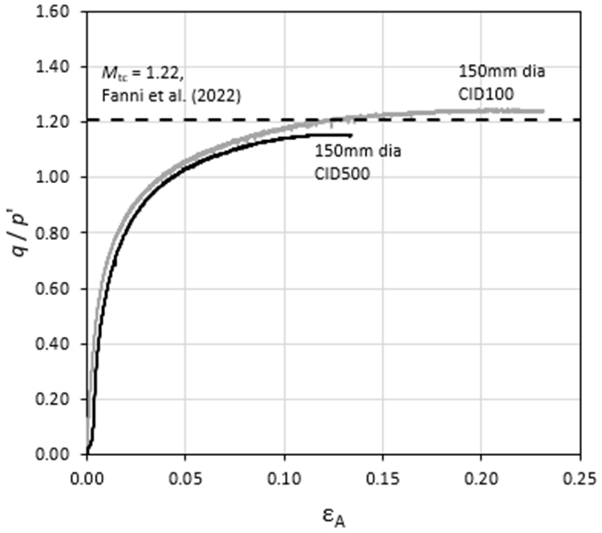

Figure 5. WSP SFS test results – critical state friction ratio

3.2 *BGC testing*

The results of the BGC testing are summarized as a state diagram in Figure 6, drained tests as mobilized friction ratio vs. axial strain in Figure 7, a comparison of the undrained shearing responses as q/p'_c vs. p/p'_c in Figure 8, and the undrained tests as instability stress ratio (η_{IL}) vs. initial state parameter Ψ_0 in Figure 9.

The larger data set available in this test program clearly shows indistinguishable CSLs are obtained for 70 mm and 300 mm samples in the summary in Figure 6. For the Fredericton sand, significant curvature was seen for the CSL with both sample diameters which is attributed to particle compression and crushing at higher stress levels. As with the WSP testing on SFS, no effect of sample diameter on M_{tc} was seen.

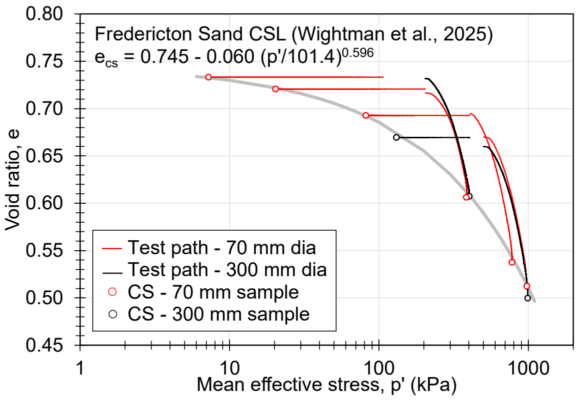

Figure 6. BGC Fredericton sand test results – state diagram

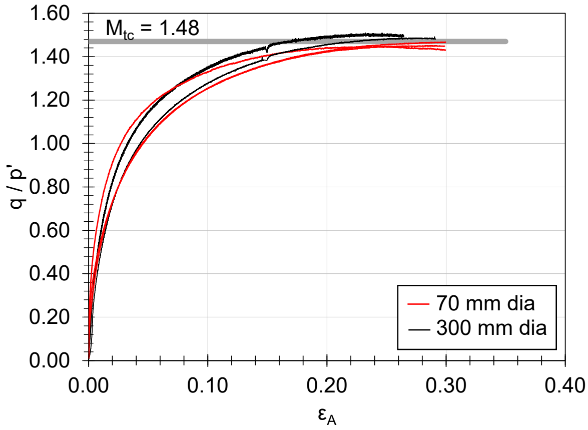

Figure 7. BGC Fredericton sand test results – critical state friction ratio

For the undrained test shear responses presented in Figure 8, a consistent trend is seen between the tests of both diameters – peak strength and η_{IL} vary consistently with initial state parameter Ψ_0, while increasing p'_c results in less post-peak strength loss owing to the curvature of the CSL. The summary of these tests in Figure 9 clearly shows the consistent trend between η_{IL} and Ψ_0 for both sample diameters, although this conclusion being based on a single 300 mm diameter specimen is acknowledged.

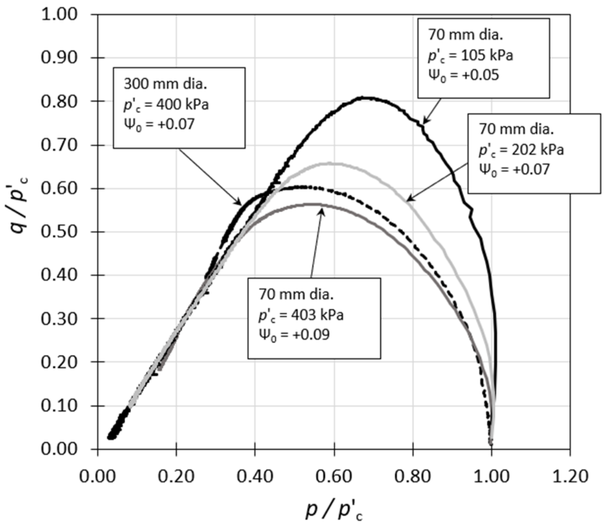

Figure 8. BGC Fredericton sand test results – instability stress ratio vs. initial state parameter (70 mm samples after Wightman et al. 2025)

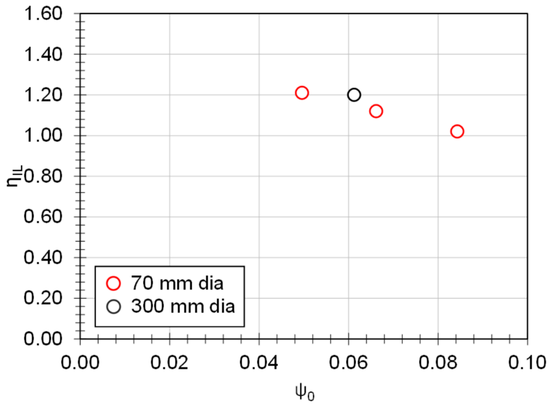

Figure 9. BGC Fredericton sand test results – instability stress ratio vs. initial state parameter

4 CONCLUSIONS

An investigation of the effects of sample size on the CSL was carried out by two laboratories on two reference sands. In both cases, there was no discernible effect from sample diameter on CSL elevation, M_{tc}, or the trend of η_{IL} vs. Ψ_0. These results differ from some earlier studies, which is suggested to be a result of the higher accuracy means for measuring sample density adopted in the current study. The results provide improved confidence in the use of smaller diameter specimens (i.e. 70 – 72 mm diameter) to simulate sand behaviour in a critical state framework.

DATA AVAILABILITY STATEMENT

All electronic data for the tests presented in the current paper can be found at the following repository: https://osf.io/kp5uy/?view_only=30e098eb75a546ada5ac6069b860dea2

MATERIAL AVAILABILITY STATEMENT

The soils used in the current testing program can be provided to others for comparison testing if requested.

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