

1 **Effect of saturation procedures on direct simple shear testing of silt tailings**

2

3 **David Reid (Corresponding author)**

4 ORCID: 0000-0002-1867-1676

5 Adjust Research Fellow. The University of Western Australia, Perth, Australia

6 Principal Tailings Engineer. Red Earth Engineering, Perth, Australia

7 david.reid@uwa.edu.au

8

9 **Riccardo Fanni**

10 Principal Tailings Engineer. WSP, Perth, Australia

11

12 **Felipe Urbina**

13 PhD Candidate. The University of Western Australia, Perth, Australia

14

15 **Andy Fourie**

16 Professor. The University of Western Australia, Perth, Australia

17

18

19 Words: 2038 (Main body text)

20 Figure: 5

21 Tables: 3

22

23

24 **Manuscript submitted to Géotechnique Letters October 2024**

25 **Abstract**

26 The direct simple shear (DSS) test carried out under constant volume (CV) conditions forms one
27 of the primary laboratory devices to characterise soils and tailings. The use of CV conditions to
28 simulate undrained shearing is supported by historical evidence on the testing of a saturated
29 clay and dry sands, with this evidence being incorporated into current guidelines and state of
30 practice procedures. However, some recent comparisons of the results of undrained hollow
31 cylinder simple shear (HCSS) and CV DSS tests on predominately silt gold tailings adopting
32 state of practice test procedures (i.e., inundation of the sample after loose moist tamping)
33 showed much less post-peak strength loss in the gold tailings than the undrained HCSS tests.
34 The current study investigated this discrepancy further by carrying out CV DSS tests under high
35 back pressures, undrained confined simple shear (CSS) tests and CV DSS tests after flushing
36 with carbon dioxide and with use of a 10 kPa back pressure. In all cases, the undrained (CSS)
37 tests or CV DSS tests with greater effort put towards saturation exhibited more pronounced
38 post-peak strength loss more consistent with the HCSS results and the critical state line. The
39 importance of these results on the estimation of tailings brittleness in engineering practice was
40 outlined.

41

42

43

44 **Introduction**

45 The direct simple shear (DSS) forms one of the key laboratory tests for the monotonic and cyclic
46 characterisation of soils. An important aspect of common DSS testing is the use of the
47 constant volume (CV) approach to reproduce undrained shearing conditions. There is strong
48 evidence that for saturated clays CV tests produce results indistinguishable from undrained
49 shearing (Dyvik et al. 1987). Further, for sands, it has been found that the CV technique allows
50 tests on dry sands to give the same results as saturated sands (Finn and Vaid 1977), with the
51 approach of testing near-dry specimens being advocated more generally for non-plastic soils
52 (Chen et al. 2022) and adopted in determination of the critical state line (CSL) by means of CV
53 DSS tests (Chen and Olson 2021). However, it is noted that for cyclic testing of clayey sands
54 this similitude between dry and saturated samples has been questioned (Monkul et al.
55 2015). Further, Fanni et al. (2022) showed that simple shear tests carried out in a hollow
56 cylinder torsional shear system (HCSS tests) showed far more brittle behaviour than CV DSS
57 tests of the same gold tailings at similar states, raising questions about the efficacy of
58 conventional saturation procedures.

59 Mine tailings, which comprise a wide range of material types and gradation from sands to clays,
60 often consisting predominantly of low plasticity silts, are increasingly being characterised using
61 CV DSS (e.g. Jefferies et al. 2019). Such tests are often prepared initially unsaturated using
62 loose moist tamping (LMT) and saturated through flushing, followed by keeping samples in
63 contact with water at atmospheric pressure. Current standards for CV DSS testing, and
64 specifically their requirements around sample saturation (or not) are as follows:

- 65 • Cyclic DSS testing (ASTM 2019): testing of dry or saturated samples are permitted, with
66 saturated samples to be “inundat[ed] with water”.

67 • Monotonic testing of fine grained soils (ASTM 2017), which does not include mention of
68 testing dry samples and also requires saturated samples to be “inundat[ed] with
69 water”.

70 As noted, the current standards either permit testing dry samples or mandate inundation.
71 However, as emphasised by the results of Monkul et al. (2015) and Fanni et al. (2022) there
72 remains uncertainty as to whether testing tailings silts dry, or even saturated through flushing
73 and then keeping the sample in contact with water at atmospheric pressure (i.e. “inundation”),
74 will ensure reliable results. The purpose of the current study is to expand on the work of Fanni
75 et al. to further investigate this issue and provide preliminary recommendations on means to
76 improve the monotonic response of LMT-prepared tailings silts in CV DSS tests.

77 **Materials and methods**

78 ***Materials***

79 The study was carried out on a low plasticity gold tailings previously used by Fanni et al. (2022),
80 having been characterised in a number of parallel studies (Reid et al. 2022; Ayala et al. 2022;
81 Fanni et al. 2024) and a low plasticity platinum tailings batch previously used for cyclic and
82 limited monotonic testing (Reid, Fanni, and Fourie 2024; Reid and Fanni 2024) with the critical
83 state line (CSL) obtained by Reid (2022). The index properties and CSL of the two materials are
84 summarised in Table 1.

85 ***Table 1: Index properties of soils tested in this study***

Property	Gold tailings	Platinum tailings
% < 75 µm	59	72
% < 38 µm	43	60
Liquid limit (%)	18	18
Plastic limit (%)	16	12
Plasticity Index	2	6
Specific Gravity (-)	2.78	3.04

86

87 ***Conventional CV DSS approach***

88 The first set of tests were carried out on gold tailings using “conventional” CV DSS testing to
89 confirm and expand the results of Fanni et al (2022). The tests carried out are summarised in
90 Table 1. Samples of 100mm diameter were prepared in an SGI DSS manufactured by GDS
91 Instruments. Active CV control was applied by means of a linear variable displacement
92 transducer mounted directly to the top cap, recording displacement on a smooth stainless
93 steel “track” mounted to the base of the bottom platen.

94 Samples were prepared using LMT, then placed within the DSS and a bedding load ranging from
95 25 - 500 kPa applied, with saturation bedding load used to target different loose densities as per
96 Reid et al. (2023). The samples were flushed from bottom to top with deionised water until
97 bubbles ceased exiting the top of the specimen and saturation collapse as tracked through
98 vertical displacement of the sample ceased. Both ends of the sample were then connected to
99 the deionised water reservoir placed at the same height as the sample - i.e., an approach to
100 saturation that is consistent with typical industry practice for the testing of moist tamped
101 tailings silts (Jefferies et al. 2019) and aligns with the requirement for “inundation” of samples
102 as per ASTM (2017). Samples were then consolidated to the target vertical effective stress,
103 prior to CV shearing at 5%/hour.

104 **Table 2: Summary of tests carried out on gold tailings in current study and Fanni et al. (2022)**

Test no.	Test type	Test source	Consolidated state				Shearing response			
			Vertical effective stress, σ'_{vc} (kPa)	Drained static shear stress, τ_{vh-c} (kPa)	Consol. void ratio, e_c	ψ_0	Peak τ_{vh} (kPa)	σ'_v at end of shear (kPa)	τ_{vh} at end of shear	I_B
G-DSS1	Inundate only	Fanni et al. (2022)	300	0	0.70	0.09	46	63	37	0.20
G-DSS2		Fanni et al. (2022)	300	0	0.70	0.09	47	61	37	0.20
G-DSS3		Fanni et al. (2022)	200	0	0.72	0.10	30	37	23	0.23
G-DSS4		Fanni et al. (2022)	496	0	0.69	0.11	76	117	59	0.22
G-DSS5		This study	200	0	0.72	0.10	28	45	22	0.23
G-CSS1	CSS	This study	202	0	0.71	0.09	29	3	5	0.81
G-DSS-500BP-1	500 kPa BP	This study	199	0	0.69	0.07	29	9	10	0.66

105

106 ***Confined simple shear***

107 A second set of tests on the gold tailings were carried out in a confined simple shear (CSS)
108 system, also manufactured by GDS, where lateral confinement is applied through a cell
109 pressure. This form of testing was outlined by Boulanger et al. (1993) and is commonly referred
110 to as “Berkeley-type” simple shear.

111 Samples were prepared using LMT within a membrane-lined split mould. Initial flushing was
112 carried out under an 50 kPa vertical bedding load with the split mould still in place. After
113 saturation collapse ceased, a suction of 20 kPa was applied to the sample using a
114 pressure/volume controller and the split mould was removed. This process allowed the sample
115 diameter to be accurately measured after saturation collapse, removing the most significant
116 uncertainty in calculating sample volume. The samples were then back pressure (BP) saturated
117 to 500 kPa, achieving a minimum B value of 0.95.

118 Consolidation was carried out to a vertical effective stress of 200 kPa while maintaining a K_0 of
119 0.5, then the drainage valves closed, and the sample sheared undrained at 5%/hour. During
120 shearing, the cell pressure was held constant.

121 ***CV DSS within CSS***

122 Another test on the gold tailings was carried out using the CV DSS approach with lateral
123 confinement provided by Teflon rings, but with the entire sample within the CSS system
124 enabling a BP of 500 kPa to be applied, resulting in a B value of 0.95.

125 ***CV DSS with small BP***

126 Given the promising results seen in the CSS and BP CV DSS tests on the gold tailings, another
127 form of CV DSS was carried out that could be performed in a conventional apparatus. This was
128 to produce a method of improved saturation and more realistic monotonic behaviour in a

129 system far more common in industry than the CSS. This set of tests was carried out on the
130 platinum tailings, with the test on this material summarised in Table 3.

131

132 **Table 3: Summary of Platinum tailings CV DSS tests carried out in this study and Reid and Fanni (2024)**

Test no.	Test type	Test source	Consolidated state				Shearing response			
			Vertical effective stress, σ'_{vc} (kPa)	Drained static shear stress, τ_{vh-c} (kPa)	Consol. void ratio, e_c	ψ_0	Peak τ_{vh} (kPa)	σ'_v at end of shear (kPa)	τ_{vh} at end of shear	I_B
P-IU-1	Inundate only	This study	200	0	0.72	0.10	29	32	16	0.44
P-IU-2		This study	200	0	0.75	0.13	27	32	16	0.39
P-IU-3		This study	200	0	0.79	0.17	25	24	11	0.56
P-IU-4		Reid and Fanni (2024)	250	25	0.73	0.12	45	52	26	0.43
P-IU-5		Reid and Fanni (2024)	250	25	0.73	0.11	46	50	26	0.43
P-IU-6		This study	250	25	0.70	0.09	45	47	25	0.44
P-IU-7		This study	500	0	0.66	0.09	76	97	54	0.29
P-SAT-1	CO2 flush and 10kPa BP	This study	250	25	0.67	0.05	45	25	13	0.72
P-SAT-2		This study	250	25	0.71	0.10	40	16	7	0.83
P-SAT-3		This study	500	0	0.66	0.08	71	29	16	0.77

133

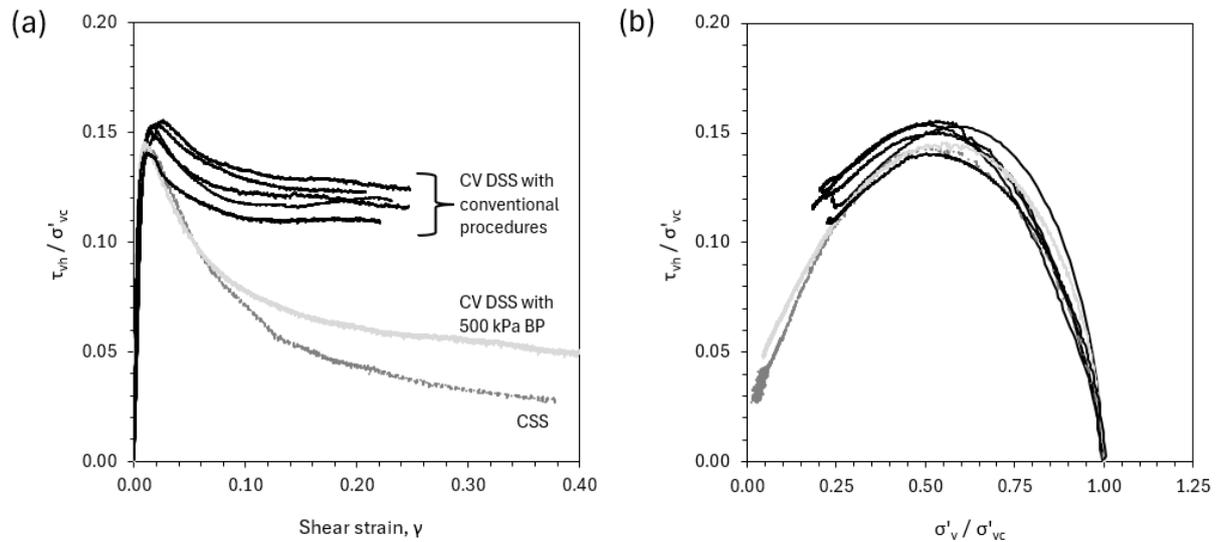
134

135 The modified procedure involved LMT preparation and application of a bedding load of 50 kPa,
136 followed by flushing with CO₂ and then deaired water. After bubbles had ceased exiting the
137 sample and saturation collapse was complete (same criteria as standard CV DSS tests
138 previously outlined), the reservoir of deaired water was placed 1m above the sample and
139 connected to both ends of the specimen to provide a 10 kPa BP. It was found that with use of
140 four o-rings to secure the membrane to the top platen, this magnitude of BP could be applied
141 without leakage.

142 **Results**

143 ***Gold tailings***

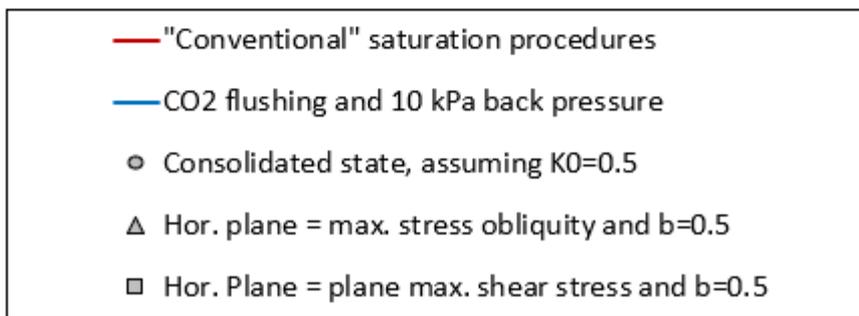
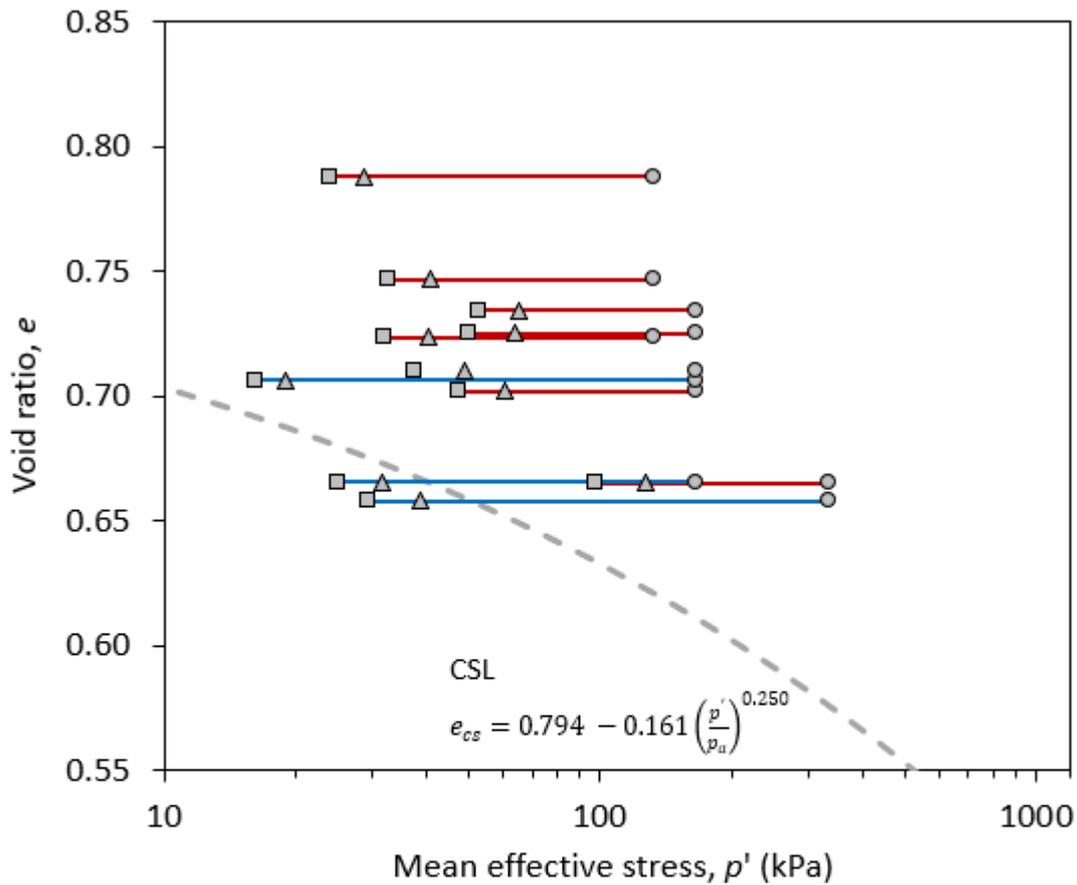
144 A summary of the gold tailings shearing behaviour as shear stress-strain and vertical effective
145 stress - shear stress plots are provided in Figure 1. The response of the CSS tests and CV DSS
146 test with BP is seen to be qualitatively different to those using standard saturation procedures
147 despite similar consolidated void ratios (e_c) - a far greater post-peak reduction in strength is
148 evident, consistent with the differences seen between CV DSS and HCSS in the previous
149 comparison presented by Fanni et al. (2022). All the conventional CV DSS tests appear to
150 achieve a steady state condition at high strain that would typically be assumed to represent a
151 critical state condition in such testing (e.g. Chen and Olson 2021). The CV DSS with back
152 pressure and CSS are still slightly softening at high strain yet may be approaching a critical
153 state condition.



154

155 **Figure 1: Summary of gold tailings CV DSS and CSS tests: (a) horizontal shear stress vs**
 156 **shear strain, (b) horizontal shear stress vs. vertical effective stress**

157 The results of the gold tailings tests are summarised as a state diagram in Figure 2, with the CSL
 158 obtained by Fanni et al. (2024) included for reference. Calculation of initial mean effective
 159 stress (p') assumed a K_0 of 0.5. In recognition of the uncertainty in calculating p' in the DSS at
 160 high strain, based on Chen and Olson (2021) maximum and minimum principal effective
 161 stresses σ'_1 and σ'_3 were calculated assuming: (i) that horizontal plane was equal to maximum
 162 obliquity or (ii) that horizontal plane was the plane of maximum shear stress. Intermediate
 163 principal effective stress σ'_2 was calculated assuming that the intermediate principal stress
 164 ratio at high strain was 0.5. Based on these assumptions, at high strain CSS and CV DSS with
 165 BP appear to tend much closer towards CSL for the gold tailings obtained from triaxial tests, in
 166 contrast to the conventional CV DSS tests. It is emphasised that for this gold tailings there is no
 167 evidence for a Lode angle dependency on CSL elevation in the compression plane (Fanni et al.
 168 2024), and thus no reason why shearing under simple shear loading should not tend towards
 169 the triaxial-determined CSL.



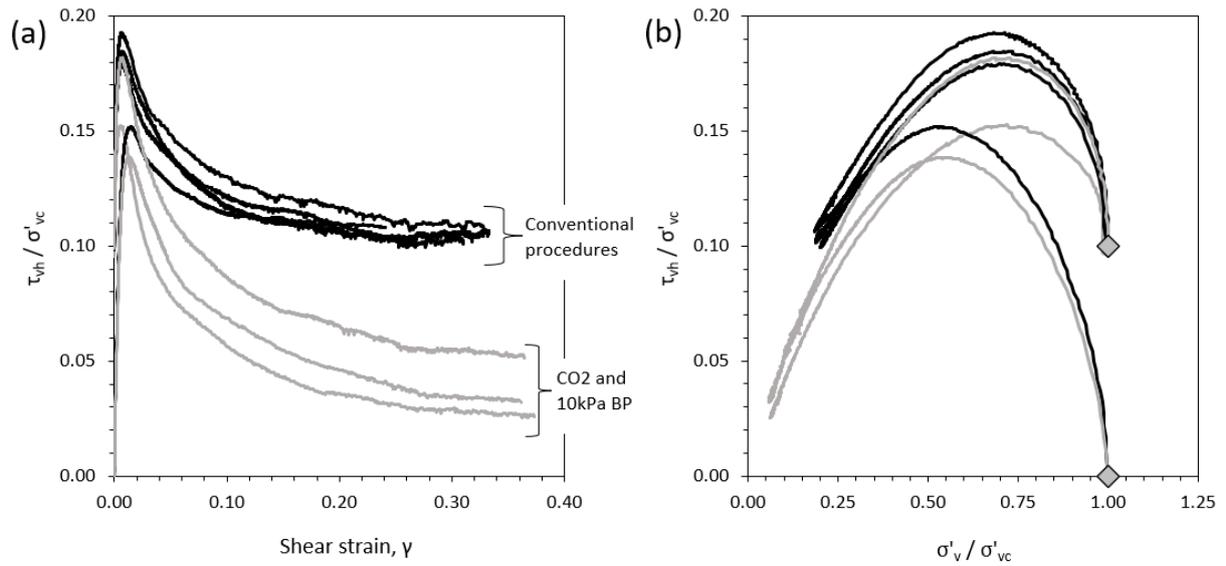
170

171 **Figure 2: State diagram of gold tailings CV DSS and CSS tests, with CSL Fanni et al. (2024)**

172 **Platinum tailings**

173 The shearing response of the platinum tailings is summarised in Figure 3. Like the gold tailings,
 174 the samples with BP exhibited a qualitatively more brittle response than conventional tests,
 175 with the end points of all tests appearing to represent a critical state condition.

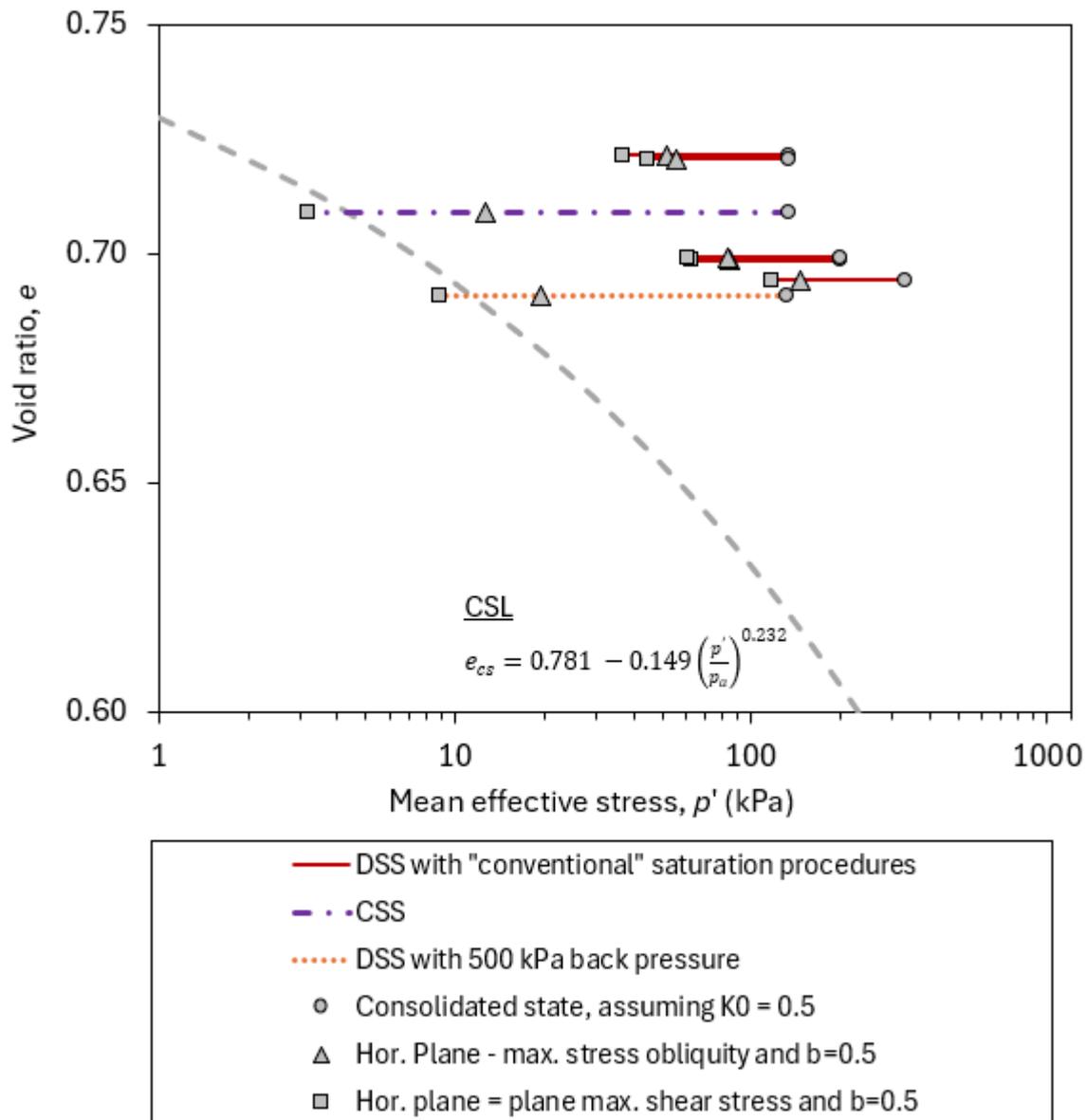
176



177

178 **Figure 3: Summary of platinum tailings CV DSS: (a) horizontal shear stress vs shear strain,**
 179 **(b) horizontal shear stress vs. vertical effective stress**

180 The platinum tailings tests are summarised as a state diagram in Figure 4 using the same
 181 assumptions as the previous gold tailings plot. The results are qualitatively similar - tests with
 182 CO2 flushing and 10 kPa BP align far better with the triaxial-inferred CSL than those using
 183 conventional saturation procedures.



184

185 **Figure 4: State diagram of platinum tailings CV DSS tests, with CSL from Reid (2022)**

186 As to the likely cause of the response seen, insufficient saturation of conventional tests may

187 mean some matric suction remains, and thus the samples are tending to a CSL at a higher

188 elevation (e.g. Wheeler and Sivakumar 1995). It is noted that predominantly silt tailings

189 prepared using LMT there is a greater potential for matric suction to exist and thus for suction-

190 hardening of the CSL than sands. Therefore, historic testing of dry sands, and the approaches

191 developed largely from the conclusions drawn therein, may not be useful guides as to the

192 importance of saturation in the CV DSS testing of tailings silts.

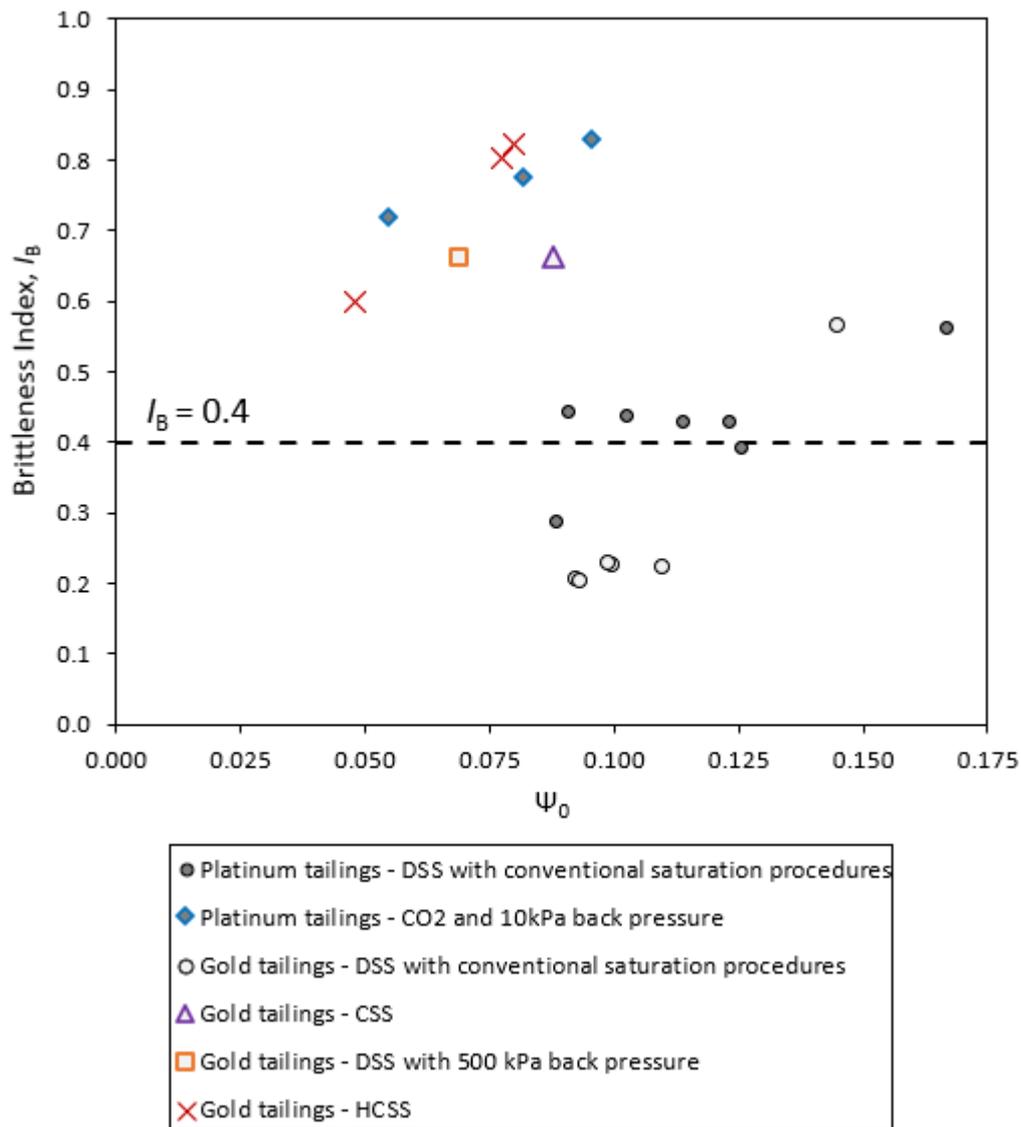
193 ***Brittleness index synthesis***

194 To examine the practical implications of use of conventional-saturation CV DSS on engineering
195 practice, Figure 5 presents a synthesis of all the results from the study as Brittleness Index
196 I_B (Bishop 1967) against consolidated state parameter, with Ψ_0 calculated adopting the same K_0
197 = 0.5 assumption as previous. For reference, I_B is calculated as:

198
$$I_B = \frac{\tau_p - \tau_r}{\tau_p}$$

199 Where τ_p and τ_r are peak and residual shear strength, respectively. An I_B value of 0.4 is also
200 highlighted based on the work of Robertson (2017) showing that historic examples of flow
201 liquefaction are generally of greater I_B . It can be seen from this synthesis that conventional CV
202 DSS tests exhibit far greater brittleness at a particular value of Ψ_0 , with these agreeing well with
203 the results of previous HCSS testing. Further, the lesser brittleness of loose samples in
204 conventional CV DSS could lead to potentially erroneous conclusions regarding the risk
205 associated with a particular deposit of tailings (e.g. ICOLD 2023).

206



207

208 **Figure 5: State diagram of platinum tailings CV DSS tests, with CSL from Reid (2022)**

209 **Conclusions**

210 The current study involved a more detailed investigation of previously-documented issues with
 211 the large strain monotonic CV DSS shearing response of LMT-prepared silt tailings. This was
 212 carried out by further conventional and back-pressure saturated CV DSS tests and CSS tests on
 213 a gold and platinum tailings. The results of the study can be summarised as follows:

- 214 • CV DSS tests saturated using methods that represent current standard/conventional
215 approaches (i.e. “inundation”) show less post-peak loss of strength and contractive
216 tendency than implied by their initial state.
- 217 • CSS and CV DSS tests with varying levels of BP saturation show a behaviour more
218 consistent with the sample initial states, tending much closer to the CSL.
- 219 • The results strongly suggest that a more accurate monotonic large-strain
220 characterisation of silt tailings is achieved in the CV DSS if greater efforts are made to
221 improve saturation compared to that specified in current testing standards and
222 common industry methods.
- 223 • The reduced I_B seen from conventional CV DSS tests could lead to erroneous
224 conclusions regarding the risk of flow liquefaction of loose tailings deposits.

225 **Data availability statement**

226 Data generated or analysed during this study are available in the OSF repository at
227 DOI 10.17605/OSF.IO/EU8PG, direct link:
228 https://osf.io/eu8pg/?view_only=aae417a84eba40a6879ace035120980a

229 **Material availability statement**

230 Material used for testing in this study are available from the corresponding author upon
231 reasonable request.

232 **References**

233 ASTM International. 2017. Standard Test Method for Consolidated Undrained Direct Simple
234 Shear Testing of Fine Grain Soils. West Conshohocken, PA: ASTM International.

235 ASTM International. 2019. Standard Test Method for Consolidated Undrained Cyclic Direct
236 Simple Shear Test under Constant Volume with Load Control or Displacement Control.
237 West Conshohocken, PA: ASTM International.

238 Ayala, J., Fourie, A., and Reid, D. 2022. Improved Cone Penetration Test Predictions of the State
239 Parameter of Loose Mine Tailings. *Canadian Geotechnical Journal* 59 (11): 1969–80.

240 Bishop, A. W. 1967. Progressive Failure-with Special Reference to the Mechanism Causing It.
241 *Proc. Geotech. Conf.*, Oslo 2:142–50.

242 Boulanger, R., Chan, C., Seed, H., Seed, R., and Sousa, J.. 1993. A Low-Compliance Bi-
243 Directional Cyclic Simple Shear Apparatus. *Geotechnical Testing Journal* 16(1).

244 Chen, J, Olson, S.M., Banerjee, S., Dewoolkar, M.M., and Dubief, Y.. 2022. Water Content of
245 Moist-Tamped Nonplastic Specimens for Constant-Volume Direct Simple Shear Testing.
246 *Geotechnical Testing Journal* 45 (2): 20210125.

247 Chen, J., and Olson, S.M. 2021. SHANSEP-Based Interpretation of Overconsolidation Effect on
248 Monotonic Shearing Resistance of Contractive Nonplastic Soils. *Journal of Geotechnical
249 and Geoenvironmental Engineering* 147 (12): 04021155.

250 Dyvik, R., Berre, T., Lacasse, S., and Raadim, B. 1987. Comparison of Truly Undrained and
251 Constant Volume Direct Simple Shear Tests. *Géotechnique* 37 (1): 3–10.

252 Fanni, R., Reid, D., and Fourie, A.. 2022. On Reliability of Inferring Liquefied Shear Strengths
253 from Simple Shear Testing. *Soils and Foundations* 62 (3): 101151.

254 Fanni, R., Reid, D., Fourie, A. 2024. Drained and Undrained Behaviour of a Sandy Silt Gold
255 Tailings under General Multiaxial Conditions. *Géotechnique*. Ahead of print.
256 <https://doi.org/10.1680/jgeot.23.00186>.

257 Finn, W. D. L., and Y. P. Vaid. 1977. Liquefaction Potential from Drained Constant Volume cyclic
258 Simple Shear Tests. In *Proceedings of the Sixth World Conference on Earthquake*
259 *Engineering*, 2157–62.

260 ICOLD. 2023. Tailings Dam Safety. Bulletin 194. Paris, France: ICOLD.

261 Jefferies, M., Morgenstern, N.R., Van Zyl, D.V., and Wates, J. 2019. Report on NTSF
262 Embankment Failure, Cadia Valley Operations, for Ashurst Australia. Australia, Ashurst.

263 Monkul, M.M., Gültekin, C., Gülver, M., Akın, O., and Eseller-Bayat, E. 2015. Estimation of
264 Liquefaction Potential from Dry and Saturated Sandy Soils under Drained Constant
265 Volume Cyclic Simple Shear Loading. *Soil Dynamics and Earthquake Engineering* 75
266 (August):27–36.

267 Morgenstern, N. R., Vick, S.G., and Van Zyl, D.V. 2015. Report on Mount Polley Tailings Storage
268 Facility Breach. Report of Independent Expert Engineering Investigation and Review Panel.
269 Prepared on behalf of the Government of British Columbia and the Williams Lake and
270 Soda Creek Indian Bands.

271 Reid, D. 2022. Slope Stress Prediction Benchmarking Exercise: Triaxial Calibration Data. Slope
272 Stress Prediction Benchmarking Exercise: Triaxial Calibration Data.
273 <https://doi.org/10.17605/OSF.IO/RTJ3P>.

274 Reid, D., Fanni, R., and Fourie, A.B. 2024. Drained Static Bias Effects on Very Loose Silt Tailings.
275 *Japanese Geotechnical Society Special Publication 10 (27)*: 995–1000.

276 Reid, D., and Fanni, R. 2024. Discussion of ‘Flow Failure Assessments for Dams and
277 Embankments’ by T.D Stark, J. Lin and H. Jung. *Canadian Geotechnical Journal*. Under
278 review.

279 Reid, D., Fanni, R., and Fourie, A. 2022. Effect of Tamping Conditions on the Shear Strength of
280 Tailings. *International Journal of Geomechanics* 22 (3): 04021288.

- 281 Reid, D., Urbina, F., Tiwari, B., Fanni, R., Smith, K., and Fourie, A. 2023. Effect of Saturation
282 Confining Pressure on Accessible Densities and Shear Behaviour of a Sandy Silt Tailings.
283 *Géotechnique Letters* 13 (2): 1–5.
- 284 Robertson, P. K. 2017. Evaluation of Flow Liquefaction: Influence of High Stresses. *PBD III*,
285 *Earthquake Geotechnical Engineering*. Vancouver, B.C.
- 286 Wheeler, S. J., and Sivakumar, V.. 1995. An Elasto-Plastic Critical State Framework for
287 Unsaturated Soil. *Géotechnique* 45 (1): 35–53.