Canadian Geotechnical Journal

Discussion

Discussion of "Mechanism of failure of the Mount Polley Tailings Storage Facility"

David Reid, **Riccardo Fanni**, and **Andy Fourie**

Department of Civil Environmental and Mining Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia

Corresponding author: **David Reid** (email: david.reid@uwa.edu.au)

Introduction

The authors present an interesting and detailed examination of the failure mechanism of the Mount Polley Tailings Storage Facility (TSF). Indeed, such rigorous modelling seems likely to contribute to increased efforts across the industry to better simulate physical processes within and below TSFs. Our discussion focusses on a particular aspect of the behaviour of the Upper Glaciolacustrine Unit (GLU) that appears to have been assumed by the authors—i.e., that a particular element or shear band of the Upper GLU will, once having undergone post-peak strain weakening, "stay" weakened in the future. For example, the authors indicate plastic shear strains having occurred in the Upper GLU at least as early as Stage 7, some 2 years before the eventual failure.

The current state of knowledge regarding some fundamental aspects of the strain weakening and remoulding processes of clays seems to suffer from uncertainty as noted by Thakur et al. (2014) and Zabolotnii (2020, pp. 357–358). For drained strain weakening there seems to be evidence of negligible healing following post-peak strain weaking (Mesri and Huvaj-Sarihan 2012), consistent with that form of behaviour being dominated by alignment of clay particles. Specific to the question posed by this discussion, on the behaviour of elements having undergone post-peak strain weakening through undrained shearing that features significant shear-induced pore pressure generation, the discussers are unaware of any evidence in the literature on this topic. It seems plausible to the discussers that the dissipation of such shear-induced pore pressures over time could lead to some strength recovery, particularly given the thin shear bands where strains appear to have been concentrated in the Upper GLU and thus the short drainage path length. Therefore, the purpose of this discussion is to examine this issue further with some direct simple shear (DSS) tests on clay.

Direct simple shear testing

The discussers carried out a series of DSS tests on a kaolin clay produced by Suva Minerals of Australia, having liquid limit of 74%, plasticity index of 30%, and clay-sized fraction (<2 μm) of 35%. This soil was selected as being a reasonable proxy of clayey soil behaviour, with respect to remoulding processes at high strains and the potential for "permanent" damage from alignment of clay particles during large strains (Lupini et al. 1981).

A first set of tests carried out to investigate the potential post-strain weaking behaviour were multistage DSS, using similar procedures to those adopted for such tests on the Upper GLU as used by the authors to develop their strength profile for numerical analyses.

1) Consolidation to target vertical effective stresses (200, 400, 600 kPa) without drained bias ($\alpha_c = 0$).
2) "Multistage" monotonic constant volume (CV) shearing at an approximate shearing rate of 5% per hour, where the direction of shearing was reversed repeatedly to allow shearing to high displacements/strains despite the horizontal displacement limits of the DSS apparatus.

In addition to the conventional form of testing outlined above, the following additional stages were carried out to estimate the behaviour of the soil should shear-induced pore pressures be allowed to dissipate and thus reconsolidation occurs in situ.

3) The final multistage shearing movement was set to finish at zero displacement—i.e., near the commencement of the initial CV shearing process in terms of horizontal displacement.
4) The specimen was then reconsolidated to the initial consolidated vertical effective stress under zero shear stress, with the specimen ramped to these two targets over a period of 15 min.
5) After a subsequent consolidation period of 120 min, CV shearing was recommenced from this stage at approximately 5% per hour.

A summary of the three multistage tests carried out is included in Table 1. The test protocol of shearing under CV conditions and then reconsolidating to initial effective stresses to

Table 1. Summary of DSS tests.

Test	Test type	Consolidated vertical effective stress, σ'_{vc}	Consolidated void ratio, e_c	Initial CV shearing, peak s_u/σ'_{vc}	Consolidated void ratio, after reconsolidation	Post-reconsolidation CV shearing, peak s_u/σ'_{vc}
MS-1	Multistage	200	1.65	0.19	1.48	0.21
MS-2		400	1.39	0.18	1.22	0.19
MS-3		600	1.29	0.18	1.14	0.19
Bias-1	Bias	400	1.36	0.21	1.31	0.24
Bias-2		600	1.24	0.21	1.19	0.23

Fig. 1. Undrained strength ratio vs. shear strain results for test MS-1, showing both "conventional" multistage shearing and subsequent shearing after reconsolidation process.

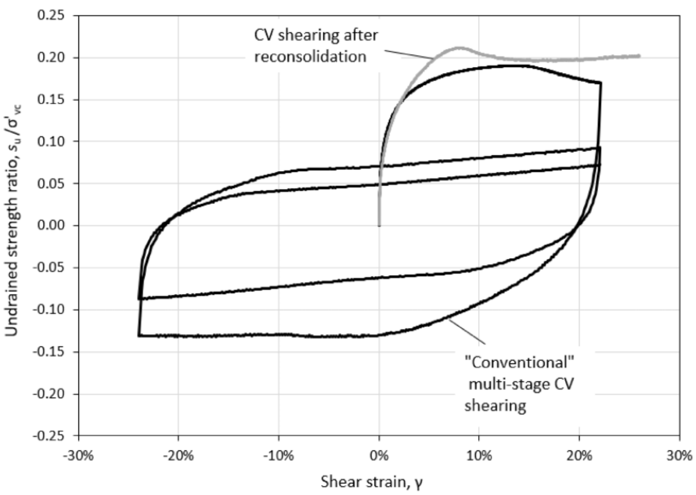
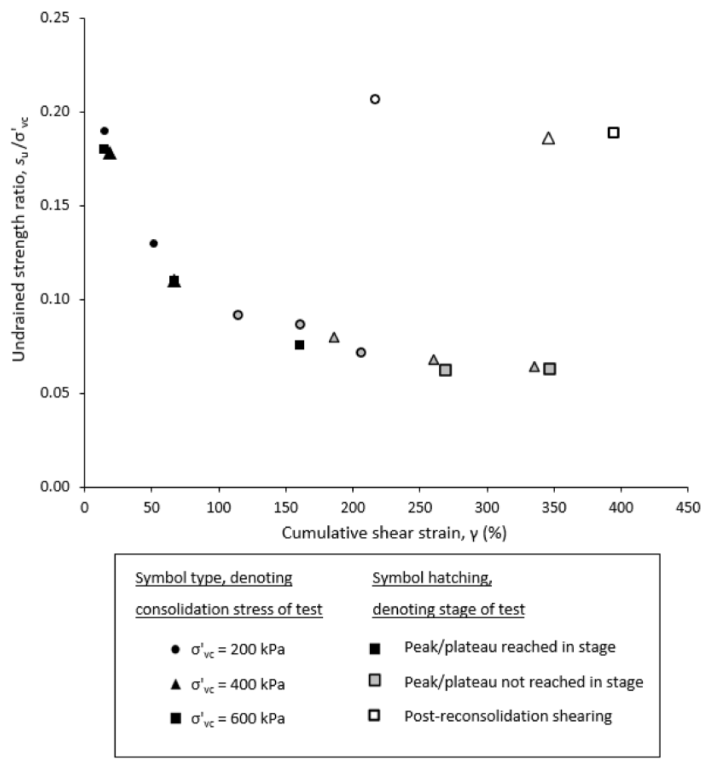


Fig. 2. Synthesis of tests MS-1, MS-2, and MS-3, showing the maximum undrained strength ratio against cumulative shear strain for the test. The results of both the conventional multistage shearing cycles, and subsequent shearing after reconsolidation, are shown.



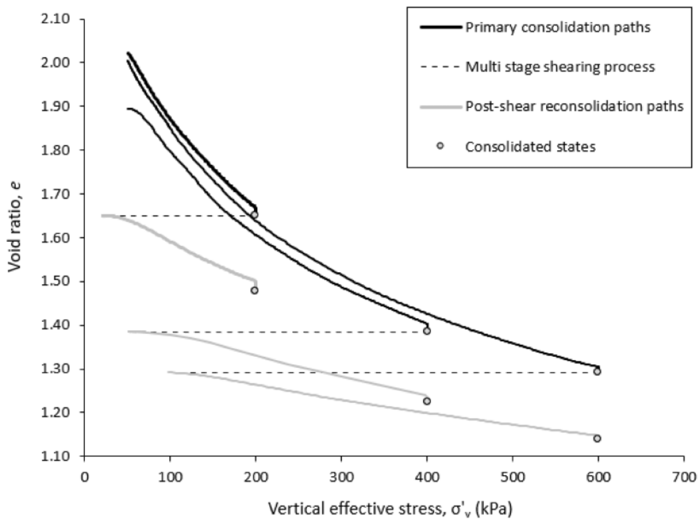
investigate subsequent behaviour shares similarities with the tests of Price et al. (2017), which were used to investigate the effects of reconsolidation on the cyclic behaviour of silts. It is also noted that although shear-induced pore pressures do not actually occur within specimens during CV DSS shearing, the equivalence between the shearing response and excess pore pressure development in truly undrained tests (Dyvik et al. 1987) is such that CV techniques are suitable for the investigation carried out.

The shearing behaviour of test MS-1 is presented in Fig. 1, with the "loops" from the reversing shear episodes evident, and a typical decay in strength and stiffness with increasing shear. Also common to such testing is the lack of a defined peak/plateau in some shearing stages as strains accumulate and stiffness decreases, thus raising a question around what the relevant strength at such strains is—an issue somewhat beyond the scope of the current discussion. Finally, the post-reconsolidating shearing is presented, showing a higher peak strength than the initial CV shearing.

Figure 2 summarizes all the multistage tests as the maximum strength ratio obtained in each shearing stage against the cumulative shear strain at that point, which shows a similar decay in strength for all three tests. Also consistent is the increase in shear strength after reconsolidation. The increase in density during reconsolidation is illustrated in Fig. 3 where the consolidation behaviour of each multistage tests is presented, showing consistent virgin consolidation of all three tests, the reduction in vertical effective stress during multistage CV shearing, and finally the increase in density during reconsolidation.

While the multistage DSS may be useful for examining large strain strength reduction and remoulding processes, it is not a perfect analogue of what would occur in the Upper GLU under the combination of events relevant to this discussion. For example, multistage tests involve shearing in two directions owing to the strain limitations of the DSS, distinct from unidirectional shearing that would occur in the Upper GLU (or below any slope) under static loading, and during the reconsolidation process the specimen is not exposed to shear stress, likely inconsistent with what would oc-

Fig. 3. Consolidation behaviour of multistage tests under initial consolidation, multistage shearing, and subsequent reconsolidation.



cur in situ. Therefore, an additional program of two tests was carried out to further examine the potential for recovery of strength from reconsolidation.

- Consolidation was carried out under a drained static bias ($\alpha_c = 0.15$), to better represent stress conditions below a slope.
- Monotonic CV shearing at 5% per hour was then carried out until appreciable post-peak strain weakening had occurred.
- The specimen was then reconsolidated to the original consolidated vertical effective stress, with the shear stress during reconsolidation being held at the final value recorded during the preceding CV shear stage. This simulates, as best as the discussers can conceive, conditions in zones of the GLU that have undergone post-peak weakening but are then allowed to dissipate shear-induced pore pressures over time, all while bearing some magnitude of shear stress owing to the geometry of the overlying embankment (which has not failed at this point, either in the model or in the idealized reproduction of the model attempted in the DSS element test procedure).
- Monotonic CV shearing was then recommenced until the displacement limits of the DSS apparatus were reached.

The results of test Bias-2 are presented in Fig. 4, showing all the test stages as undrained strength ratio against horizontal displacement. This format is used to show the multiple episodes of CV shearing in the context of the strain limitations of the device. Like the multistage tests, a recovery in undrained strength is seen following reconsolidation. This recovery is of a lesser proportional magnitude (i.e., less increase from the strain weakened condition) as less post-peak strain weakening had occurred in the initial CV shearing in a single direction. Both bias tests are summarized in Fig. 5 in a more conventional format of undrained strength ratio against shear strain, where shear strain is taken as starting from the beginning of each episode of CV shearing. This shows that the reconsolidation process has led to an overall increase in shear strength and an initially stiffer shearing response, both consistent with an increase in the specimen's density from reconsolidation.

The discussers do not view the results presented herein as a definitive assessment of the potential for healing of post-peak undrained strain weakening/remoulding of clayey soils. However, the consistency of the results of both types of test does suggest that at least some recovery of undrained shear strength with the dissipation of shear-induced pore pressures

Fig. 4. Undrained strength ratio against horizontal displacement for test Bias-2, illustrating consolidation to a drained static bias, initial CV shearing, reconsolidation, and CV shearing after reconsolidation. All test stages presented against horizontal displacement, to present shearing behaviour in the context of displacement limits of DSS apparatus.

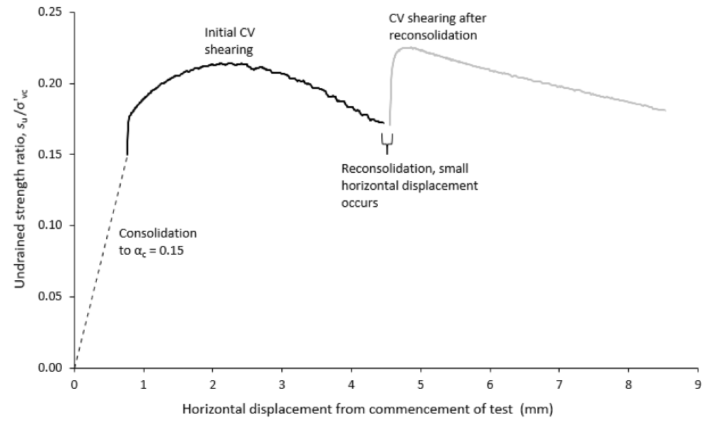
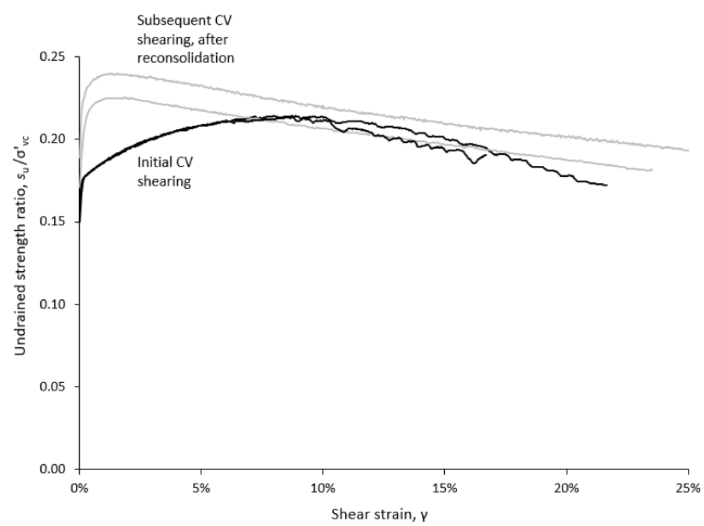


Fig. 5. Undrained strength ratio against horizontal displacement for test Bias-3, illustrating consolidation to a drained static bias, initial CV shearing, reconsolidation, and CV shearing after reconsolidation. All test stages presented against horizontal displacement, to present shearing behaviour in the context of displacement limits of DSS apparatus.



appears possible. While unlikely to be relevant to the Mount Polley analyses presented by the authors (their view on this would be of great interest), perhaps there may be cases where these issues may play a greater role. As such, the discussers view this as a productive future area of investigation both for element tests and numerical analyses.

Article information

History dates

Received: 20 August 2022
Accepted: 14 December 2022
Accepted manuscript online: 17 May 2023
Version of record online: 17 May 2023

Notes

Article appears in Canadian Geotechnical Journal, **59**. doi:10.1139/cgj-2021-0036.

Copyright

Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Author information

Author ORCIDs

David Reid https://orcid.org/0000-0002-1867-1676

Author contributions

Conceptualization: DR, RF, AF
Investigation: DR
Writing – original draft: DR
Writing – review & editing: RF, AF

Competing interests

The authors declare there are no competing interests.

Funding information

There are no funders to report for this submission.

References

Dyvik, R., Berre, T., Lacasse, S., and Raadim, B. 1987. Comparison of truly undrained and constant volume direct simple shear tests. Géotechnique, **37**: 3–10. doi:10.1680/geot.1987.37.1.3.

Lupini, J.F., Skinner, A.E., and Vaughan, P.R. 1981. The drained residual strength of cohesive soils. Géotechnique, **31**: 181–213. doi:10.1680/geot.1981.31.2.181.

Mesri, G., and Huvaj-Sarihan, N. 2012. Residual shear strength measured by laboratory tests and mobilized in landslides. Journal of Geotechnical and Geoenvironmental Engineering, **138**: 585–593. doi:10.1061/(ASCE)GT.1943-5606.0000624.

Price, A.B., DeJong, J.T., and Boulanger, R.W. 2017. Cyclic loading response of silt with multiple loading events. Journal of Geotechnical and Geoenvironmental Engineering, **143**: 04017080. doi:10.1061/(ASCE)GT.1943-5606.0001759.

Thakur, V., Jostad, H.P., Amundsen, H.A., and Degago, S.A. 2014. How well do we understand the undrained strain softening. *Edited by* L'Heureux, Locat, Leroueil, Demers, and Locat Landslides in Sensitive Clays. Advances in Natural and Technological Hazards Research. **Vol. 36**, Springer, Dordrecht. doi:10.1007/978-94-007-7079-9_23.

Zabolotnii, E. 2020. Three-dimensional slope stability effects in the failure at the Mount Polley Tailings Storage Facility. University of Alberta.