Documentation of a "Class A" prediction on the effect of a dry-wet cycle on runout in a physical model of hard rock tailings

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Abstract: The use of desiccation to strengthen mine tailings by transforming their undrained behaviour from relatively contractive to relatively dilative is a technique of long standing in many jurisdictions around the world. Practice in application has been governed by rules of thumb, such as drying to the shrinkage limit; however, the authors have recently tried to apply modern unsaturated soils theory to analyze the role of desiccation in strength gain. In the present paper, stress history effects of desiccation are handled by adjusting the initial size of the yield surface in the Norsand model, which in turn is employed in a large deformation simulation of tailings runout. Specifically, this paper reports on design of the physical model and the analysis thereof using material point method. Here the physical model is designed but not undertaken, allowing this paper to document the large deformation analysis as a Class A prediction.

Introduction

Desiccation has a long tradition in tailing management as a means to strengthen tailings through stress history effects; in particular, the rule of thumb that tailings desiccated to the shrinkage limit will be rendered dilative crops up in several well-known documents, for example the ICOLD (2001) report summarizing tailings dam failures. However, analysis of this observed increase in dilation using unsaturated soils mechanics concepts has not been undertaken, until recently. Qi et al. (2020) applied the Modified Steady State Model and the Glasgow Coupled Model (MSSM and GCM) to consolidation analysis of layered tailings deposition where desiccation occurs, using mesoscale physical models for model testing (Daliri et al. 2016;2014); Mofrad et al. (2023) has begun to extend this work to shear behaviour and to simulating the extent of dilation imparted by desiccation in element tests.

This paper further extends this work to the implications of desiccation to failure consequence, and the potential runout from containment breach. Runout post-breach is a subject of large importance in the tailings community, where tailings dams fail at a rate from one to two order of magnitude larges than water dams (Rana et al. 2021). To this end, the authors have employed large deformation modelling using the MPM technique and an effective stress constitutive model commonly used for hard rock tailings (Norsand) to simulate tailings flows in a 1 m high by 1 m long by 0.5 m wide physical model of tailings, where failure is initiated by removal of a gate. Using single point analysis to determine the effect of desiccation on the yield surface, the authors have predicted the behaviour for the deposit, with and without desiccation history. Both deposits are saturated or at least register only positive-pore pressures after rewetting, but one is dried to ~ 50 kPa matric suction before rewetting, the other never desiccated. Here we present the Class A predictions before the experiments have been conducted, which will be conducted in May leading up to the conference. We anticipate explaining at the conference just how "off" our predictions are, but also anticipate reporting some insights afforded by this comparison.

Methods

Experimental – tailings characterization

The tailings were obtained from field sampling at an undisclosed site in Northern Canada. They are typical of hard rock tailings, showing low plasticity (plastic limit and liquid limits of 20% and 23%) and grain size distribution in the sand to silt range. The tailings are non-acid generating. When prepared at water contents close to their deposition water content (~ 55%) they consolidate to water contents of 28%, at which point they have a yield stress (by slump test Pashias et al, 1996) of 200 Pa, which is again, not atypical (Henriquez and Simms 2009). The SWCC as evaluated by axis-translation and a WPT4 dewpoint hydrometer is show in Figure 1, showing an AEV ~ 50 kPa, again in the expected range for hard rock tailings (Bussiere 2007).

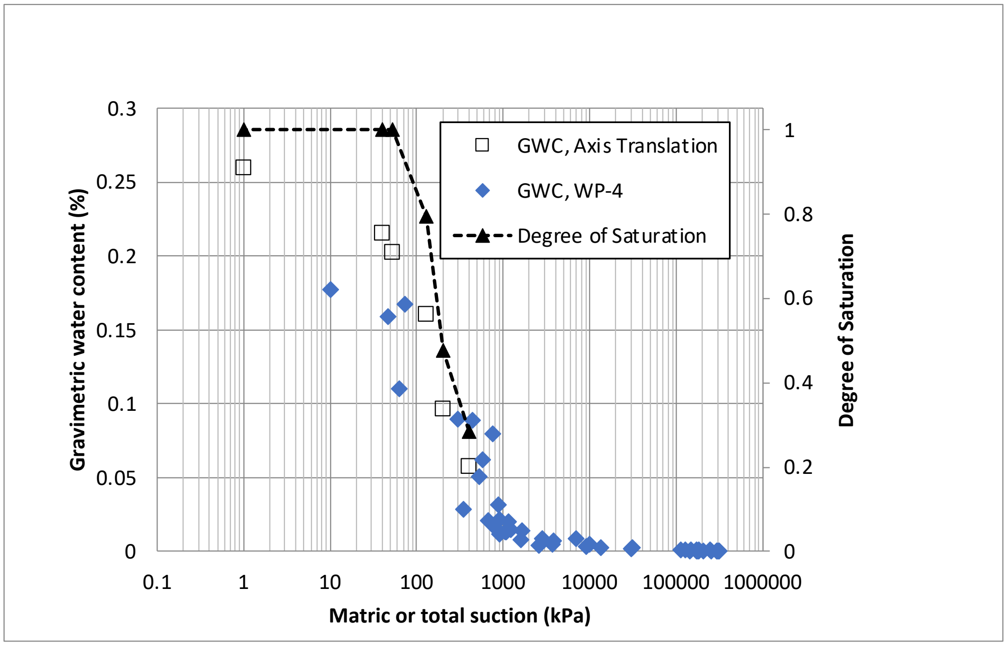

Figure 1: Tailings SWCC – measurements made by axis-translation (< 400 kPa matric suction) and WPT4 Dewpoint Hygrometer (> 500 kPa total suction)

The shear strength behaviour is characterized by the same methodology of Daliri et al. (2014) and Daliri et al. (2016); where simple shear tests are dried in the simple shear mold, before rewetting and consolidation. The results presented in Figure 2 show a sample that has been dried to ~ 30 kPa matric suction, the value is an estimate as a tensiometer is inserted in a duplicate sample. The influence on desiccation is clear, as despite the slightly higher void ratio of the desiccated sample (due to additional stiffness, reducing volume change during consolidation to 50 kPa), the sample exhibits greater dilation. Different from the tests reported by Daliri et al. (2014), the sample never dried is slightly dilative, as opposed to contractive. The grain size and AEV of these tailings is somewhat coarser and lower than the tailings tested by Daliri.

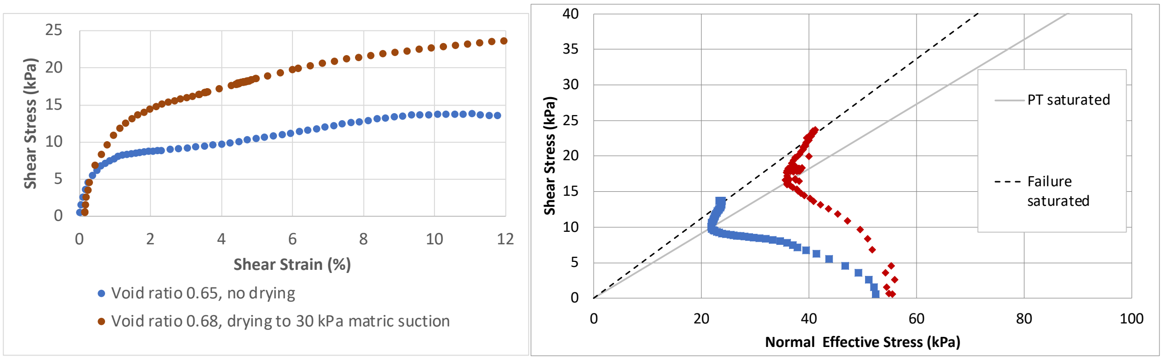

Figure 2: Undrained simple shear response of the tailings, one test dried to ~ 30 kPa matric suction before rewetting and consolidation

Experimental – design of flume experiment

The flume experiments will be conducted in an existing 8 m long by 1.5 m high by 0.5 m wide flume, constructed out of polycarbonate panels with a steel frame. The tailings will be initially deposited to a height of 1 m in a 0.5 m long reservoir at one end of the flume, constrained by a gate. There is a gate mechanism operated by a moto that will remove the gate out of the way of the tailings in 0.4 seconds.

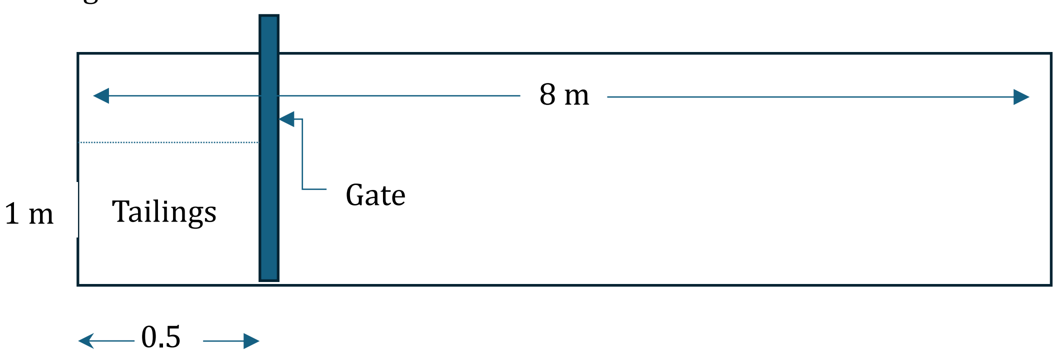

Figure 3: Profile view of flume, location of gate, height of tailings reservoir. Flume is 0.5 m wide.

The tailings will be deposited at a water content of ~ 38% at a slightly higher elevation than the target depth (~1.1 m). This will allow the tailings to -self-weight consolidate, where the bottom 2/3rd's of the tailings will reach a consistent void ratio of ~0.85. Two pore-water pressure / matric suctions sensors (T5 tensiometers manufactured by UMS) will be installed at 0.05 m from the bottom, and one inserted into the top of the tailings after self-weight consolidation is complete. Bleed water retained on the top of the tailings will be removed. In Test A, the gate will be lifted immediately after consolidation. In Test B, the tailings will be allowed to dry in the ambient conditions in the laboratory (from experience in our laboratory, a potential evaporation of ~ 5 mm/ day can be generated in May). Based on a target suction of ~ 50kPa, and using SWCC and simple mass-volume relationships, we need to remove about 5 cm of water through evaporation. Assuming uniform removal of water, this would be 10 days, so we believe achieving 50 kPa matric suction at the bottom (as monitored by the bottom T5 tensiometer) will certainly be achievable under a month. After 50 kPa is achieved, water will be slowly added to the surface of tailings, to gently bring the measure pore-water pressures to positive values. Two miniature vanes will be used to estimate the shear strength at two depths.

The lifting of the gate, and subsequent runout of the tailings (if any), will be monitored using video cameras, mounted from the side, giving a top view, and from the end of flume looking horizontally back towards the gate. After runout, the strength of the tailings will be estimated using a fall-cone, starting at the toe and moving back – this is because of our groups experience noting that post-runout consolidation occurs very quickly at the toe. Water contents by oven-drying will also be obtained.

Multiple configurations (different heights) of the experiment with no drying will be conducted, this will help interpret any sidewall influence on the runout

Experimental- numerical

We employ a version of the Anura 3D MPM software, will some improvements made by Martinelli and Galavi (2022) that allow for enhanced stability, permitting simulations without artificial damping and the use of more complex constitutive models, such as Norsand. Here we will employ undrained simulations using Mohr-Coulomb, Mohr-Coulomb strain softening, and Norsand. Undrained total strength parameters will be obtained from the vane strength tests noted above, while elastic parameters and plasticity parameters can be estimated by calibration of Norsand to the simple shear tests.

An example simulation using MPM and Mohr-Coulomb constitutive mode, with simulation of gate lifting, in shown in Figure 4. This simulation was calibrated to a real flume test using a natural soft clay, where the gate is lifted in the simulation at the same rate as measured in the real test. This test is 0.30 m high, with initial shear strength of 1.2 kPa and 0.3 kPa residual, where strength is degraded in the model as a function of plastic deviatoric strain.

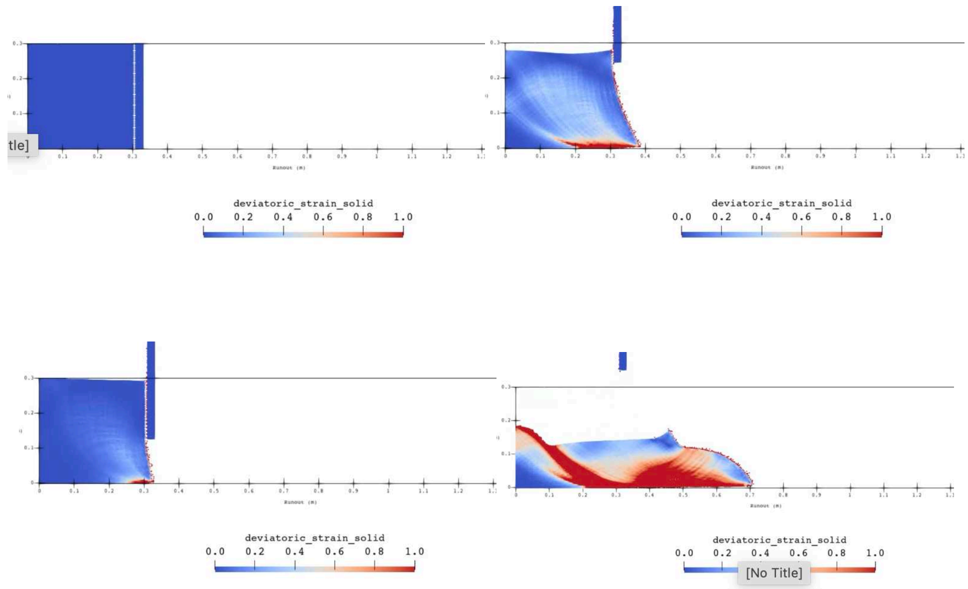

Figure 4: Example of Mohr-Coulomb strain softening simulation with gate lifting

How desiccation is incorporated into the initial condition in these saturated only large deformation models

In the simpler constitutive models (Mohr-Coulomb) the effect of desiccation is factored into changes in the peak strength, which will be measured by the vane tests prior to lifting the gate. For Norsand, the effect of desiccation is principally handled by i) increasing the size of the initial yield surface and ii) the ratio of p and q will change due to the stress history of isotropic desiccation. The degree of each of these effects depends on the assumed hydromechanical coupling that occurs during the increase in matric suction. Mofrad et al. (2023) has developed coupling strategies for shear strength models developed for sand (Norsand, Wan and Guo), Here the authors simply calibrate the same saturated Norsand models with identical parameters (excepting the slight difference in void ratio), where the only difference is the initial size of the yield surface (due to matric suction of 30 kPa) before consolidation to 50kPa. In Figure 5 and 6, one can see that most of the effect of the initial drying path (isotropic loading to 30 kPa) is erased by plastic yielding on the inner cap. The inner cap in Norsand is imposed to maintain a maximum degree of dilation and to preserve normality. The authors wonder whether this softening is physical or well-calibrated for this type of problem and this is an issue for further investigation.

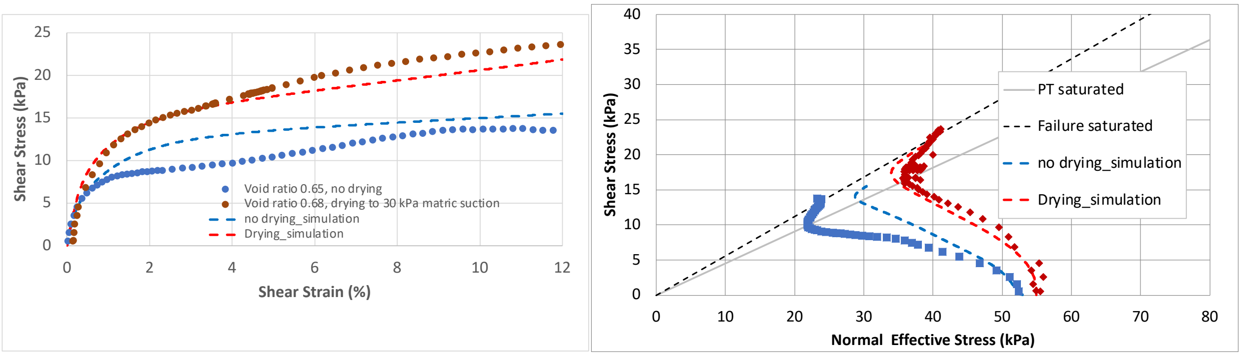

Figure 5: Fitting simple shear test with Norsand, both tests with identical parameters.

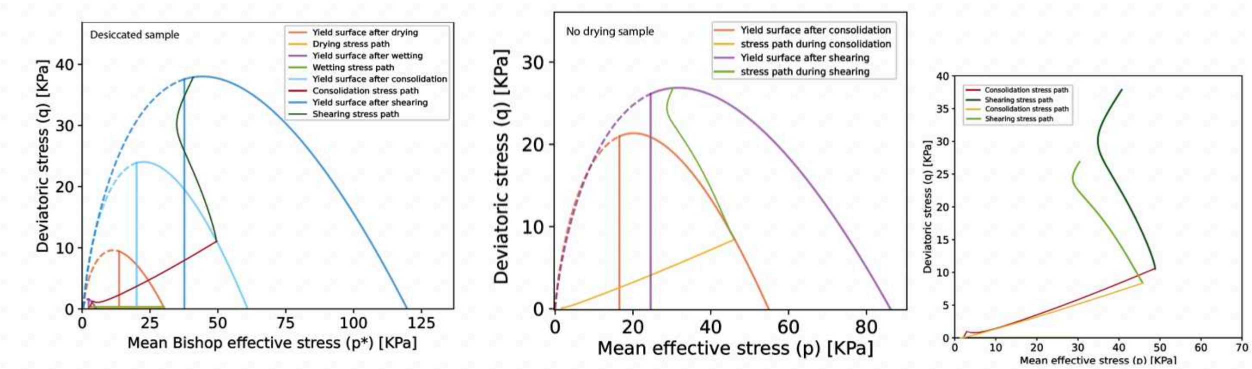

Figure 6:. The stress paths of the two samples as simulated with Norsand, showing changes in the yield surface through initial isotropic loading (drying), yielding during rewetting (unloading), hardening during consolidation, and finally shearing.

However, inducing such an over-consolidated state into the MPM model is non-trivial. For the prediction shown in Figure 8 we induce a mechanical consolidation to generate the same size of yield surface as we would have after 50 kPa desiccation-rewetting Here, a large mechanical load is applied at the surface during the first phase, so as to generate 50 kPa effective stress at the bottom of the sample. In this first phase the gate does not move. Subsequently, the load is removed, generating a stress state inside the yield surface. When the gate is lifted, the sample will be in an over-consolidated state, though somewhat different than the state expected from desiccation-rewetting stress path.

The stress path for the experiment is different from the stress path in the simple shear experiments. There will be substantially larger initial self-weight consolidation in the 1 m tall deposit than in the very thin simple shear sample. Also, there is no consolidation step in the flume experiment following wetting.

The prediction

Figures 7 and 8 show the prediction of runout with and without prior matric suction application of 50kPa. The difference is quite stark, there being no runout with application of the dry/wet cycle. This is perhaps arguably a trivial result, as we do expect a substantial increase in strength due to the dry/wet cycle. More interesting will be the comparison of vane strengths at different depths from what is expected from theory.

Additionally, we have performed flume experiments where we load the deposit at the surface gradually with weights until it fails – we have the capacity to simulate this in the MPM software. If indeed the tailings for the dry/wet experiment remain standing, we will perform this additional step.

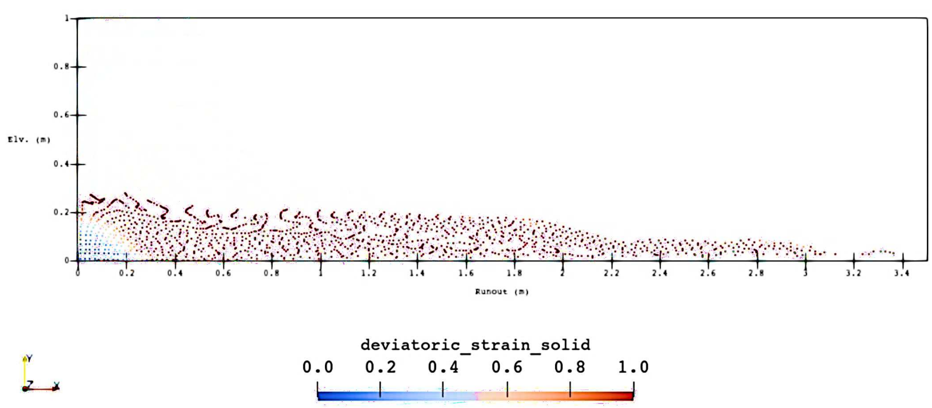

Figure 7: Predicted runout for “no drying” Test A

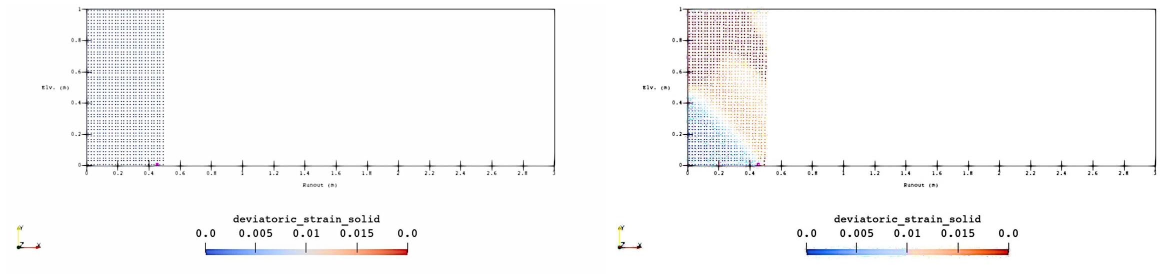

Figure 8: Predicted runout for Test B, with drying and rewetting step

Summary and Conclusions

A Class A prediction of tailings runout is made for a 1 m high by 0.5 m long by 0.5 m wide deposit failed in a rectangular flume through a gate lifting mechanism. Using Norsand calibrated to two simple shear tests, predictions are made for i) A 1 m deposit allowed to self-weight consolidate before lifting of the gate, and ii) the same deposit, where the sample is allowed to dry until a maximum matric suction of 50 kPa is measured near the bottom, following by a rewetting step before gate lifting. The prediction shows that (i) will experience runout to ~ 3 m, while (ii) will not fail. The deposits, pre and post failure, will be interrogated by vane and fall-cone testing, as well as water content analyses. If indeed (ii) does not fail upon gate lifting, weight will be slowing added until failure occurs. The flume experiments will be conducted in May, and these results and their analyses will be presented at the conference.

References

[1] Bussière B. 2007. Colloquium 2004: Hydrogeotechnical properties of hard rock tailings from metal mines and emerging geoenvironmental disposal approaches. Canadian Geotechnical Journal, 44(9): 1019–1052.

[2] Rana, N.W., Ghahramani, N., Evans, S.G., McDougall, S., Small, A., and Take, A.W. 2021. Catastrophic mass flows resulting from tailings impoundment failures. *Engineering Geology*, doi.org/10.1016/j.enggeo.2021.106262.

[3] Daliri F., Kim H., Simms P., and Sivathayalan S. 2014. Impact of desiccation on monotonic and cyclic shear strength of thickened gold tailings. *Journal of Geotechnical and Geoenvironmental Engineering*, 140(9): 040104048

[4] Daliri F., Simms P., and Sivathayalan S. 2016. Shear and dewatering behaviour of densified gold tailings in a laboratory simulation of multi-layer deposition. Canadian Geotechnical Journal, **53**(8): 1246–1257.

[5] Martinelli, M., and Galavi, V. 2022. An explicit coupled MPM formulation to simulate penetration problems in soils using quadrilateral elements. *Computers and Geotechnics* 145: 104697.

[6] Mofrad M, Pouragha M, Simms P. 2023. Constitutive modelling of unsaturated gold tailings subjected to drying and wetting cycles. *Int J Numer Anal Methods*. 2023; 47: 1936-1949. https://doi.org/10.1002/nag.3545

[7] Qi S., Simms P., Daliri F., and Vanapalli S. 2020. Coupling elasto-plastic behaviour of unsaturated soils with piecewise linear large-strain consolidation. *Géotechnique*, 70(6): 518–537.