Hydro-mechanical coupling in dewatering simulations for mine tailings management

Q. Shunchao
Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada

S. Paul
Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada

ABSTRACT: Mine tailings are the fine-grained residue from various resource extraction processes, comprising particles ranging from fine sand to clay size. Tailings are conventionally deposited as a slurry, with water contents well above their liquid limit. Some operations dewater the tailings before deposition, to the extent that the tailings have sufficient strength to form gentle sloped deposits. In such dewatered deposits, deposition may be cycled between different points in the impoundment, allowing time for a freshly placed layer to undergo evaporation before subsequent burial by the next layer. Therefore, the dewatering of the tailings and the strength they manifest is influenced by hydro-mechanical coupling, where parts of the tailings are undergoing large strain consolidation and other parts are undergoing dewatering under unsaturated conditions. Memory (irreversible volume change and changes in the yield surface) is important. This paper presents simulations of multi-layer tailings deposition using some of constitutive models recently proposed for elasto-plastic modelling of unsaturated soils, including the modified State Surface Model (SSM) and the Glasgow Coupled Model (GCM), embedded in a numerical framework for both saturated and unsaturated large strain consolidation. Simulations of selected cases are shown and the relative applicability of these unsaturated soil constitutive models to this problem is discussed.

1 INTRODUCTION

Mine tailings are the residue of resource extraction involving mining of rock or overburden. For the former case, tailings' particles are generated by the crushing and grinding of rock, while for the latter the tailings are the residual soil material, potentially modified by the extraction process. In the former case, most of the particles lie between 10 and 100 µm, as this is the optimal range to facilitate extraction of the desired mineral grains. For the latter, overburden soils associated with resources such as bauxite and bitumen may contain a substantial amount of clay minerals. In all cases, the tailings are transported as a high-water content slurry between different operations in the mill. Most commonly, the tailings are deposited directly into a dammed impoundment, where the water content is usually at least double of their liquid limit. Some sites employ a dewatering step before deposition, with the goal of recovering water and recycling it within the mill, reducing water management requirements, reducing the volume of the tailings, and improving geotechnical performance of the tailings deposit (Simms 2017).

The majority of new mines deposit tailings at a rate over ¼ million m^3 a day for mine lives in the order of decades. Such rates of mining result in very large deposits, often covering several square kilometres, with dam heights now contemplated up to 400 m.

Unfortunately, tailings dams fail with some regularity, at a rate of 4 or 5 a year. Some of these failures incur loss of life and up to billions of dollars in damage to property and/or associated environmental clean-up costs. Tailings dams fail due to a variety of reasons, including poor foundation conditions, poor water level control, and damage due to seismic events. Industry response to these failures has been twofold: either to improve the level of care afforded to tailings dams, through changes in regulation or management culture, or to implement technologies that improve the geotechnical performance of the tailings themselves. The latter usually involve dewatering tailings to some degree by thickening or filtration before deposition, which facilitates quicker consolidation and better geotechnical performance. Often, such dewatered or thickened tailings are deposited at varying points in a tailings impoundment. This allows for evaporation to assist in further dewatering and densification of the tailings before deposition cycles round again and those tailings are buried.

Part of such post-deposition dewatering and strength gain of the tailings is governed by hydromechanical coupling in an unsaturated state. Figure 1 indicates the progress of dewatering of a given layer of tailings conceptually. Initially, the tailings dewater through sedimentation and consolidation. The deformations at this stage are large, transiting void ratios above 3 to void ratios close to 1. Simultaneously, the upper part of the layer may begin to desaturate –an analysis of this stage requires a smooth transition between large strain consolidation and coupled hydro-mechanical behaviour in the unsaturated zone. With the addition of a new layer, many complex behaviours will manifest, including the effect of additional weight on the previously desiccated tailings, the accelerating of consolidation of the new layer due to rewetting occurring in the bottom layer, and the potential for wetting induced collapse behaviour in the previously desiccated lower layers.

The authors recently developed the coupled large strain consolidation – unsaturated flow code, UNASTCON. This code extends the piece-wise linear approach to solving large strain consolidation developed by Fox and Berles (1997) to unsaturated soils. The authors have described this model and showed its applicability to field cases and laboratory studies for monotonic dewatering in Qi et al. (2017a, b). To tackle the multilayer problem, the authors have subsequently implemented several elasto-plastic constitutive models for unsaturated soils in the UNSATCON platform, including:

i) the modified State Surface Method (SSM) proposed by Zhang and Lytton (2009) coupled to a simple void ratio dependent water retention curve;
ii) the Barcelona Basic Model (BBM). coupled to the same simple water retention model;
iii) the SSM and BBM models coupled to bounding plasticity water-retention model of Gallipoli et al. (2015) and
iv) the Glasgow Coupled Model (GCM).

Comparisons of these implementations with laboratory and field data are shown by Qi (2017), using data from Daliri et al. (2016) and Rozina et al. (2015).

The aim of this paper is to compare the implementation and results between two relatively different elasto-plastic models, SSM and GCM, to present the problem of modelling thickened tailings deposition. We believe this comparison is of interest to the wider unsaturated soils community for two reasons: i) it gives a new example of applicability of such complex soil behaviours to a real-world problem and ii) it may shed some light on, how the different assumptions of the models bear out in boundary value problems.

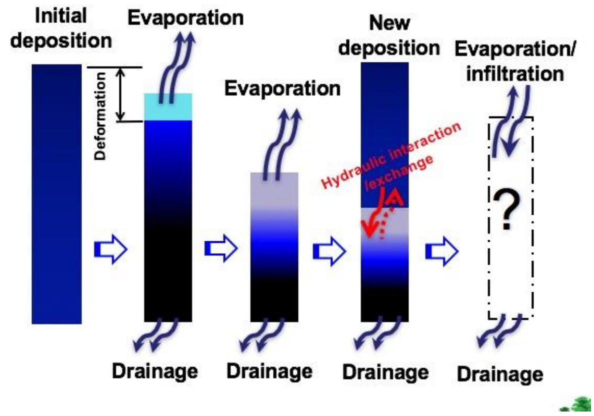

Figure 1. Stages of tailings multilayer deposition.

2 MATERIALS AND METHODS

2.1 *Constitutive models employed*

Two models are employed, i) SSM coupled with a void ratio dependent SWCC and ii) an integrated form of GCM.

The SSM employs three concepts: i) a stationary plastic surface which describes void ratio dependency on matric suction and total stress; ii) a moving elastic plane in the same space and iii) a void ratio dependent SWCC that accounts for hysteresis. The plastic surface is adopted from Vu and Fredlund (2006):

$$e = a + b\log\left[\frac{1 + c(\sigma - u_a) + d(u_a - u_w)}{1 + f(\sigma - u_a) + g(u_a - u_w)}\right] \qquad (1)$$

Though this surface has many parameters they are well-constrained by commonly obtained data, namely, the SWCC and the saturated compressibility curve. The parameter *a,* fixes the position of the surface, whereas *b* gives the average slope of the compressibility data is $\log_{10}$ stress space. Two of the parameters disappear when either suction or stress approach zero – *c*, *d*, *f*, and *g* describe the curvature of the function at either low or high values of stress or suction, allowing for the description of a traditional S shaped SWCC.

The movable elastic surface is a plane in the same space, with constant log-linear slopes. The form of the elastic surface is the same as adopted in BBM.

The void ratio dependent SWCC is described by a family of lines in log suction space, similar to those proposed by Dangla et al. (1997):

$$S_r = 1 - \kappa_{ss}\ln(s+1) \qquad (2)$$

$$S_r = \kappa_{ss}\ln(10^6+1) - \kappa_{ss}\ln(s+1) \qquad (3)$$

$$S_r = C_{drying} - \lambda_{se}e - \lambda_{sr}\ln(s+1) \qquad (4)$$

$$S_\mathrm{r} = C_{wetting} - \lambda_{se} e - \lambda_{sr} \ln(s+1) \quad (5)$$

$$S_\mathrm{r} = C_{scanning} - \lambda_{se} e - \kappa_{ss} \ln(s+1) \quad (6)$$

Equations 2 and 3 define the SWCC for suctions before the AEV and after the residual water content. Equations 4 and 5 define the main drying and wetting lines. The degree of hysteresis is given by the difference between the anchor points, C_{wettng} and C_{drying}, while the position of both curves is shifted equally by the void ratio through the term $\lambda_{se.}$

In UNSATCON, the global analysis provides *w* and total stress at each point after a given time step. A bisection method is used to find the relevant surface and correct pairing of S_r and *e*. Details are given in Qi (2017).

GCM is a highly coupled model proposed by Wheeler et al. (2003) with recent applications described in Lloret-Cabot et al. (2017). GCM employs the Bishops's stress to describe mechanical behaviour, while modified suction (the product of matric suction and porosity) is assumed to govern changes in S_r. This choice is in part due to the definition of work conjugate strains and stresses purposed by Houlsby (1997), though Wheeler et al. (2003) offers other reasons, such as the dominance of S_r rather than suction itself to characterize the influence of meniscus water on the mechanical behaviour. Wheeler et al. (2003) described the model in incremental terms, using two coupling parameters to link yielding in saturation space (hydraulic) or yielding in void ratio space (mechanical). Lloret-Cabot et al. (2017) developed equations in an integrated form for simultaneous yielding. Qi et al. (2018) and Qi (2017) developed an integrated form that is valid for any stress path. The following equations describe this integrated form of GCM for plastic changes in void ratio and degree of saturation:

$$v = N_0 - \frac{k_1(\lambda - \kappa)}{\lambda_s - \kappa_s} S_\mathrm{r}^\mathrm{p} - \lambda \ln p^* \quad (7)$$

$$S_\mathrm{r} = \Omega_{w0,d0} + \frac{k_2(\lambda_s - \kappa_s)}{\lambda - \kappa} v^\mathrm{p} - \lambda_s \ln s^* \quad (8)$$

Where, *v* is the specific volume (1+e); N_0 and Ω_0 are anchoring points for the saturated compressibility function and the initial primary drying or wetting curve. Ω can be obtained from a drying SWCC by calculating the amount of plastic strain until the real AEV. The coupling parameters k_1 and k_2 must be obtained through calibration; λ and λ_s are the log-linear slopes of the compressibility and water-retention lines respectively; κ and κ_s are slopes for elastic volume change or changes in degree of saturation. For problems involving transition, elastic changes in degree of saturation are ignored (Lloret-Cabot et al. 2017) and κ_s=0. The Bishops's stress p^* and the modified suction s^* are $\sigma + S_r\, s$ and *ns* respectively.

Using this integrated formulation, which also includes a moving elastic line for volume change (slope κ), the role of the coupling parameters can be readily visualized: k_1 quantifies the shift of the compressibility curve due to the influence of meniscus water, while k_2 relates the change in AEV to plastic volume change. The yield stress function in Wheeler et al. (2003) will emerge from the intersection of these plastic lines with the elastic volume change line and the S_r=*1* line in modified suction – Bishop's stress space.

As with SSM, the global analysis in UNSATCON provides *w* and total stress at each point after a given time step, and then the unknowns (S_r, v, p*, s*) must be calculated using an iterative process, which is described in Qi (2017). The interaction process uses trial values of S_r as these are physically bounded between 1 and 0.

For both GCM and SSM, the same permeability relationship is used to solve boundary value problems. The function is employed consists of two parts, one accounting for void ratio, and the other (van Genuchten 1980) for effect of desaturation, expressed as:

$$k_r = S_\mathrm{r}^{1/2}[1-(1-S_\mathrm{r}^{1/M})^M]^2 \quad (9)$$

$$k_{sat} = H_1 \times e^{H_2} \quad (10)$$

2.2 *Tailings analysed and model calibration*

The tailings analysed are generated from an overburden bitumen extraction process and contain clay minerals (Table 1). Theses tailings are deposited as a high-water content slurry at about *w* = 180%. The compressibility curve, shrinkage curve and the SWCC are presented in Figures 2, 3 and 4, respectively along with the corresponding functions predicted from the SSM and GCM constitutive functions. Model specific parameter values are given in Tables 2 and 3. In the case of the compressibility function, the best fit log-linear slope becomes λ in GCM, while the *c* and *f* parameters are obtained by fitting Equation 1 at zero suction to the compressibility data. The value of *b* in Equation 1 is the $\log_{10}$ equivalent of λ. For SSM, the void ratio from Equation 1 from near zero total stress for given suctions are matched with water contents given the void ratio dependent SWCC (Equations 2, 3 and 4) for a drying path for the same given suctions. For GCM, an expression for the shrinkage curve can be derived (Qi et al. 2018) assuming zero total stress: The GCM shrinkage curve is obtained using k_1 and k_2 values both equal to 0.7.

Similarly, the water content and degree of saturation versus water content curves for the drying SWCC can be calculated, are shown in Figure 4. The slight curvature of the saturation curve for GCM is because the equations are shown in suction not modified suction space. The value λ_s in GCM was chosen to be equal to the slopes of the drying curves in SSM. Both models are more closely calibrated to the void ratio (saturated compressibility and shrinkage curve), and somewhat under-predict water content and therefore degree of saturation but agree well with each other. The shrinkage behaviour of the real soil is bimodal, characterized by desaturation down to about 70% at a few kPa suction, followed by further volume change until a second AEV is reached, evident in Figure 3, which makes it difficult for either model to perfectly describe both the shrinkage and water content curves.

Table 1. Properties of analysed tailings.

Properties	Values
LL, PL, SL, Specific gravity	80 45 47 2.2
D90, D60, D30, D10, % < 2 um	75 10 3 0.8 30%
Clay content by Methylene Blue Index (MBI)	0.30
Quantitative mineralogy from XRD	70% Illite 30% Kaolinite
Pore-water electrical conductivity and dominant ions	~1.6 mS/ cm Na (~300 mg/L) Cl (~100 mg/L)

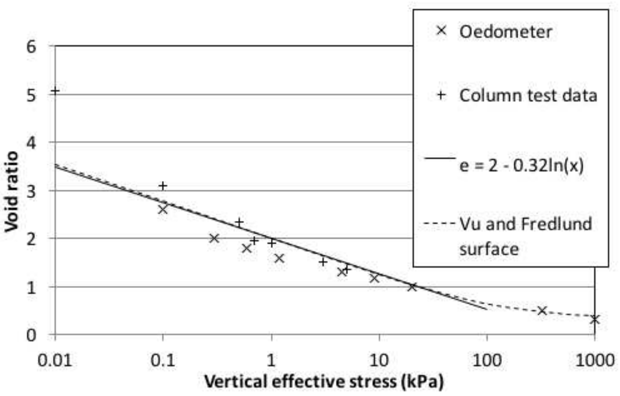

Figure 2. Compressibility data fitted with log-linear slope and with Vu and Fredlund surface.

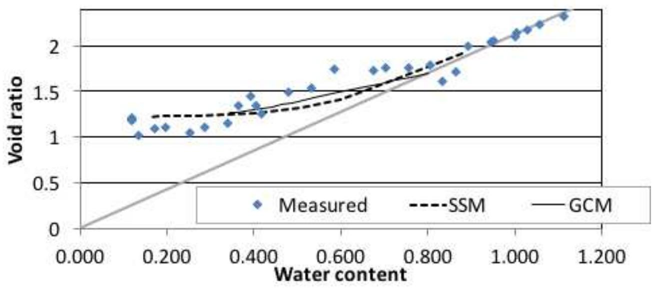

Figure 3. Shrinkage curve with SSM and GCM model predictions at low total stress.

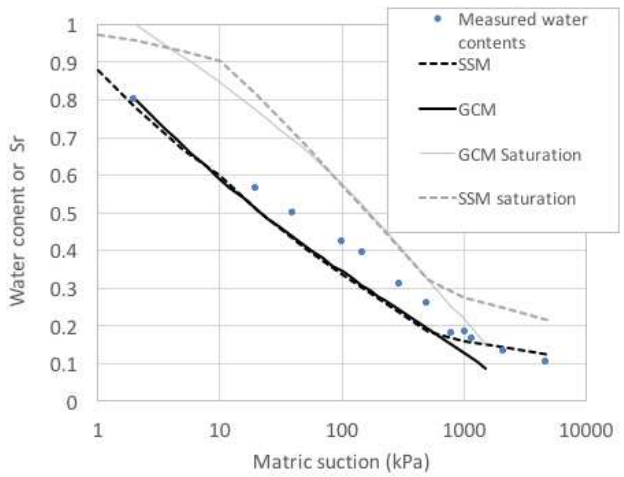

Figure 4. SWCC with model predictions at low stress.

Table 2. SSM model parameters.

Volume change					
Plastic					
A	B	C	D	F	G
4.5	0.78	0.0076	0.136	1620	2170
Elastic					
κ	κ_s				
0.05	0.005				
Water retention					
λ_{sr}	κ_{ss}	λ_{se}	C_{dry}	C_{wet}	
0.16	0.04	0.15	1.5	1.35	

Table 3. GCM model parameters.

Volume change		
λ	κ	N_0
0.32	0.05	3.1
Water retention		
λ_s	$\Omega_{0,\ dry}$	$\Omega_{0,\ wet}$
0.16	0.50	0.23
Coupling parameters		
k_1	k_2	
0.7	0.7	

3 HYPOTHETICAL ANALYSES OF TAILINGS DEPOSITION

Tailings are deposited at a void ratio of 4.0. The top boundary is the greater of bleed water flux from consolidation or evaporation. Evaporation is 2 mm/day and is only applied during summer (from 5th May to 1st October). It is to be noted that, during the summer, desaturation can occur only when the evaporation rate is higher than the bleed water flux. Zero flux is applied at the bottom of the bottom-layer tailings.

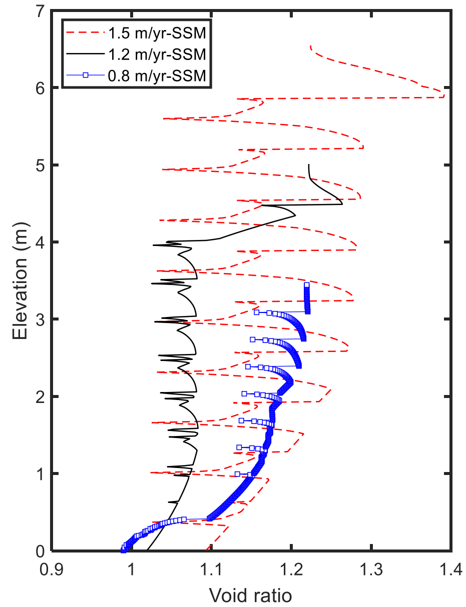

Figure 5. Predicted void ratio profile after 10 years using SSM.

Tailings are deposited over 10 years, with deposition of a single layer occurring at the end of the summer. This is done to maximize the contributions of evaporation and consolidation. If tailings are deposited in the summer, then the evaporation demand will be partly satisfied by bleeding water from consolidation, and thus evaporation will provide relatively less dewatering.

Results for yearly deposition of 0.6 to 1.5 m per year is shown in Figures 5 and 6, for SSM and GCM respectively. Time profiles of void ratio and saturation between the second and third layer depositions are shown in Figure 7. The practical context is that oil sands fine tailings deposits are expected to require void ratios less than 1, to provide sufficient undrained strength to support gently sloped reclaimed landforms. The void ratios must achieve this throughout the depth of profile, to prevent deep seated slope stability failures. The variability of the void ratio profiles with depth is largely due to differing degrees of desiccation within a given layer before burial under new tailings.

While the general range of results predicted using the two different models are similar, there are some differences with important practical consequences.

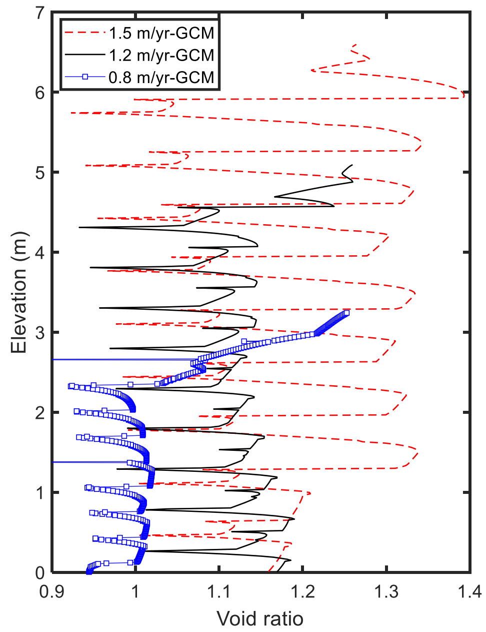

Figure 6. Predicted void ratio profile after 10 years using GCM.

For SSM (Fig. 5), an optimal deposition scheme is found (1.2 m per year), as for thinner layers the effects of drying and consolidation begin to cancel each other out. In SSM, the position of the elastic surface after initial desiccation is such that most subsequent deformation during burial will be elastic, with a slight plastic volume change due to increased self-weight with each layer. In GCM, by contrast, rewetting and collapse returns the tailings to the virgin consolidation line, which increases compression for tailings at depth. This can be shown by inspection of the stress path shown in Figure 8 for the specific volume - Bishop's stress space.

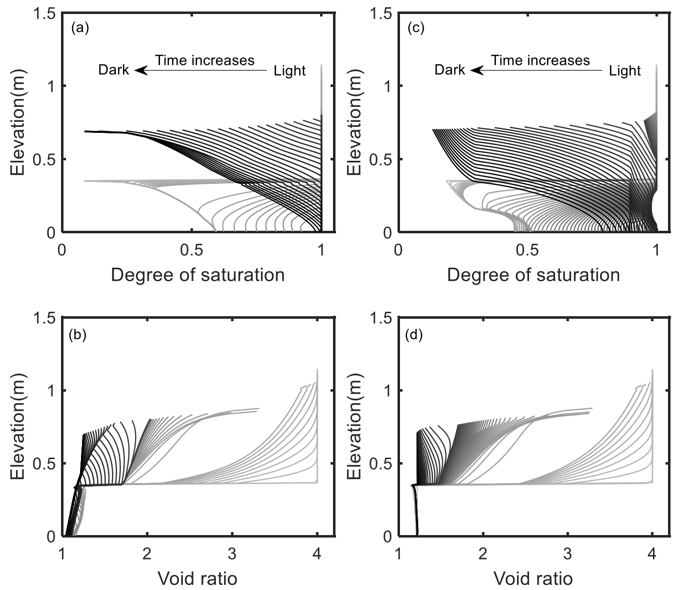

Figure 7. Profiles of saturation and void ratio after second deposition, -colour changes with time from light at time = 0 to dark: (a) S_r by GCM; (b) e by GCM; (c) S_r by SSM; (d) e by SSM.

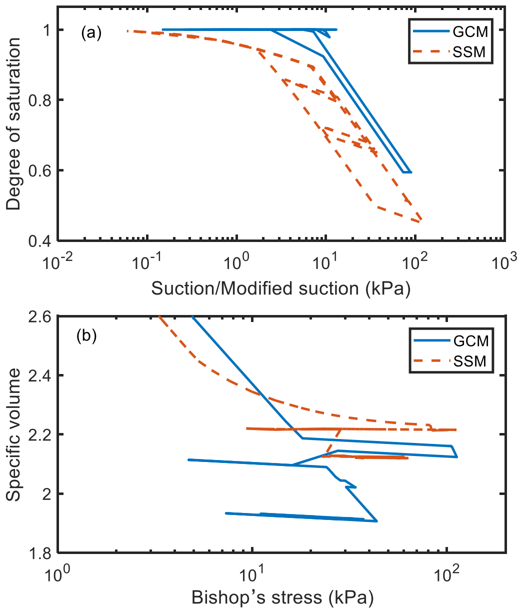

Figure 8. Stress paths at bottom of deposit in first four years (blue GCM): (a) in the S_r-$s(s^*)$ plane; (b) in the v-p^* plane.

The post-collapse compression, predicted by GCM but not by SSM, would have important implications for the final state of the tailings for a given deposition scheme. While the authors have undertaken experiments on multilayer deposition at a wide range of scales (such as- the drying box tests described in Simms et al. 2017 and Daliri et al. 2016), the total stress levels in these tests have not been high enough to investigate collapse and post-collapse behaviour in these tailings.

4 SUMMARY AND CONCUSIONS

The SSM and GCM models were implemented into the UNSATCON platform and used to analyse hypothetical deposition scenarios for oil sands tailings. The models were calibrated using compressibility and drying SWCC data and were deliberately calibrated to give similar reproductions of the drying SWCC and the shrinkage curve. While the results produced from the hypothetical deposition analyses were broadly similar, producing void ratio versus depth predictions in similar ranges, important differences with practical consequences exist. For example, using the GCM model predicts higher density at depth, due to the return to virgin compression behaviour post-collapse. These results have prompted further experimental work to examine the post-collapse behaviour of the tailings.

5 ACKNOWLEDGEMENTS

Authors are grateful for funding from Canada's Oil Sands Innovation Alliance and from the Natural Science and Engineering Council of Canada.

6 REFERENCES

Daliri, F., Simms, P. & 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.

Dangla, P., Malinsky, L. & Coussy, O. 1997. Plasticity and imbibition-drainage curves for unsaturated soils: a unified approach. In *Proc. 6th Int. Symp. Numer. Models Geomech.* NUMOG VI: 141-146.

Fox, P.J. & Berles, J.D. 1997. CS2: A piecewise-linear model for large strain consolidation. *International Journal for Numerical and Analytical Methods in Geomechanics* 21(7): 453-475.

Gallipoli, D., Bruno, A.W., D'Onza, F. & Mancuso, C. 2015. A bounding surface hysteretic water retention model for deformable soils. *Géotechnique* 65(10): 793-804.

Houlsby, G.T. 1997. The work input to an unsaturated granular material. *Géotechnique* 47(1): 193-6.

Lloret-Cabot, M., Wheeler, S.J. & Sánchez, M. 2017. A unified mechanical and retention model for saturated and unsaturated soil behaviour. *Acta Geotechnica* 12(1): 1-21.

Qi, S. 2017. Numerical Investigation for Slope Stability of Expansive soils and Large Strain Consolidation of Soft Soils. PhD Dissertation, University of Ottawa, 581 pp.

Qi, S., Simms, P. & Vanapalli, S. 2018. Discussion of ''From saturated to unsaturated conditions and vice versa'' by Martı´ Lloret-Cabot, Simon J. Wheeler, Jubert A. Pineda, Enrique Romero, and Daichao Sheng. *Acta Geotechnica,* First online https://doi.org/10.1007/s11440-017-0625-2.

Qi, S., Simms, P. & Vanapalli, S. 2017. Piecewise-linear formulation of coupled large-strain consolidation and unsaturated flow. I: Model development and implementation. *Journal of Geotechnical and Geoenvironmental Engineering* 143(7): 04017018.

Qi, S., Simms, P., Vanapalli, S. & Soleimani, S. 2017. Piecewise-linear formulation of coupled large-strain consolidation and unsaturated flow. II: testing and performance. *Journal of Geotechnical and Geoenvironmental Engineering* 143(7): 04017019.

Rozina, E., Mizani, S., Malek, M., Sanchez, M. & Simms, P. 2015. Desiccation and consolidation in a laboratory simulation of multilayer deposition of oil sands fine tailings. In *Proceedings of Paste* 2015, Cairns, Australia, June 2015, Australian Centre for Geomechanics.

Simms, P. 2017. Colloquium of the Canadian Geotechnical Society: Geotechnical and Geoenvironmental behaviour of high-density tailings. *Canadian Geotechnical Journal* 54(4): 455-468.

Simms, P., Soleimani, S., Mizani, S., Daliri, F., Dunmola, A., Rozina, E. & Innocent-Bernard, T. 2017. Cracking, salinity and evaporation in mesoscale experiments on three types of tailings. *Environmental Geotechnics*: 1-15.

Van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. *Soil science society of America journal* 44(5): 892-898.

Vu, H.Q. & Fredlund, D.G. 2006. Challenges to modelling heave in expansive soils. *Canadian Geotechnical Journal* 43(12): 1249-1272.

Wheeler, S.J., Sharma, R.S. & Buisson, M.S.R. 2003. Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils. *Géotechnique* 53(1): 41-54.

Zhang, X. & Lytton, R.L. 2009. Modified state-surface approach to the study of unsaturated soil behaviour. Part I: Basic concept. *Canadian Geotechnical Journal* 46(5): 536-552.