Multi-stage Thermal Creep Characteristics of Frozen Tailings

Dana Amini[1,3](✉), Pooneh Maghoul[1,2], and Amade Pouya[3]

[1] University of Manitoba, Winnipeg, MB, Canada
aminid@myumanitoba.ca
[2] Polytechnique Montréal, Montréal, QC, Canada
[3] Navier Laboratory, École des Ponts ParisTech, Paris, France

Abstract. The deformation of tailings dams due to creep has been identified as a significant threat to their stability and overall life-cycle performance. In northern regions, tailings dams constructed mostly on traditionally frozen foundations, are subject to hazards resulting from permafrost degradation due to climate non-stationarity. Due to the rapid rate of global warming in these regions, such time-dependent irrecoverable deformations can be significantly accelerated. Such failures were remarkably monitored in upstream-raised tailings storage facilities where tailings material are subject to incremental mechanical loading. Hence, deep understanding of tailings behavior under constant and rate-dependent thermal and mechanical loads is urgently needed. A parametric study is performed in the present work to capture the first-order multi-stage thermal creep characteristics of frozen geomaterials (mine tailings and foundation) under uniaxial loading. For this purpose, a Critical State Soil Mechanics (CSSM)-based Thermo-Elasto-Viscoplastic (TEVP) constitutive model is developed and employed to investigate such time- and temperature-dependent behaviors.

Keywords: Thermal Creep Characteristics · Tailings viscosity · Frozen Geomaterials · Constitutive Model

1 Introduction

The stability and overall life-cycle performance of tailings storage facilities depend heavily on the properties of the tailings. To date, numerous studies have been conducted to examine the mechanical behavior of tailings (e.g., [4, 9]), with particular emphasis on their shear strength. In addition, slow-rate time-dependent deformation (i.e., viscous or creep deformation) of tailings under incremental loads resulting from sequential dumping and compaction of tailings are reported in the literature. This is a common failure mechanism in upstream-raised tailings storage facilities, where the tailings undergo incremental mechanical loading [5]. Such time-dependent irrecoverable deformations are also observed under constant load during the service life of the tailings storage facility. Such creep deformations can lead to shearing and reorganization of the inter-particle microstructure of tailings, highlighting the impact of the materials' creep behavior on the long-term integrity of the storage facility.

R. E. Hammah et al. (Eds.): RIC 2023, AHE 19, pp. 309–316, 2023.
https://doi.org/10.2991/978-94-6463-258-3_32

In mine sites located in northern regions, the freezing of tailings before their compaction, or the presence of ice and water in the tailings, is a plausible scenario. In addition, most tailings storage facilities in these regions are constructed on permafrost or discontinuous permafrost in problematic alluvial geomaterials such as soft clays, which possess relatively high strength and bearing capacity in their frozen state. However, with the rapid pace of global warming in permafrost regions in recent years, the thawing of these frozen foundations can result in substantial non-recoverable plastic or permanent deformations, leading to instability, liquefaction, and settlement issues for the overlying tailings storage and other built infrastructure. Furthermore, the stability of such highly plastic foundation geomaterials can also be affected by permanent creep deformations.

Tailings and natural soils are heterogeneous materials; and their response to short- and long-term mechanical and thermal loads depends on several factors such as geological history, microstructure, and interaction with pore fluids [6, 7]. In general, temperature, confining stress level, strain rate, ice content, and structure of materials are known as factors controlling the evolution of creep deformations for most frozen geomaterials [2]. However, temperature and stress levels are known as the main factors that greatly affect the rheological properties and subsequently creep rate of ice-contained geomaterials such as frozen tailings. The creep in tailings can be defined in terms of secondary compression that initiates at some time after the end of primary (instant) deformation. However, it is demonstrated that the creep rate of ice-rich geomaterials increases with an increase in its thermal state or stress level [8], leading to accelerated deformation (i.e., tertiary creep deformation). It necessities the investigation of thermal creep deformation of tailings which is of great importance for the design and construction of tailings storage facilities in northern sites.

To date, numerous human-made geohazards have been caused by significant creep deformations of tailings storage facilities (e.g., [3, 10]). These geohazards highlight the necessity of a performance-based design paradigm to address the severe impacts of natural hazards such as climate non-stationarity on the life-cycle integrity assessment of tailings storage facilities. Such a design paradigm typically demands a thorough and realistic stress-strain analysis of tailings storage facilities throughout all construction phases, as well as post-construction thermal and mechanical loads. This analysis necessitates an advanced constitutive model capable of capturing the rate-dependent behavior of frozen geomaterials.

Previous studies have investigated the impact of stress level, strain history, and temperature on the evolution of irrecoverable deformations of frozen geomaterials under multi-stage creep tests. In most experimental studies, stepwise increased loading was applied to frozen geomaterials under constant temperature. However, the rate-dependent behavior of frozen geomaterials can also change under transient thermal conditions at constant stress levels. A limited number of experimental studies have investigated the creep behavior of frozen geomaterials under stepwise increased temperature. Additionally, the rate of temperature change is another crucial factor that can significantly affect the creep straining of frozen grounds. To our knowledge, no studies have explicitly quantified the impact of temperature change rate on the creep deformations of frozen geomaterials. Hence, this study aims to investigate the first-order multi-stage creep characteristics of an arbitrary frozen tailings sample under uniaxial loading conditions, considering the impact of temperature change rate. For this purpose, different stepwise increased stress levels are applied on the frozen tailings sample at a constant temperature. The impact of gradually and stepwise increased transient thermal conditions at a constant stress level is also investigated. The Critical State Soil Mechanics (CSSM)-based Thermo-Elasto-Viscoplastic (TEVP) geomechanical constitutive model developed by Amini et al. [1] to investigate the rate-dependent behavior of frozen geomaterials is employed for the simulations. This model can satisfactorily capture thermal creep deformations and the creep-induced shear failure of tailings.

2 Constitutive Model

The TEVP constitutive model is developed based on the two state variables framework where the solid phase stress, as the first stress state variable, is defined as:

$$\boldsymbol{\sigma}^{*} = \boldsymbol{\sigma} - S_w P_w \boldsymbol{I} \tag{1}$$

in which $\boldsymbol{\sigma}$ $(= \sigma_{ij})$ denotes the total stress tensor; $\boldsymbol{I}$ $(= I_{ij})$ is the second-order isotropic tensor with component δ_{ij}, where δ_{ij} is the Kronecker delta, which returns values of 0 for $i \neq j$ and 1 for $i = j$; and the second stress state variable, the cryogenic suction, S, is defined as:

$$S = P_{ice} - P_w \tag{2}$$

in which P_{ice} and P_w denote the pressure of the ice and water phases, respectively. The cryogenic suction can be approximated by the thermodynamic equilibrium at the ice-water interface described by the Clausius-Clapeyron equation as follows:

$$S \approx \rho_w L \ln\left(\frac{T}{273.15}\right) \tag{3}$$

where ρ_w stands for the density of unfrozen water, L is the latent heat of freezing due to the phase change of water (approximately 3.34×10^5 J kg^{-1}), and T indicates temperature. In the TEVP model, strain decomposition is assumed as follows:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\sigma} + \dot{\boldsymbol{\varepsilon}}^{suc} = \left(\dot{\boldsymbol{\varepsilon}}^{\sigma e} + \dot{\boldsymbol{\varepsilon}}^{\sigma Tvp}\right) + \dot{\boldsymbol{\varepsilon}}^{suc} \tag{4}$$

where $\dot{\boldsymbol{\varepsilon}}$ $(= \dot{\varepsilon}_{ij})$ is the second-order total strain rate tensor and the over-dot indicates the rate of change ($\dot{\varepsilon}_{ij} = \delta\dot{\varepsilon}_{ij}/\delta t$, where t is the time); $\dot{\boldsymbol{\varepsilon}}^{\sigma}$ and $\dot{\boldsymbol{\varepsilon}}^{suc}$ are the strain rate due to the solid phase stress changes and cryogenic suction changes, respectively; $\dot{\boldsymbol{\varepsilon}}^{\sigma e}$ and $\dot{\boldsymbol{\varepsilon}}^{\sigma Tvp}$ are the elastic and thermo-viscoplastic components of the strain rate due to changes in the solid phase stress, respectively. The strain rate due to cryogenic suction changes ($\dot{\boldsymbol{\varepsilon}}^{suc}$) is assumed to be elastic and volumetric; thus, it can be calculated as follows:

$$\dot{\boldsymbol{\varepsilon}}^{suc} = \left(\boldsymbol{D}^{suc}\right)^{-1}\dot{S} = \left(\frac{1}{3V}\frac{\kappa_s}{S + P_{atm}}\boldsymbol{I}\right)\dot{S} \tag{5}$$

where $\dot{S}$ denotes the cryogenic suction rate and $\boldsymbol{D}^{suc}$ is the elastic cryogenic suction-strain tensor; κ_s is the elastic stiffness parameter for changes in cryogenic suction; V is the specific volume; and P_{atm} is the atmospheric pressure. Thermo-viscoplastic strain rates ($\dot{\boldsymbol{\varepsilon}}^{\sigma Tvp}$) at the current stress state are given by

$$\dot{\boldsymbol{\varepsilon}}^{\sigma Tvp} = \underbrace{\left(\eta \frac{\psi_T}{V_m} \frac{\mathrm{Li}^{-1}(\Phi)}{\ln\left(\mathrm{Li}^{-1}(\Phi)\right)} \frac{1}{|\partial F_{VPPS}/\partial p^*|} \right)}_{\Lambda\text{: Scalar Multiplier}} \frac{\partial F_{VPPS}}{\partial \boldsymbol{\sigma}^*} \tag{6}$$

where V_m stands for the time-dependent specific volume of the frozen geomaterial under isotropic compression (p_m^*) corresponding to the current stress state, η is a temperature- and stress-dependent parameter controlling the creep going into the tertiary stage, ψ_T is a temperature- (or cryogenic suction-) dependent creep parameter, F_{VPPS} stands for the viscoplastic potential surface (VPPS) passing through the current stress state, p^* is the mean solid phase stress, and

$$\Phi = \frac{V_m - N_f + \lambda_f \ln p_m^*}{-\psi_T} + \mathrm{Li}\left(\exp(\eta t_o)\right) \tag{7}$$

in which λ_f is the elastoplastic compressibility coefficient of the geomaterial in a frozen state, N_f is the specific volume at unit pressure in the current cryogenic suction, t_o is a material parameter denoting the initiation time of purely creep compression deformations, and Li denotes logarithmic integral function. The readers are referred to [1] for more detailed information about the TEVP model.

3 Results and Discussion

In this section, a set of parametric studies is conducted to qualitatively investigate the thermal creep characteristics of frozen tailings. For this purpose, several multi-stage uniaxial creep tests at different stress levels and temperatures are simulated. In the simulations (see Table 1), the axial stress level and temperature are increased in a way that allows the different stages of the creep curve to be developed. The material properties for these simulations are provided in Table 2. The TEVP model predictions of multi-stage uniaxial creep tests at different stress levels and temperatures are represented in the following.

3.1 Uniaxial Multi-stage Creep Tests at Constant Temperatures

In the first set of simulations, the creep deformation of the frozen tailings at two temperatures (−5 and −15 °C) and different stepwise increased axial loads are investigated. At a constant temperature of −5 °C, four tests and at a constant temperature of −15 °C, three tests are simulated where in each test the axial loads are increased over time. The increase in the applied axial stress levels over time is indicated in Fig. 1(a) and (c). The

Table 1. Stress levels and temperatures considered in the simulations.

Test Series	Test No.	Axial Loading (MPa)	Temperature (°C)
1	1	0.1 → 0.3 → 0.6 → 1.2	−5.0
	2	0.8 → 1.5 → 2.0 → 2.5	
	3	2.2 → 2.6 → 3.0	
	4	2.6 → 2.9 →4.0	
2	1	0.5 → 1.0 → 3.0 → 5.0	−15.0
	2	4.0 → 5.0 → 6.25 → 7.5	
	3	4.0 → 6.25 → 9.0	
3	1	0.5	−5.0 → −3.0 → −1.0
	2		−3.0 → −1.0 → −0.5
	3		−1.2 → −0.5 → −0.3
4	1	0.5	−5.0 → −1.0
	2		−3.0 → −0.5
	3		−1.2 → −0.3

Table 2. Model parameters used in the simulations. The readers are referred to [1] for the detailed definition of the model parameters.

Param	G_o	E_o	a_E	κ_o	λ_o	N_o	P_o^*	P_r^*	M	ν_f	a_λ	b_λ
	MPa	MPa	K^{-1}	—	—	—	MPa	MPa	—	—	—	MPa^{-1}
Value	5	140	0.1	0.006	0.02	3.75	0.28	0.05	1.1	0.48	0.49	0.15
Param (Cont.)	$p_{t_b}^*$	a_s	κ_s	ψ_o	a_ψ	t_{fo}	σ_{co}^*	a_σ	a_t	t_o	Z	
	MPa	MPa^{-1}	—	—	K^{-1}	min	MPa	K^{-1}	—	min	—	
Value	12	0.053	0.008	0.014	0.006	359×10^3	1	0.093	7.8	30	1	

results of the TEVP model for these tests are plotted in Fig. 1(a) and (c) for temperatures −5 °C and −15 °C, respectively.

As shown in Fig. 1(b) and (d), at a constant temperature, the history of axial stress level as well as its magnitude can strongly affect the creep deformation of frozen samples in terms of magnitude and type (i.e., primary, secondary, or tertiary). A primary creep followed by more prolonged secondary creep deformations is observed for low stepwise increased stress levels. At higher axial stress levels (Tests 3 and 4 at $T = -5$ °C and Tests 2 and 3 at $T = -15$ °C), the tertiary creep stage associated with increasing creep rates is developed. More increase in axial stress levels results in tertiary creep accelerating toward failure. As expected, significantly lower rates of creep deformations are captured at $T = -15$ °C compared to those of at $T = -5$ °C at the same stress levels. This is because of the influence of a decrease in temperature on the strength of intergranular ice and unfrozen water contents in a frozen material [2]. Therefore, as shown in Fig. 1(d), higher axial stress levels are required for the tertiary creep stage to be developed at $T = -15\,°\mathrm{C}$.

3.2 Uniaxial Multi-stage Creep Tests Under Transient Temperature Conditions

In this subsection, the impact of varying temperatures at a constant stress state on the creep deformations of the same frozen tailings is investigated. As mentioned earlier, the impact of the temperature and its increasing rate are both studied. It should be noted that temperatures close to 0 °C can cause failure or instability, leading to failure of the frozen materials even at low stress levels. At such temperatures, the ice inclusion within the frozen body gradually begins to melt. It reduces the strength of geomaterials abruptly due to the disappearance of ice bonding. Therefore, a set of uniaxial creep tests are simulated under stepwise increased temperatures ranging from $-5\,°\mathrm{C}$ to $-0.3\,°\mathrm{C}$. Another set of tests is also simulated where the temperature gradually increases during a specific time and then remains constant. Changes in temperature are shown in Fig. 2(a) and (b) for each creep test. It should also be noted that most creep tests reported in the literature were carried out on frozen samples at stress levels greater than 1.0 MPa. However, these pressures are not quite realistic in geo-infrastructures. Hence, the axial stress level is assumed to be as low as 0.5 MPa for the simulations conducted in this subsection.

The axial strain of the frozen samples under the aforementioned transient thermal conditions and constant stress state are plotted in Fig. 2(b) and (d). As shown in Fig. 2(b), an increase in the thermal state of the frozen samples results in more significant creep deformations. It is much more pronounced at temperatures close to 0 °C (see Test 3 in Fig. 2(b)) where small stepwise increased temperature (from $-1.2\,°\mathrm{C}$ to $-0.3\,°\mathrm{C}$) leads to more pronounced tertiary creep deformations. The time-dependent axial strains observed under gradually increased temperature tests are slightly greater than those under stepwise increased thermal conditions. However, the creep rates sharply increase when gradually increased temperatures reach closer to 0 °C temperatures (see Test 3 in Fig. 2(b) and (d)). As shown in Fig. 2(c) and (d), the history of thermal conditions of frozen materials as well as the rate of the temperature changes, both contribute to the development of creep strains. It can be seen in Fig. 2(d) that even slow rates of temperature changes can dictate the initiation of failure (or instability followed by failure) of the frozen samples (see Test 3).

4 Conclusion

The first-order multi-stage thermal creep characteristics of frozen tailings are investigated in this study. Thermal creep deformations of frozen materials under uniaxial loading conditions are studied within a TEVP geomechanical constitutive model. Different uniaxial creep tests are simulated to highlight the impact of stepwise increased stress levels as well as the impact of gradually and stepwise increased transient thermal conditions on the development of irrecoverable time- and temperature-dependent deformations. Simulations show that stepwise increased stress levels and temperatures can significantly increase creep rates. The more accelerated rates are captured when, at

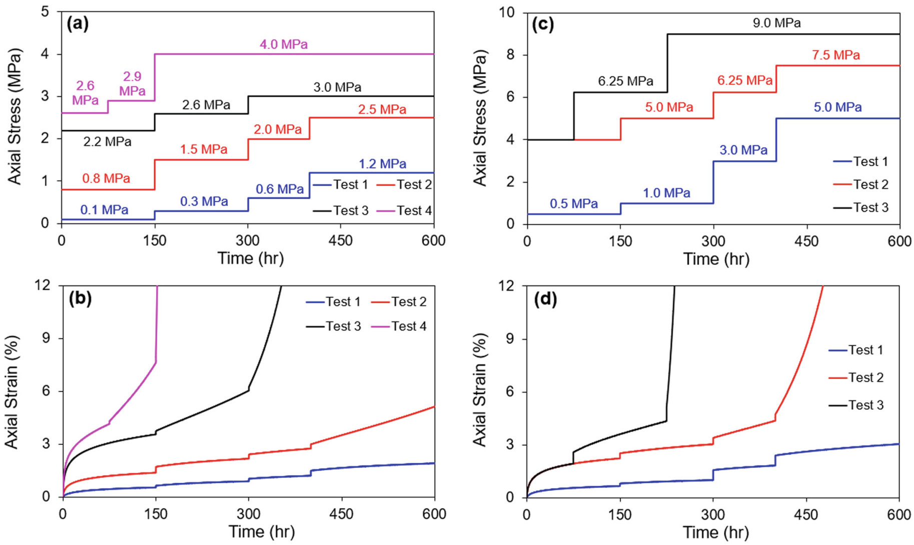

Fig. 1. Uniaxial multi-stage creep tests on frozen samples: (a) axial stress-time plot, (b) axial strain-time plot at T = −5 °C and (c) axial stress-time plot, (d) axial strain-time plot at T = −15 °C.

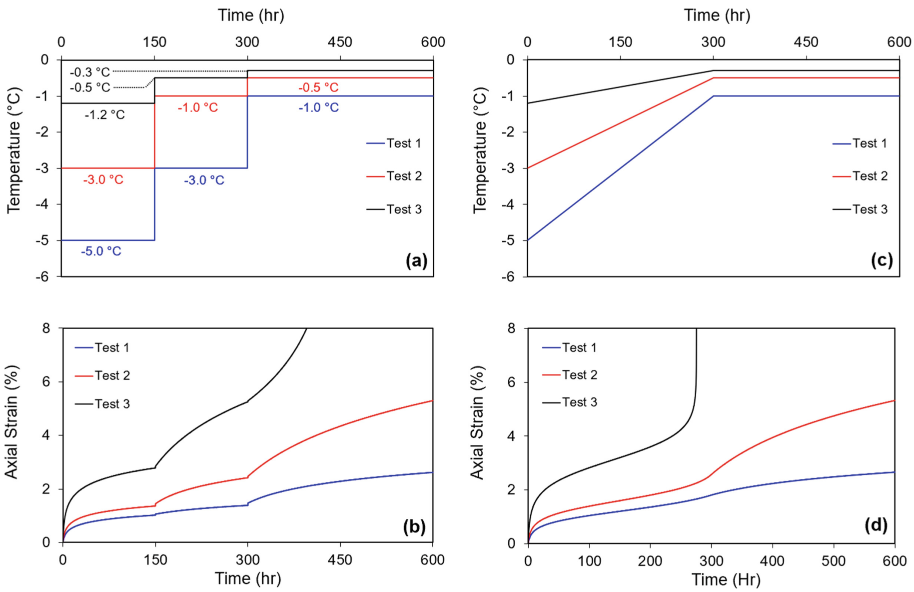

Fig. 2. Uniaxial multi-stage creep tests on frozen samples: (a) temperature-time plot, (b) axial strain-time plot under stepwise increased temperature and (c) temperature-time plot, (d) axial strain-time plot under gradually increased temperature.

a constant stress level, the temperature of materials increases gradually, demonstrating the impacts of temperature change rates. It is concluded that the history and magnitude of stress level and temperature strongly govern the rate-dependent behavior of frozen tailings.

References

1. Amini, D., Maghoul, P., Holländer, H., Bilodeau, J.: A critical state-based thermo-elasto-viscoplastic constitutive model for thermal creep deformation of frozen soils. In Review (2023)
2. Andersland, O.B., Ladanyi, B.: Frozen ground engineering. John Wiley & Sons, Hoboken, New Jersey (2003)
3. Azam, S., Li, Q.: Tailings dam failures: a review of the last one hundred years. Geotechnical news **28**(4), 50–54 (2010)
4. Bhanbhro, R.: Mechanical properties of tailings: basic description of a tailings material from Sweden. Ph.D. thesis, Luleå tekniska universitet (2014)
5. Bhanbhro, R., Rodriguez, J., Edeskär, T., Knutsson, S.: Evaluation of primary and secondary deformations and particle breakage of tailings. In: From Fundamentals to Applications in Geotechnics, pp. 2481–2488. IOS Press (2015)
6. Fathalikhani, M., Graham, J., Kurz, D., Maghoul, P.: Investigation and modification of a CSSM-based elastic–thermoviscoplastic model for clay. International Journal of Geomechanics **22**(10), 04022161 (2022)
7. Gens, A.: Soil–environment interactions in geotechnical engineering. Géotechnique **60**(1), 3–74 (2010)
8. Hjort, J., Streletskiy, D., Doré, G., Wu, Q., Bjella, K., Luoto, M.: Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment **3**(1), 24–38 (2022)
9. Qiu, Y., Sego, D.: Laboratory properties of mine tailings. Canadian geotechnical journal **38**(1), 183–190 (2001)
10. Rotta, L.H.S., Alcântara, E., Park, E., Negri, R.G., Lin, Y.N., Bernardo, N., Mendes, T.S.G., Souza Filho, C.R.: The 2019 brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in brazil. International Journal of Applied Earth Observation and Geoinformation **90**, 102119 (2020)