Saturated-unsaturated numerical modelling of a vertically heterogeneous monolayer cover with an elevated water table: the Manitou site case study

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ABSTRACT

Acid mine drainage production by reactive mine tailings can be controlled by installing a monolayer cover with an elevated water table (MC+EWT). This reclamation technique was implemented at the abandoned Manitou tailings storage facility 2 (TSF 2) located in Abitibi, Québec. The MC made of non-acid generating fine-grained tailings was placed hydraulically at a pulp density of approximately 45-50%. This disposal method induced segregation of particles according to their grain size and created some vertical heterogeneities into the cover material. In this study, numerical modelling was used to quantify the impact of the vertical heterogeneity of particle size distribution on the hydrogeological behavior of the monolayer cover and its performance as an oxygen barrier. Modelling results from May to October 2016 are presented and discussed here. The results showed that particle size vertical heterogeneity can affect but to a limited extent volumetric water content dynamics (RMSE < 0.03 $m^3 m^{-3}$) and thereby the hydrogeological behavior of the MC+EWT.

RÉSUMÉ

La production du drainage minier acide par les résidus miniers réactifs peut être contrôlée en installant un recouvrement monocouche avec nappe phréatique surélevée (MC+NPS). Cette technique de restauration a été appliquée sur le parc à résidus 2 (Parc 2) du site minier abandonné de Manitou, en Abitibi au Québec. Le recouvrement monocouche constitué de résidus miniers fins non-générateurs d'acide a été déposé hydrauliquement sous forme de pulpe à 45-50% solides. Cette technique de déposition induit une ségrégation des particules selon la taille des grains et crée une hétérogénéité verticale dans le matériau de recouvrement. Dans cette étude, la modélisation numérique a été utilisée pour quantifier l'impact de l'hétérogénéité verticale dans la distribution de la taille des particules sur le comportement hydrogéologique du recouvrement monocouche et sa performance en tant que barrière à l'oxygène. Les résultats de la modélisation pour une période allant de Mai à Octobre 2016 sont présentés et discutés. Les résultats ont montré que l'hétérogénéité verticale dans la distribution de la taille des particules peut affecter mais de manière limitée la dynamique de la teneur en eau volumique (RMSE < 0.03 $m^3 m^{-3}$) et par conséquent le comportement hydrogéologique de la MC+NPS.

1 INTRODUCTION

The abandoned Manitou site is located in the Abitibi-Témiscamingue region at 15 km East to the city of Val d'Or in Abitibi, Québec. In the early 2000, the site was considered as one of the most problematic abandoned mine sites in Québec (Eastern Canada) due to acid mine drainage (AMD) generation from mine wastes and the needs to undertake reclamation works was considered urgent at the time (MERN 2019).

Engineered mine covers (single or multi-layered) are one of the reclamation options used to control AMD generation (Aubertin et al. 2002; 2016). An engineered mine cover aims at excluding water and/or oxygen that are responsible of the AMD production when they are brought into contact with sulphide-bearing mine wastes (Aubertin et al. 2002; 2016). Controlling oxygen migration is considered as the most efficient option to limit AMD production in temperate humid areas like the Abitibi-Témiscamingue region (Bussière et al. 2007; Aubertin et al. 2016). Therefore, a monolayer cover with an elevated water table (MC+EWT) was implemented at the abandoned Manitou tailings storage facility 2 (TSF 2) as AMD control method. The monolayer cover made of non-acid generating fine-grained tailings was placed hydraulically at a pulp density of approximately 45-50% solids (Demers et al. 2013; Éthier et al. 2018). This disposal method is known to induce segregation of particles according to their grain size and create some vertical and horizontal heterogeneities into the cover material (Blight 1987).

The main objective of this paper is to model the influence of vertical heterogeneity in particle size distribution (PSD) on the hydrogeological behavior of the Manitou MC+EWT.

2 BACKGROUND OF THE RECLAMATION STRATEGY AND THE SEGREGATION PHENOMENON

At the Manitou abandoned mine site, three tailings storage facilities were constructed as shown in Figure 1-a.

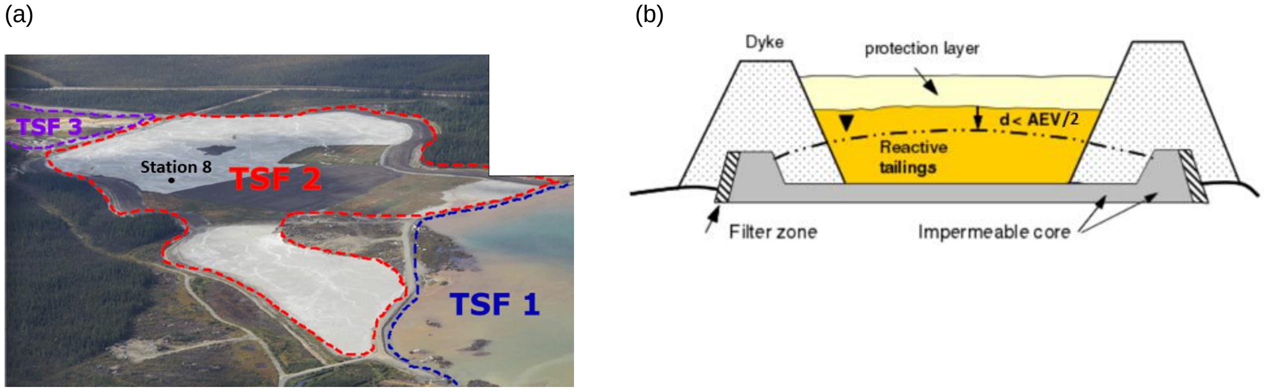

Figure 1. (a) The three tailings storage facilities (TSF 1, TSF 2 and TSF 3) at the Manitou site and location of Station 8 in the TSF 2 (adapted from Éthier 2018); (b) A schematic representation of a monolayer cover with an elevated water table (adapted from Ouangrawa et al. 2010)

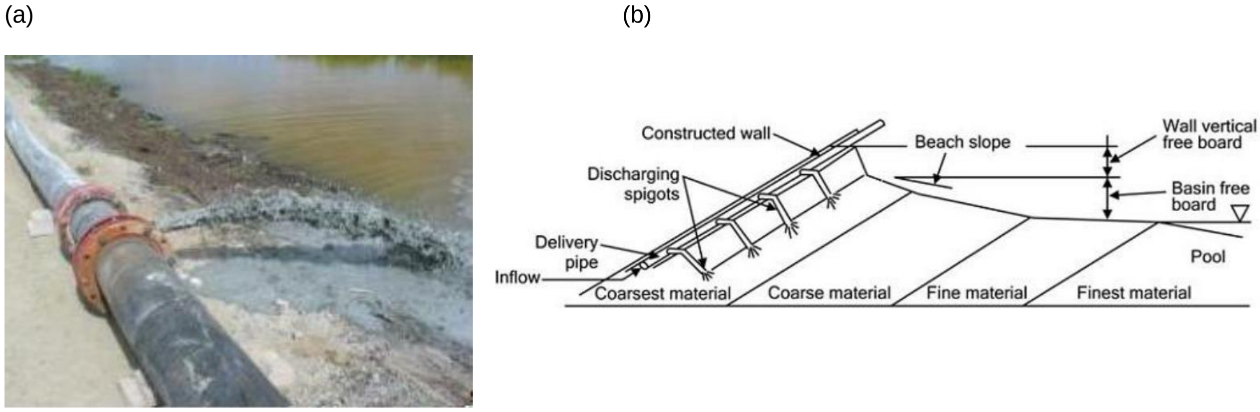

Figure 2. (a) Hydraulic deposition of Goldex mine tailings at the Manitou site (from Pabst 2011); (b) particle sorting in conventional tailings deposition (from Blight 2009)

xxxxx: strata located at different depths but characterized by similar particle size distribution curves (see Figure 4)

Figure 3. Particle size distribution (PSD) related stratification within the cover profile at Station 8

The TSF 2 has an area of 38 ha and was reclaimed in 2009 with a monolayer cover with an elevated water table (MC+EWT) (Figure 1-b) made of non-acid generating fine-grained tailings from Goldex mine located at 24 km. The principle of a MC+EWT consists in maintaining a high degree of saturation within the sulfide-bearing wastes and in the cover material made of Goldex tailings by controlling the position of the water table. This technique is based on the low level of oxygen diffusion in quasi-saturated conditions in order to reduce oxidation of the AMD-generating tailings (Orava et al. 1997; Dagenais et al. 2006; Demers et al. 2008; Ouangrawa et al. 2010).

Goldex mine tailings are transported by pipeline to the tailings pond and are hydraulically deposited at approximately 45-50% solids (Figure 2-a). Multiple deposition points are used at the tailings pond, where upon disposal the coarse particles settle close to the beach while the fine particles are carried to the center of the pond. Such deposition results in horizontal segregation of the tailings materials according to their grain size (Figure 2-b). Moreover, subsequent depositions of Goldex tailings with varying deposition point created some vertical heterogeneity with time (Figure 3) into the cover material (Vick, 1990; Blight, 2009). This was confirmed in the lab by differences in the particle size distribution (PSD) curves of materials collected at various depths (Figure 4).

3 FIELDWORK

Fieldwork has been conducted on the TSF 2 of the Manitou site from May to October 2016. Eight measurement stations (Stations 1, 3, 5, 7 under vegetation and Stations 2, 4, 6, 8 without vegetation) were installed on the TSF 2 site in 2015 to monitor the unsaturated hydrogeological behavior of the MC+EWT. At each station, volumetric water contents (θ) and suctions (Ψ) were measured with EC-TM ± 0.03 m^3 m^{-3} accuracy and Irrometer Watermark, ±1 kPa accuracy (0 to 200 kPa range), respectively. The water table level was continuously measured with dataloggers at four well points located close to the measurement stations.

Vertical heterogeneity in PSD was particularly observed at Station 8 and will be further investigated here as a case study. At other stations, vertical heterogeneity was also observed but at different extents. Thickness of the non acid-generating Goldex tailings at Station 8 is 150 cm. θ and Ψ data were recorded automatically at one hour interval and at five depths (10, 25, 40, 55 and 135 cm from the top of the cover) with dataloggers (Decagon Devices EM-50 apparatus for θ data and Irrometer Watermark for Ψ data). Data used in this study were collected at Station 8 from May to October 2016.

4 MATERIAL CHARACTERIZATION

PSD curves were determined in the lab whereas the soil water retention curve and the hydraulic conductivity function were estimated by predictive equations.

4.1 PARTICLE SIZE DISTRIBUTION

The PSD curves of material samples collected at five depths within the cover were obtained by laser-diffraction analyses using the Malvern laser particle size analyzer (Black et al. 1996). The PSD curves at 10, 25, 40, 55 and 135 cm are presented in Figure 4. Variations of PSD curves with depth were observed at Station 8. The coarsest material was found at 25 cm depth, whereas the finest material was found at 135 cm depth. PSD curves were similar at 10, 40 and 55 cm depth.

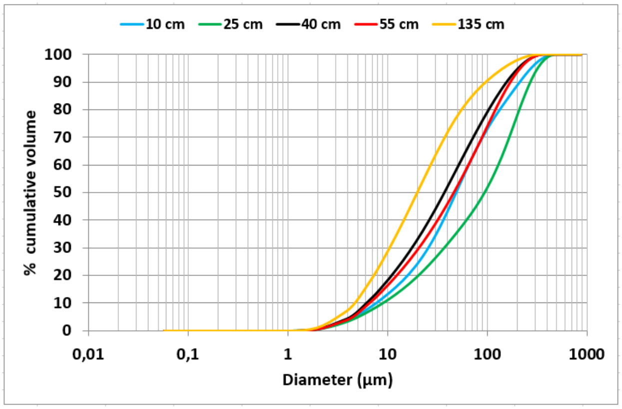

Figure 4. Particle size distribution curves of Goldex tailings materials collected at five depths within the monolayer cover profile at Station 8

4.2 WATER RETENTION CURVE

The modified Kovàcs (MK) model, initially developed for non-plastic tailings (Aubertin et al. 1998) and later extended to granular-cohesionless and plastic-cohesive soils (Aubertin et al. 2003), was used to estimate the water retention curves (WRCs) from basic geotechnical properties of the collected materials at Station 8. The main equation of the MK model can be written to relate the global degree of saturation S_w to the capillary S_c (-) and adhesion S_a (-) components that are a function of suction as follows:

$$S_w = \frac{\theta}{n} = 1 - (1 - S_c)\langle 1 - S_a \rangle$$

where θ is the volumetric water content (-) and $\langle\ \rangle$ represents the Macauley brackets $\left(\langle y \rangle = 0.5\,(y + |y|)\right)$.

The capillary and adhesion components of the MK equation are expressed as a function of the pore-size distribution parameters *e*, D_{10}, and C_U.

The MK-estimated WRCs for the Goldex tailings at five depths for an average porosity of 0.37 at Station 8 are presented in Figure 5. The AEV of each WRC has been obtained from the intersection point between the initial horizontal line (in the saturated zone) and the tangent line at the inflection point (in the transition zone) (e.g. Fredlund and Xing 1994; Wijaya et al. 2015). Results show that the air entry value (AEV) is significantly different for the sample taken at 135 cm (≈ 25 kPa) compared to the other samples (AEV ≈ 5-10 kPa).

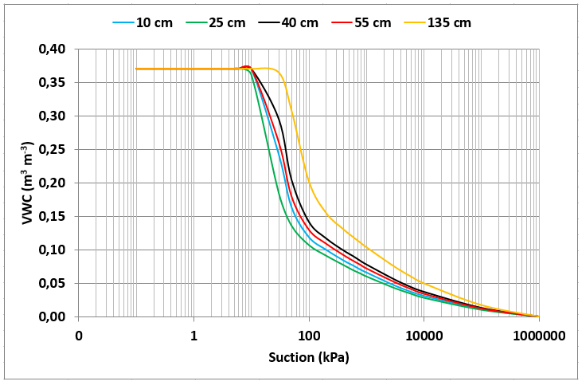

Figure 5. Water retention curves estimated with the Modified Kovàcs equation for an average porosity of 0.37 at five depths of the cover profile at Station 8

4.3 SATURATED HYDRAULIC CONDUCTIVITY

The modified Kozeny-Carman (KCM) equation (Mbonimpa et al. 2002) was used to predict the saturated hydraulic conductivity (k_{sat}, cm s^{-1}) for different porosities.

$$k_{sat} = C_G \frac{\gamma_w}{\mu_w} \frac{e^{3+x}}{1+e} C_U^{1/3} D_{10}^2$$

where, C_G (-) and x (-) are parameters that define pore tortuosity; $C_G = 0.1$ and $x = 2$ are generally employed values for non-plastic/non-cohesive materials; γ_w (9.81 kN m^{-3} at 20°C) and μ_w (10^{-3} Pa·s at 20°C) are respectively the volumetric unit weight and the dynamic viscosity of water; e (-) is the void ratio ($e = n/(1-n)$); D_{10} (cm) is the effective diameter corresponding to 10% passing on the cumulative PSD curve; C_U (-) is the uniformity coefficient ($C_U = D_{60}/D_{10}$, with D_{60} (cm) being the effective diameter corresponding to 60% passing on the cumulative PSD curve). The KCM-predicted values of k_{sat} at five different depths are presented in Table 1.

Table 1. Saturated hydraulic conductivity values predicted with the modified Kozeny-Carman equation at five depths (Porosity n = 0.37)

Depth (cm)	D_{10} (mm)	D_{60} (mm)	C_u	k_{sat} (m s^{-1})
10	0.0077	0.0654	8.5	7.7 x 10^{-7}
25	0.0077	0.1111	14.4	9.2 x 10^{-7}
40	0.0062	0.0521	8.4	5.0 x 10^{-7}
55	0.0066	0.0649	9.8	5.9 x 10^{-7}
135	0.0047	0.0272	5.8	2.5 x 10^{-7}

4.4 PERMEABILITY FUNCTION

The permeability function has been derived from the WRCs with the Mualem (1976)-van Genuchten (1980) model (MVG) as follows:

$$k(S_e) = k_{sat}\ S_e^l \left[1-\left(1-S_e^{\frac{1}{m_{vG}}}\right)^{m_{vG}}\right]^2$$

with $S_e(\psi) = (1+(\alpha_{vG}|\psi|)^{n_{vG}})^{-m_{vG}}$

where k_{sat} is the hydraulic conductivity, S_e is the degree of saturation, Ψ is suction, α_{vG}, l, n_{vG} and m_{vG}=1-1/n_{vG} are empirical fitting parameters, and α_{vG} correlates with the inverse of the air entry value of the sample material.

Permeability functions generated by the SEEP/W software (Geoslope International Ltd 2017) using the MVG equation are presented in Figure 6. Permeability functions at 10, 40 and 55 cm are similar and whereas the permeability functions at 25 cm and 135 cm depth reflect a coarser and a finer material, respectively.

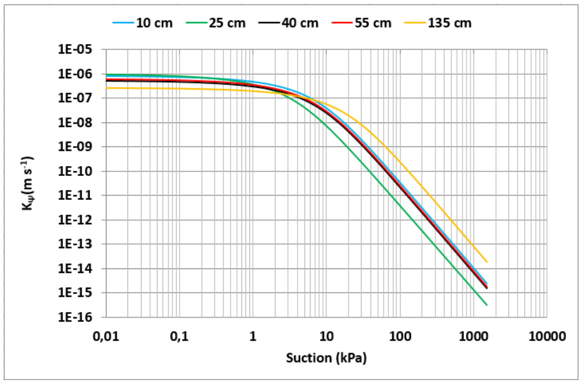

Figure 6. Permeability functions derived from water retention curves in SEEP/W

5 NUMERICAL MODELLING WITH SEEP/W

The SEEP/W software (Geoslope International Ltd 2017) was used to perform numerical simulations. It is a hydrogeological saturated-unsaturated numerical code widely used in the design and performance evaluation of mine engineered cover systems across Canada (e.g. Aubertin et al. 2009; Song and Yanful 2010; Kalonji Kabambi et al. 2017).

5.1 NUMERICAL ONE-DIMENSIONAL MODELS IN SEEP/W

In this paper, three one-dimensional (1-D) conceptual models were built to represent three different segregation scenarios as shown in Figure 7. These models are based on different air-entry values (AEV) derived from different WRCs that were estimated by lab-determined PSD curves, dividing the 1-D numerical domain in strata with different material properties.

The first 1-D numerical model (Figure 7-a) represents Scenario 1 in which the segregation process has resulted in the highest level of PSD heterogeneity with four particle-size related strata: Stratum 1 that corresponds to a fine material with an AEV of 10 kPa, Stratum 2 that refers to a coarse (loose) material with an AEV of 5 kPa, Stratum 3 that has the same properties as Stratum 1 (i.e. AEV = 10 kPa) and Stratum 4 that corresponds to a very fine material with an AEV of 25 kPa. Scenario 1 is the one with the highest degree of heterogeneity and corresponds to the situation observed at Station 8 (real case).

The second 1-D numerical model (Figure 7-b) represents Scenario 2 in which the segregation process has generated only two particle-size related strata: Stratum 1 that corresponds to a fine material with an AEV of 10 kPa and Stratum 4 that corresponds to a very fine material with an AEV of 25 kPa. Scenario 2 corresponds to a hypothetical situation in which the cover profile is dominated by a fine material.

The third 1-D numerical model (Figure 7-c) represents Scenario 3 in which the segregation process has generated two particle-size related strata: Stratum 2 that corresponds to a coarse material with an AEV of 5 kPa and Stratum 4 that corresponds to a very fine material with an AEV of 25 kPa. Scenario 3 corresponds to a hypothetical situation in which the cover profile is dominated by a coarse material.

Stratum 4 that is located on top of the interface between the Goldex and the stratum Manitou tailings will not influence the numerical simulations because it is permanently saturated as confirmed by field Ψ and water table level data and with a k_{sat} estimated at 2.54 x 10^{-7} m s^{-1}. Therefore, the hydrogeological behavior of the MC+EWT will be evaluated based on the "hydrogeologically active" strata i.e. Strata 1, 2 and 3.

Some properties of the Manitou tailings used as inputs during simulations in SEEP/W are as follows: thickness of the Manitou tailings = 1 m; AEV = 22 kPa, n_{vG} = 1.89, θ_{sat} = 0.46 m^3 m^{-3}; k_{sat} = 1 x 10^{-7} m s^{-1}.

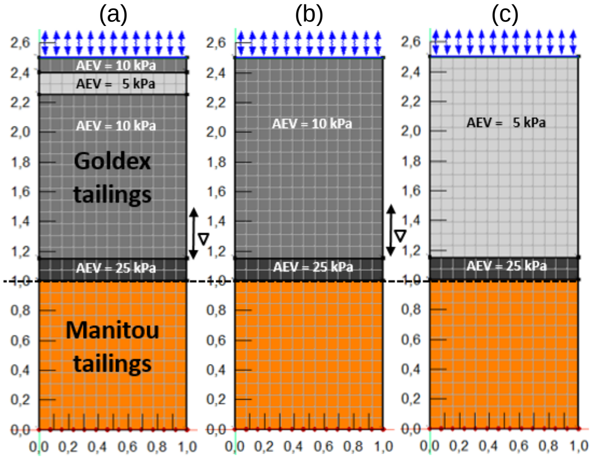

Figure 7. Conceptual 1-D models in SEEP/W representing three different segregation scenarios: (a) Scenario 1 (real case, heterogeneous profile with the presence of a coarse material in a profile dominated by fine materials), (b) Scenario 2 (hypothetical case, more homogeneous profile dominated by fine materials) and (c) Scenario 3 (hypothetical case, more homogeneous profile dominated by coarse materials)

5.2 LAND-CLIMATE INTERACTION BOUNDARY CONDITION

5.2.1 UPPER BOUNDARY CONDITIONS

The local climate in the Abitibi region is cold temperate. Daily data on air temperature, precipitations, relative humidity and wind speed as well as solar radiation and a selected albedo of 0.15 were used as inputs for the land-climate interaction boundary condition in SEEP/W. The Penman-Wilson evaporation method was selected. The temperature and precipitation data that were used in the numerical simulations are shown in Figure 8. From May to October 2016, maximum temperatures were around 25°C whereas the highest volume of precipitation recorded was around 35 mm.

No vegetation parameters were included in the land-climate interaction boundary condition because vegetation was absent at Station 8 (i.e. bare soil) and runoff was considered to be negligible due to a flat topography.

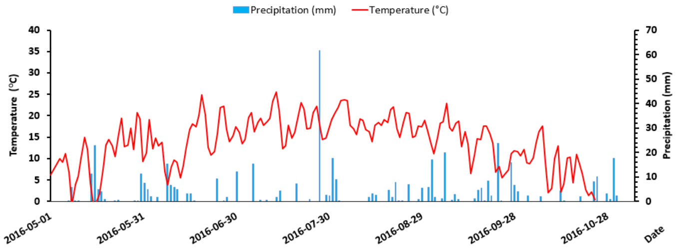

Figure 8. Evolution of daily temperatures and precipitation from May to October 2016 recorded at the Val d'Or meteorological station (15 km distance from the Manitou site)

5.2.2 LOWER BOUNDARY CONDITIONS

Based on monthly observations of water table level in well points in combination with Ψ data at various depths, a sinusoidal function was generated by SEEP/W to simulate the variation of the water table with time from May to October 2016 (Figure 9). It represents the lower boundary condition.

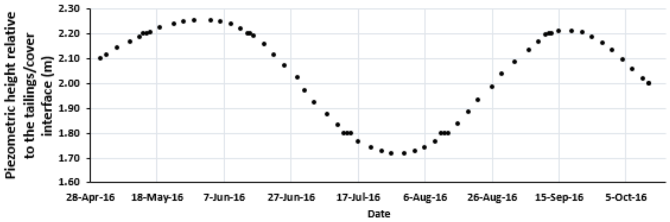

Figure 9. Sinusoidal function of the water table level generated by SEEP/W from well point height data relative to the tailings/cover interface

6 PRELIMINARY SIMULATION RESULTS OF VOLUMETRIC WATER CONTENT DYNAMICS

Volumetric water content (VWC) values measured by the EC-TM sensors and recorded with the EM-50 datalogger at Station 8 from May to October 2016 are depicted in Figure 10 (black circled line).

Discrepancies between measured and simulated VWC values can be quantified using the root mean square error (RMSE) index.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\theta_{s_i} - \theta_{m_i}\right)^2}$$

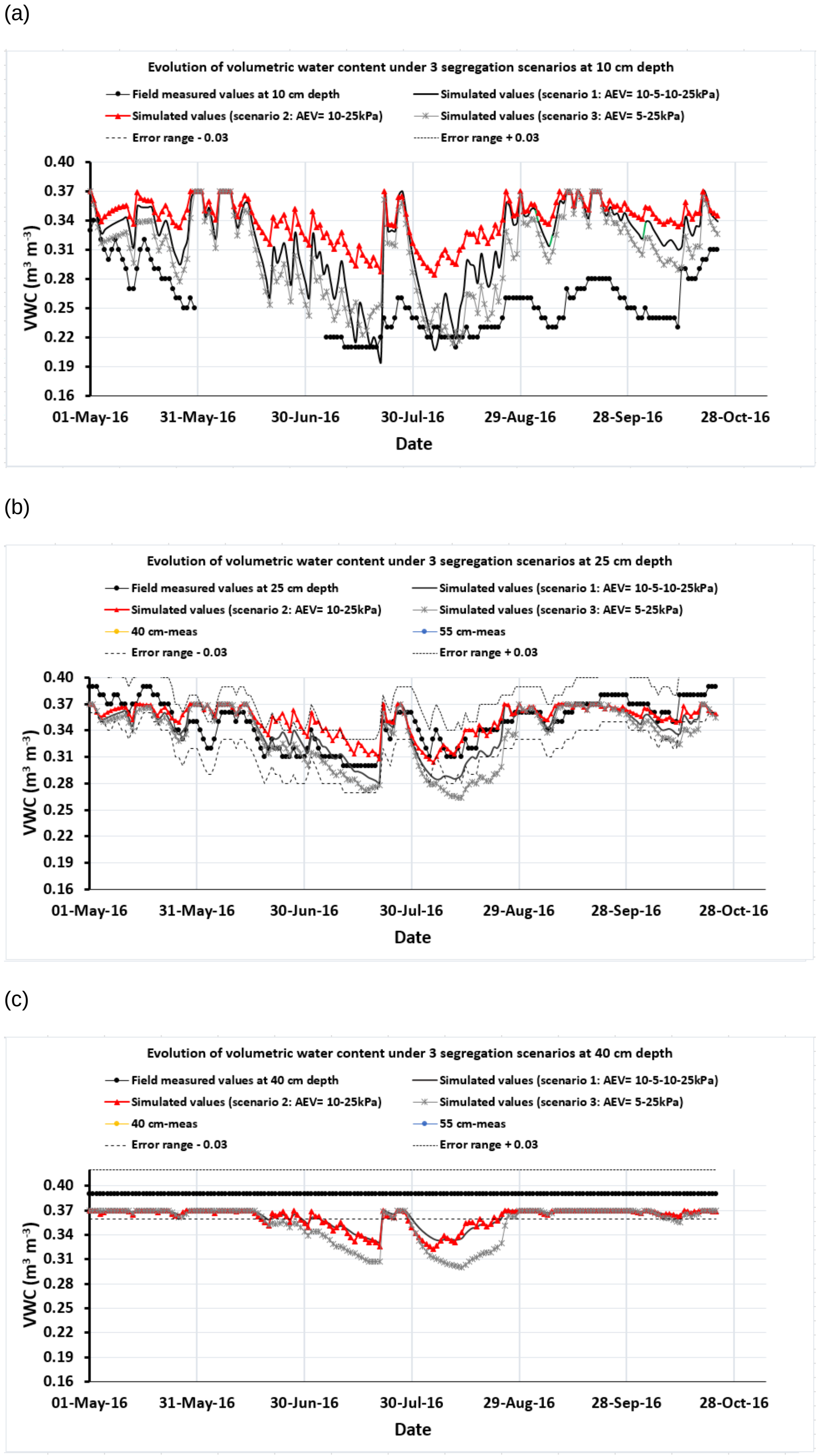

Figure 10. Evolution of volumetric water contents measured and simulated under three segregation scenarios at 10, 25 and 40 cm depth from May to October 2016

where θ_{si} and θ_{mi} are the simulated and measured VWCs at a given depth for the i^{th} day ($m^3\ m^{-3}$), respectively and N is the number days of simulation or measurement.

Field measured values did not correspond to simulation values at 10 cm depth with high RMSE values of 0.069, 0.087 and 0.056 $m^3\ m^{-3} > 0.030\ m^3\ m^{-3}$ for Scenarios 1, 2 and 3, respectively as shown in Figure 10-a. This might be due to difficulties of the model to correctly simulate evaporation processes occurring at the surface of the MC. Also, we speculate that the sinusoidal function generated in SEEP/W did not represent all the variations of the water table that have been observed in the field during the study period. Another reason of the discrepancies might be that important material properties such as the WRC and the HCF were estimated from predictive functions.

Both measurement and simulation results reported a desaturation of the monolayer cover at 25 cm depth from mid-June to 20 July and in August 2016 (Figure 10-b). The SEEP/W numerical model was able to simulate the evolution of VWC from 25 to 135 cm depths under three scenarios with a RMSE < 0.030 $m^3\ m^{-3}$ which is considered as the measurement error range of the EC-TM sensor. In Scenario 1, a slight underestimation of VWC at 25 cm depth was observed in August whereas a slight overestimation was observed from mid-June to around 20 July in Scenario 2 resulting in a relatively low RMSE value of 0.020 $m^3\ m^{-3}$ for Scenario 1 and of 0.021 $m^3\ m^{-3}$ for Scenario 2. An underestimation of VWC was observed from 10 to 20 July and was more pronounced in August in Scenario 3 resulting in a higher RMSE value of 0.026 $m^3\ m^{-3}$.

The EC-TM sensors data indicated that MC+EWT was water saturated at 40 cm as shown in Figure 10-c and particularly at 55 and 135 cm depths (results not shown here) whereas simulation results showed a desaturation from end-June to 20 July and in August at 40 cm depth (Figure 10-c) and a slight desaturation for the same period at 55 cm depth for all the 3 scenarios (results not shown here). At 40 cm depth, a similar trend to the simulations at 25 cm depth was observed for Scenarios 1, 2 and 3 but with higher RMSE values (= 0.030, 0.031 and 0.042 $m^3\ m^{-3}$) mainly due to discrepancies between simulated and observed VWC values during summer. A slight desaturation during summer showed by the numerical model results were not corroborated by the sensors measurements showing water saturation from May to October 2016. This desaturation might be due to the influence of the sinusoidal function of the water table level.

At 55 cm depth, a similar situation was observed as with 40 cm depth but with slightly lower simulated VWC values during summer that were not measured on the field by the sensors and resulting in RMSE values around 0.024, 0.025 and 0.027 $m^3\ m^{-3}$ for Scenarios 1, 2 and 3 (results not shown here).

At 135 cm depth, both field and simulation results showed that the MC+EWT was permanently saturated at the Goldex-Manitou tailings interface for all 3 scenarios with RMSE values of 0.004 $m^3\ m^{-3}$ (results not shown here). This confirms that the MC+EWT is an efficient technique for maintaining the Manitou reactive tailings permanently under water during humid and dry periods.

Globally, the numerical simulations showed that the presence of a coarser grained layer close to the surface (25 cm depth) due to segregation has limited effect on the hydrogeological behavior of the MC+EWT observed at Station 8, for a depth ≥ 25 cm.

7 CONCLUSION AND FUTURE WORK

Comparison of field measurements and numerical simulation results showed that vertical heterogeneity in PSD due to segregation of solid particles during Goldex tailings deposition at Station 8 has a limited effect on the hydrogeological behavior of the MC+EWT.

However, in case the segregation process results in profiles with contrasted PSD characteristics between adjacent strata that are not permanently saturated, other phenomena such as temporary capillary barrier effects to water infiltration or evaporation could occur. These effects can significantly influence the performance of the cover system and need further investigations. More studies are needed to better understand the influence of vertical PSD heterogeneity combined with other factors such as the presence of plant roots on the hydrogeological behavior of the monolayer cover at TSF 2.

Ongoing work aims at finding the causes of the discrepancies between field measurements and simulation results at the top of the MC+EWT (i.e. at 10 cm depth) and during summer periods where evaporation is the dominant process and eventually correcting the discrepancies. Moreover, numerical simulations will be done for seven other stations among which four stations covered with herbaceous vegetation. The influence of vegetation on the water balance of the MC+EWT will also be investigated.

8 ACKNOWLEDGEMENTS

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