3D numerical assessment of the permeable envelope concept for in-pit disposal of reactive mine wastes

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ABSTRACT
In-pit disposal of mine waste is a promising alternative management approach to piles and tailings impoundments deposition. Yet, the presence of dissolved oxygen and ferric ions in underground water could contribute to acid mine drainage (AMD) generation. The permeable envelope or pervious surround approach could contribute to limit contact between fresh underground water and reactive mine wastes. It consists of non-reactive waste rocks placed along the pit walls to create preferential paths for underground water. The performance of such an approach was assessed in this paper using high resolution 3D numerical models. Simulation showed that a permeable envelope could reduce flow rate in the back-filled tailings by 90%. Model validation and a preliminary sensibility analysis were also carried out. The paper presents the numerical approach and discusses the main results from the 3D models.

RÉSUMÉ
La déposition des rejets dans les fosses est une alternative prometteuse à la déposition dans les haldes et les parcs à résidus. Cependant, la présence d'oxygène dissous et d'ion ferrique dans l'eau souterraine pourrait contribuer à la formation de drainage minier acide (DMA). La technique de l'enveloppe perméable a été proposée afin de limiter le contact entre l'eau souterraine et les rejets miniers réactifs. Elle consiste à ajouter une couche de stériles non réactifs le long des murs de la fosse afin de créer des chemins d'écoulement préférentiels. La performance de cette technique a été étudiée à l'aide d'un modèle numérique 3D haute résolution. Les simulations montrent que l'enveloppe perméable pourrait réduire de près de 90% les débits circulant dans les résidus miniers remblayés. Une validation du modèle ainsi qu'une étude de sensibilité préliminaires ont également été réalisées. Cet article présente l'approche numérique, discute des principaux résultats des modèles 3D et propose quelques recommandations afin d'améliorer la représentativité des simulations.

1 INTRODUCTION

Open-pit mining generates large volumes of waste rocks and tailings, which are usually disposed of at the surface. The dimensions of waste rock piles and tailings impoundments can exceed hundreds of meters in height and hundred of hectares. Waste rock and tailings also sometimes contain sulfides which can oxidize and generate acid mine drainage (AMD) or contaminated neutral drainage (CND) (Aubertin et al. 2002, Blowes et al. 2014, Nordstrom et al. 2015).

In-pit disposal is an alternative approach to manage mine wastes which eliminates the need to maintain engineered structures, decrease environmental footprint and has a good social acceptance (MEND 2015). In-pit disposal can also help improve geochemical stability of reactive wastes. Various in pit disposal techniques exist, like dry disposal with cover, wet disposal with or without water cover or chemically and physically engineered mine waste deposition (MEND 2015).

Wet disposal has the advantage to keep the reactive wastes saturated, thus limiting the atmospheric oxygen diffusion and oxidation (MEND 2001). However, inflow of dissolved oxygen and iron with fresh groundwater could contribute to the oxidation of sulfide minerals and the generation of AMD or CND. For example, the Aznacollar mine pit have been back-filled with over 6.4 million cubic meters of reactive tailings, fly ash, and waste rock, which were then covered by water (Santofimia et al. 2013). Environmental monitoring during the following years have shown water acidification, a total consumption of dissolved oxygen and an increase of water temperature and electrical conductivity. Therefore, pit water in this case needs to be continuously treated before it is released in the environment. The reason suggested to explain these observations was the oxidation of the 1.4 Mm^3 of pyritic waste rock disposed of in the pit (Santofimia et al. 2013).

Exchanges with the surrounding environment therefore need to be controlled to ensure the long term geochemical stability of reactive wastes disposed of in pits. At Flambeau mine – Wisconsin, disposed tailings have been mixed with neutralizing materials to ensure good water quality (FMC 2010). At Don Rouyn mine – Quebec, tailings are kept saturated under a constant water table controlled by a spillway (Awoh et al. 2013). Finally, at Rabbit Lake – Saskatchewan, preferential flow paths have been created along the rock walls to limit the contact between groundwater and the tailings disposed of in the pit (MEND 2015). The later approach is often called the permeable envelope technique or pervious surround method; it consists in surrounding reactive mine wastes with a more conductive and non reactive material to deviate groundwater and avoid its contamination (West et al. 2003, Thériault 2004, Lange and Van Geel 2011, MEND 2015).

Previous studies analysed the performance of the pervious surround method using experimental tests and numerical modeling. Experimental work focused on the transport of contaminants from back-filled tailings to the neighboring porous medium or fractured porous medium (West et al. 2003, Lange and Van Geel 2011). Results were also simulated numerically; porous and fractured porous medium were modeled by single or double continuum approach (West et al. 2003, Lange and Van Geel 2011). These works highlighted the diffusive transport mechanism of contaminant from back-filled tailings to the environment. A parametrical study of the performance of a permeable envelope was also carried out by Thériault (2004). The effectiveness of pervious surround to deviate groundwater from the tailings was assessed using discrete fracture network approach. The effect of various parameters, like pit size, hydrogeological properties and fracture density, was also assessed. Conclusions indicated that a 5.6 meter width envelope (for a 100 m square side pit) was able to deviate 86% of the groundwater flow. Other numerical studies have shown the first importance of fractures on in pit flow and solute transport (Ben Abdelghani et al. 2014).

However, these numerical studies of the pervious surround technique were carried out in 2D or were not fully representative of realistic pit geometry. The present study therefore aims at investigating the ability of the permeable envelope technique to deviate groundwater from back-filled tailings using high resolution 3D numerical simulations and explicit fracture network flow. This paper presents preliminary results, including the numerical approach and some results from 2D and 3D models. The influence of tailings hydraulic conductivity on the permeable envelope effectiveness and on the regional flow was also assessed. Some recommendations to improve the representativeness of the simulations in future work are also presented.

2 METHODS

2.1 Conceptual model

The simulated case was composed of a 73 meters radius conic pit, with 45 degrees inclined walls, in a 460×420×200 meter domain (Figure 1). The permeable envelope width was 5.6 meters. The domain was subdivided into 4 zones: the permeable envelope (in red in Figure 1), the back-filled material (brown), the intact rock (grey) and the fracture network (green). The fracture network was composed of synthetic infinite-extended orthogonal fractures spaced of 10 meters with a constant aperture of 0.1 mm (Figure 1). This geometry was chosen as a first order approximation of a real pit (West et al. 2003) and because it was similar to previous 2D studies made by Thériault (2004).

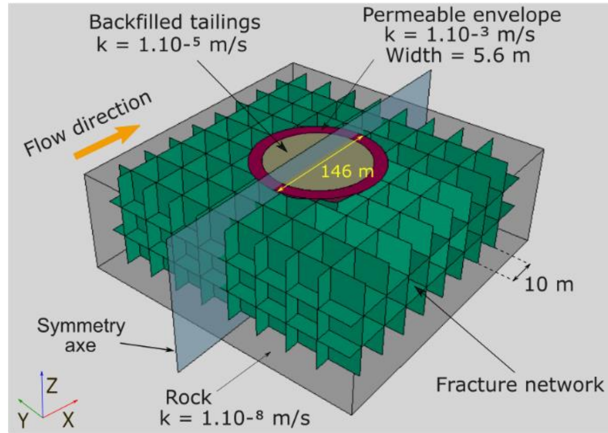

Figure 1: Conceptual model of the studied case. Four zones were defined: back-filled tailings (brown), permeable envelope (red), intact rock (grey), and fracture network (green). The closed volume defined by tailings (brown zone) was named V_T, and the volume defined by tailings and the permeable envelope (brown and red zones) was named V_P. Groundwater regional flow was oriented from negative *x* to positive *x* (yellow arrow). The conceptual model is symmetric along (Oxz) plane.

2.2 Numerical model

2.2.1 Simulation approach

Geometry definition and meshing were performed automatically with the Salomé software (Ribes and Caremoli 2007), an open-source CAD tool, using programed scripts developed by the author. Script inputs included domain size, pit size and shape, and fracture network parameters (orientation, spacing, opening). Numerical simulations of saturated flow were conducted with the HydroGeoSphere software (Therrien and Sudicky 1996), and data visualization (following data conversion and post-processing) was carried out with the Paraview software (Ayachit 2015). Calculation scheme is illustrated in Figure 2.

2.2.2 CAD model

Domain was represented by a 460×420×200 m box centered on the origin with its surface at the z=0 plane. The simulated pit was centered on the origin and was obtained by extrusion around the z axis. The permeable envelope was defined using a vertical translation of the pit walls. In the CAD model, the depth of the pit was 72.5 m. Three dimensional zones were defined by domain partition. Fracture network was modelled as a set of 2 dimensions objects represented by planes crossing the entire domain. Each plane was characterized by its aperture (assumed constant). The model was symmetric along the (Oxz) plane and only half of the domain was simulated to reduce computation time.

2.2.3 Hydrogeological properties

Waste rock, tailings and intact rock (between fractures) were considered as continuum medium and their hydraulic conductivities were $1×10^{-3}$ m/s, $1×10^{-5}$ m/s, and $1×10^{-8}$ m/s, respectively. These values are typical for waste-rock (Peregoedova 2012), sandy tailings (Bussière 2007), and hard rock crystalline matrix (Sykes et al. 2009, Zharikov et al. 2014, Shapiro et al. 2015). Rugosity was not simulated

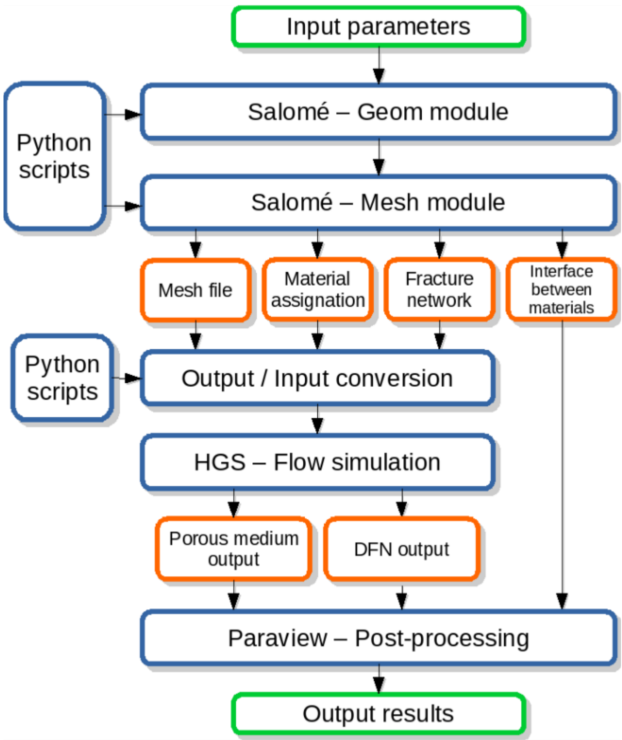

Figure 2: Calculation scheme for the simulation of groundwater flow and permeable envelope effectiveness. Python script were used to load input parameter provided by the user to Salomé. Geometry was first generated, followed by meshing. Output files (orange boxes) were converted in the adequate format to be read by HydroGeoSphere (HGS). Flow simulations were carried out with HGS. Results data were post-processed and visualized with Paraview.

in this study and each fracture was considered as a void between two parallel planes (Snow 1965). Fracture aperture was 0.1 mm, and in-fracture flow was described using the local cubic law (Berkowitz 2002). Regional hydraulic gradient was 2% and simulations were carried out assuming a fully saturated domain and steady state conditions. All the hydrogeological properties were assumed homogeneous and isotropic.

The influence of tailings properties on the permeable envelope effectiveness and regional flow was assessed by simulating hydraulic conductivities comprised between 1×10^{-8} m/s and 1×10^{-3} m/s, which corresponds to the typical range of field hydraulic conductivities for hard rock mines (e.g. Bussière 2007).

2.2.4 Initial and boundary conditions

Constant head conditions were imposed on boundaries parallel to (Oyz) plane. Water table was assumed to be located at +19.2 m at one side (negative x) and +10 m at the other side (positive x); the regional hydraulic gradient was therefore 2% and the domain was fully saturated. Boundaries perpendicular to (Oyz) were assumed impermeable (no flow). Groundwater flow was directed in the (Ox) direction from negative to positive *x* (yellow arrow in Figure 1).

2.2.5 Meshing

Meshing was performed using the open-source algorithm NETGEN (Schöberl 1997), included in the Salomé software. The permeable envelope was meshed with tetrahedral elements of maximum size 0.25 m. Mesh size was coarser in the other zones: 3 m, 3.5 m and 4 m for back-filled tailings (in the pit), 2D fracture network (triangular elements) and intact rock, respectively. The element maximum size was selected based on a preliminary sensibility analysis to ensure numerical result stability of the solution. The same mesh was used for the cases with and without envelope. The latter was simulated by giving the permeable envelope the same hydrogeological properties than the back-filled tailings.

Approximately 27 million elements were computed for the studied case. The Salomé mesh output was then converted into HydroGeoSphere input format. The default options implemented in the HydroGeoSphere code were used for solving the saturated flow: the numerical solution was based on the control volume finite element method, and the common node approach to define the discrete fracture flow domain was used.

2.3 Permeable envelope performance assessment

Permeable envelope effectiveness *E* was defined by comparing inflow through tailings in presence of a permeable envelop, Q_{with} and without a permeable envelope, $Q_{without}$ (Thériault 2004):

$$E = 1 - \frac{Q_{with}}{Q_{without}} \qquad [1]$$

$E > 0$ would mean that there is less groundwater flowing into the back-filled tailings with an envelope than without, *i.e.* the envelope is effective to divert water. Case $E = 1$ would indicate that the permeable envelope is fully effective and is able to deviate all groundwater flow from back-filled material.

2.4 Numerical model validation

A parametric analysis was carried out to determine the sensibility of calculated flow for varied domain and mesh size and validate the representativeness of the simulations. Two criteria were analyzed for model validation: (1) mass conservation law and (2) stability of numerical results versus mesh and domain size.

2.4.1 Mass conservation validation

The law of conservation of mass ensures that inflow in a given volume is equal to outflow when the domain is fully saturated. Mass conservation was verified for two closed volumes in the simulations: the first defined by the tailings, named V_T, and the second defined by the tailings and the pervious surround, named V_P (see Figure 1). The error ϵ between inflow Q_{inflow} and outflow $Q_{outflow}$ was calculated for both volumes using the following equation:

$$\epsilon = \frac{|Q_{inflow} - Q_{outflow}|}{2}\left(\frac{1}{Q_{inflow}} + \frac{1}{Q_{outflow}}\right) \qquad [2]$$

For the closed volume V_P (tailings and envelope), water was flowing in from the rock and from the fracture network. The law of conservation of mass was adapted to assess the global flow both in the rock and the fractures:

$$(Q_{rock})_{\text{in}} - (Q_{rock})_{out} + (Q_{DFN})_{\text{in}} - (Q_{DFN})_{out} = 0 \qquad [3]$$

With Q_{rock} the contribution of the rock (porous medium), Q_{DFN} the contribution of the fracture network (discrete medium), and the subscript in and out designing inflow and outflow, respectively. For the closed surface V_T, calculation was easier because there was only one contribution from a porous medium.

2.4.2 Numerical result stability and optimization

Simulations were carried out using different domain sizes comprised between 300 and 540 m in the (Ox) direction, between 300 and 460 m in the (Oy) direction, and between 150 and 200 m in the (Oz) direction to assess the effect of the domain size on the calculations. The optimal domain size minimizes both the side effects and the number of elements in the model. In other words, a domain too small would be influenced by the fixed boundary conditions, and a domain too large could increase significantly the computation time. The effect of domain size was supposed to be negligible when an enlargement of a given domain lead to the same results in terms of water flow. The effect of element (mesh) size on the results was also assessed. Permeable envelope maximal mesh size appeared to be the most critical parameter affecting the flow on closed surface V_T and V_P (see section 2.4.1), and is therefore discussed in more details in section 3.1.

3 RESULTS

3.1 Numerical results stability

Geometry generation and meshing could take up to 10 hours of computation on a Core I7 6700 machine with 16GB of RAM, for a total of approximately 27 million elements. Saturated flow was simulated in less than 15 minutes for every studied cases. Attempts to generate mesh sizes of 0.2 and 0.15 m were unsuccessful because of lack of RAM.

Domain size was optimized for each direction. Domain size in (Ox) and (Oy) directions did not have a significant influence on the results in the tested range; the error between inflow and outflow was always less than 1% (Figure 3). This error was systematic in the (Ox) direction for both closed volumes, *i.e.* 0.28% for V_P (tailings and envelope) and 0.60% for V_T (tailings only; Figure 3a and Figure 3b) and in the (Oy) direction for closed volume V_T (0.25%; Figure 3e). Reducing domain size in the (Oz) direction (vertical) lead, however, to significant variations in the contribution of fracture network Q_{DFN} on the closed

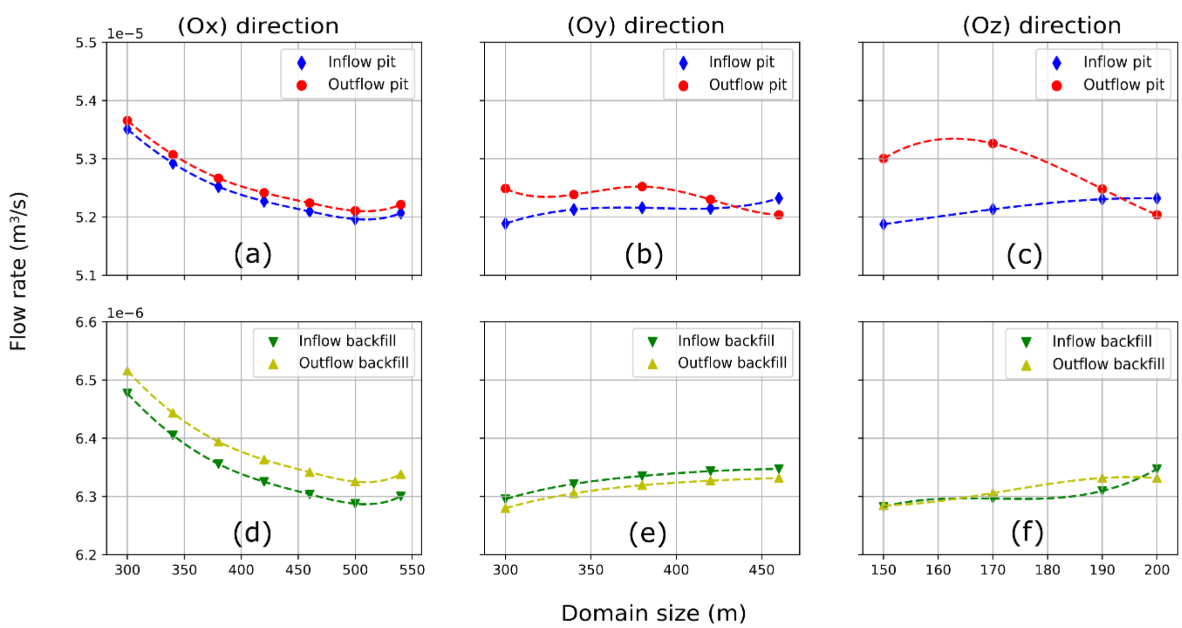

Figure 3: Inflow and outflow in closed volume V_P (a,b,c) and V_T (d,e,f) for different domain sizes in (Ox), (Oy) and (Oz) direction respectively.

volume V_P, resulting in more than 2% error for mass conservation (Figure 3c). Flow rate tended to become constant as the domain size increase. Optimal domain dimension for the studied case was 460×420×200 m, which was approximately 3 times the pit size in each direction.

The effect of the maximum element size on numerical results stability and mass conservation law was assessed in terms of flow on closed surface V_P and V_T (Figure 4a and 4b). Flow in pit and back-filled tailings, as well as mass conservation error, decreased with decreasing element size. Difference between inflow and outflow in tailings was always under 0.5% for all mesh size (Figure 4b). Flow rate showed a decrease of 30% when decreasing maximal mesh size from 0.5 m to 0.25 m, indicating that mesh size in permeable envelope have a strong influence on the flow through V_T.

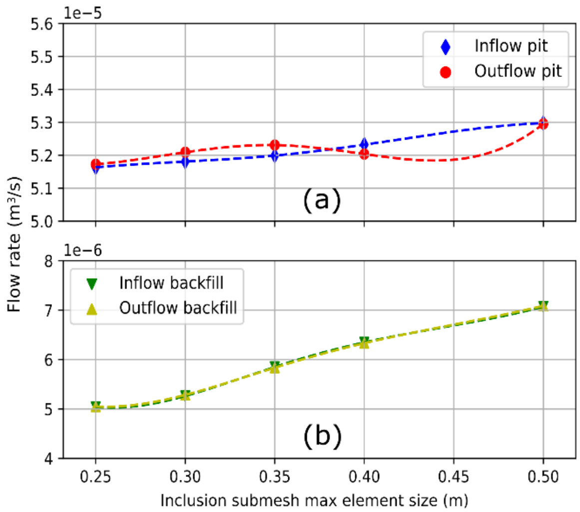

Figure 4: Inflow and outflow in closed volume V_P (a) and V_T (b) for different mesh size from 0.25 to 0.5 m.

Fracture network contribution Q_{DFN} to global flow through V_P was constant and equal to 93% in every tested case.

3.2 Permeable envelope effectiveness

Simulated inflow into back-filled material was approximately 5.0×10^{-5} m^3/s without an envelope, and around 5.0×10^{-6} m^3/s with a permeable envelope. The effectiveness of the permeable envelope was therefore 90% for the studied case.

Hydraulic heads in the fractured rock, outside the back-filled pit, were not significantly affected by the permeable envelope, and the simulated inflow in the pit for both cases (with and without an envelope) were similar (i.e. 5.2×10^{-5} m^3/s with an envelope and 5.0×10^{-5} m^3/s without an envelope; Figure 5). The effect of the permeable envelope on the flow in the pit was more pronounced. The hydraulic gradient in the back-filled tailings was equal to 2.0% (i.e. equal to the regional gradient; Figure 5a) without an envelope, but decreased to less than 0.03% with an envelope (Figure 5b). Velocities in back-filled tailings were also reduced (1×10^{-8} m/s to 7×10^{-10} m/s), and high velocities (around 7×10^{-8} m/s) were observed in the pervious surround (Figure 6), especially at the intersection between rock wall and fractures. Streamlines (Figure 7) indicated that water flow was effectively diverted in the envelope, around and below the tailings. Separated evaluation of contribution from rock and fracture network showed that the fracture network accounted for 93% of the total flow in the pit (with and without envelope).

3.3 Comparison with previous study

Thériault (2004) had numerically studied the effectiveness of the permeable envelope technique for various conditions using 2D simulations. The geometrical model was similar to the one presented in this study and composed of a square based pyramidal pit shape of 100 m side, 73 m depth with 45 degrees inclined walls; permeable envelope

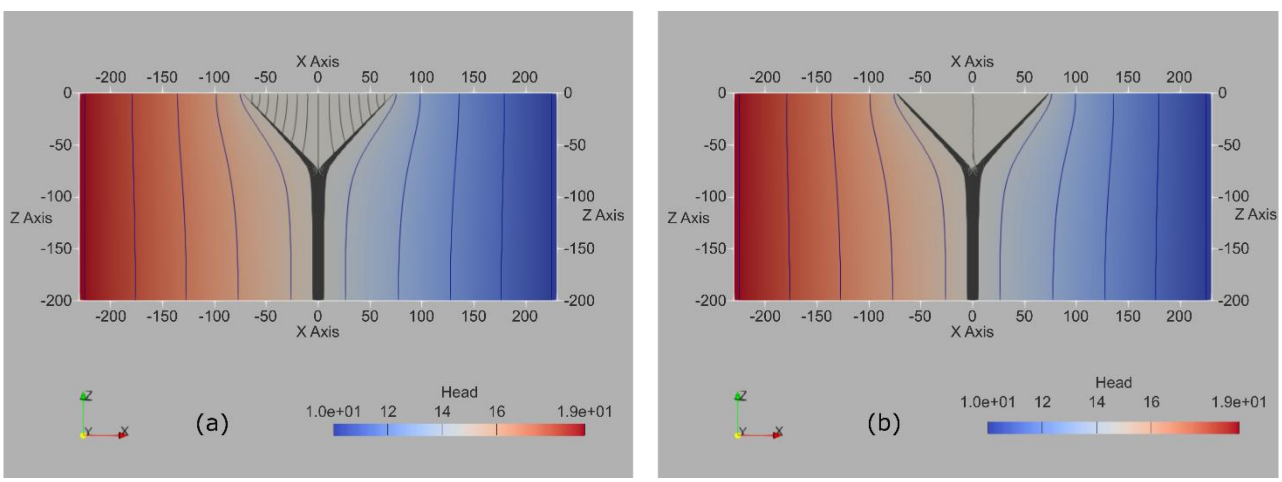

Figure 5: Hydraulic head h in y=1m cross-sectional plane (a) without envelope, and (b) with envelope. Dark blue lines are 1m isohypses from h=10.1 to h=19.1m and dark lines are 0.01cm isohypses from h=14.5 to h=14.7m. Water is flowing from the left of the figure to the right (from higher to smaller heads).

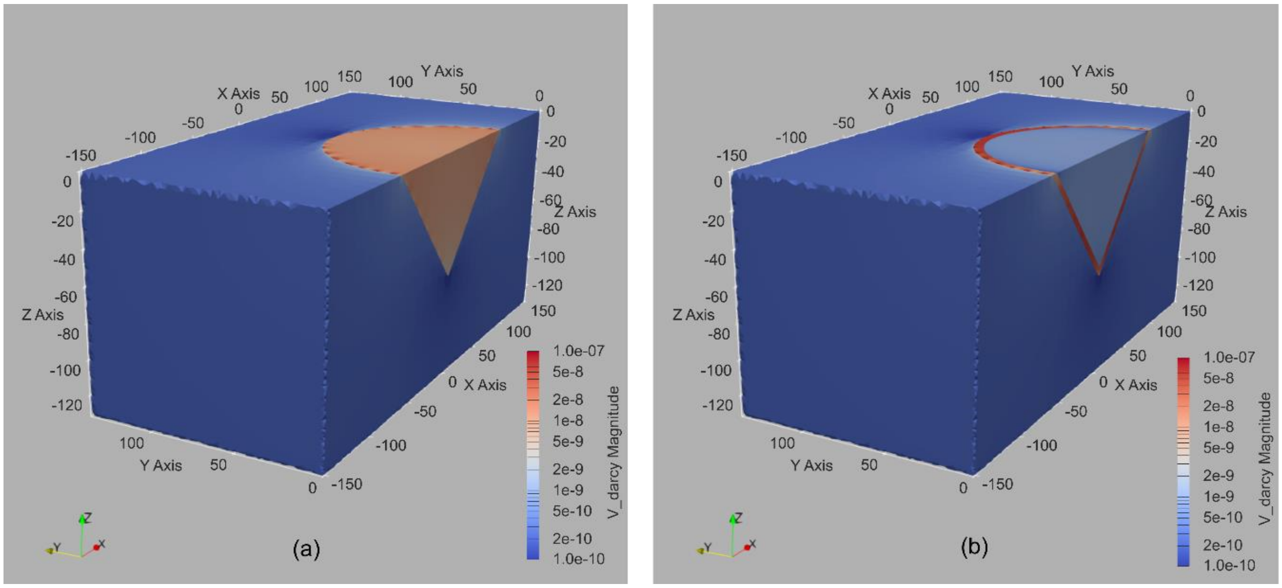

Figure 6: Flow velocities magnitude (a) without envelope and (b) with envelope. Blue color corresponds to low velocities zones and red color shows high velocities zones.

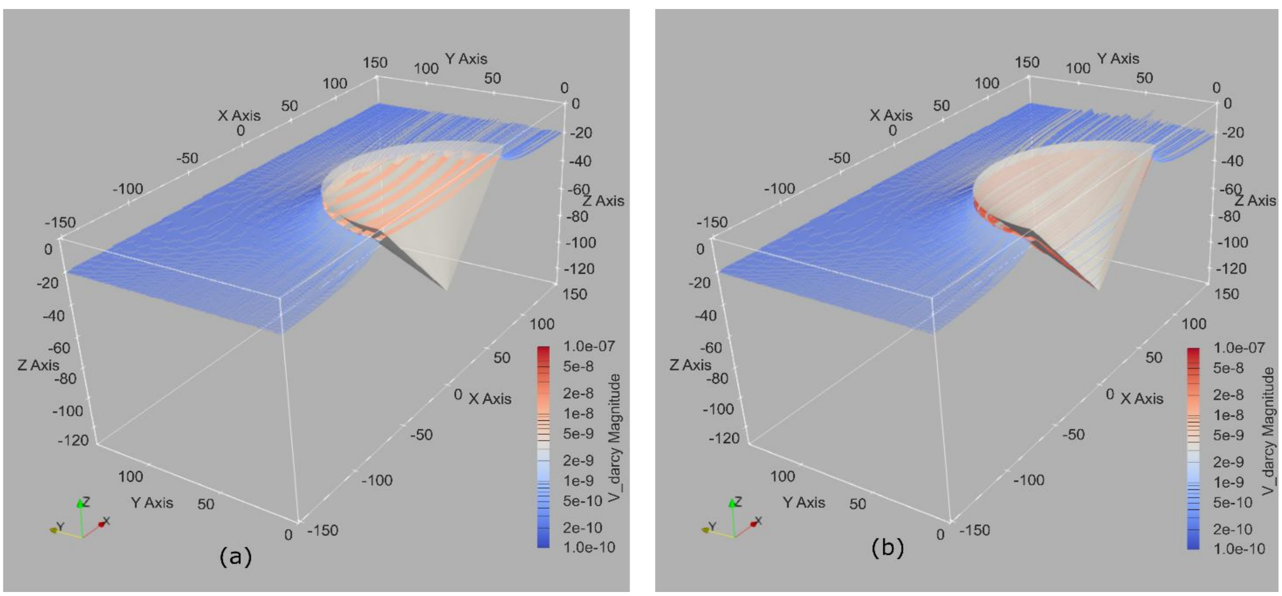

Figure 7: Streamlines for a line source at z=-20 m without envelope (a) and with envelope (b). Flow is effectively diverted on the surround and the bottom of the pit with the envelope. Blue color on streamlines is low flow velocity (in the rock) and red color on streamlines is high flow velocity (in the back-filled tailings and the envelope). Interface between the permeable envelope and back-filled tailings (V_T) is shown in light gray.

was 5.6 meters width. Hydrogeological properties were also the same as those used in this study (see section 2.2.3). A parametrical analysis was carried out, including various pit widths (from 59 to 269 m), with envelope and without envelope (Thériault 2004). These results in 2D for various pit size were upscaled in 3D and compared to the simulations presented in this article.

2D in-pit inflow versus pit depth was interpolated based on published results (blue and red dots in Figure 8; Thériault 2004) and using power-law and linear regression (blue and red dashed line on Figure 8). Regression laws were then integrated over pit depth. Upscaled flow in back filled materials was 1.8×10^{-6} m^3/s with an envelope and 1.8×10^{-5} m^3/s without an envelope (Figure 8). The envelope effectiveness was thus 90% using equation 1, i.e. in the same order of magnitude than those obtained in this study (5.0×10^{-6} m^3/s with envelope, 5.0×10^{-5} m^3/s without; see section 3.2). Upscaling should however be considered with precaution because of the difference in pit geometry and simplified extrapolation technique.

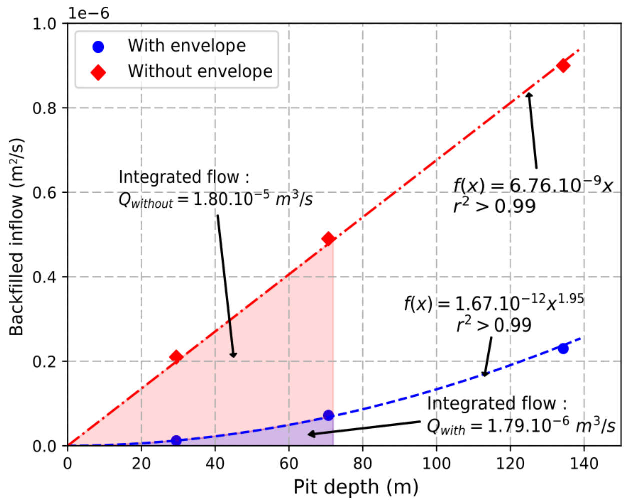

Figure 8: 3D extrapolation of 2D result from Thériault (2004) in horizontal plane, giving an upscaled effectiveness of 90%. True 3D flow in tailings for case with envelope is 5.0×10^{-6} m³/s, and without envelope 5.0×10^{-5} m³/s, for an effectiveness of approximately 90%.

3.4 Influence of tailings hydraulic conductivity

The influence of tailings hydraulic conductivity was assessed in term of water inflow through the closed volume V_P (tailings + permeable envelope) and V_T (tailings only). Inflow through V_P with an envelope was constant and equal to 5.2×10^{-5} m³/s, independently of the tailings' hydraulic conductivity (Figure 9). An efficient permeable envelope therefore hydraulically decouples tailings from the environment, *i.e.* tailings properties have no significant effect on the global domain flow. The tailings flow V_T without envelope was comprised between 3.0×10^{-5} m³/s and 5.2×10^{-5} m³/s, depending on the tailings' hydraulic conductivity. Maximum inflow was controlled by the rock mass hydraulic conductivity (Figure 9) and was equal to the

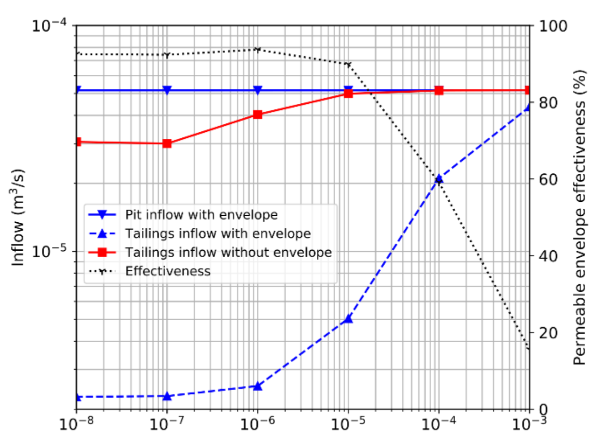

Figure 9: Inflow through closed volume V_T (back-filled tailings) and V_P (tailings + permeable envelope) with and without envelope and for various tailings conductivities. Permeable envelope effectiveness is also shown.

case with an envelope. Inflow through V_T (back-filled tailings) in the case with an envelope decreased with the tailings hydraulic conductivity (Figure 9). The minimum flow in the tailings was around 2.2×10^{-6} m³/s independently of their hydraulic conductivity. Finally, the permeable surround effectiveness was maximum (> 90%) for tailings hydraulic conductivities lower than 1×10^{-5} m/s (Figure 9).

4 DISCUSSION AND CONCLUSION

The present paper aimed to assess the effectiveness of the permeable envelope technique for in-pit disposal using 3D numerical simulations. A fast and reliable method using open-source software for generating complex 3D models, including geometrical definition and meshing, was used. Numerical simulations were conducted in three dimensions using the Hydrogeosphere code. Preliminary results indicate that a permeable envelope could reduce inflow in back-filled material up to 90%. The permeable envelope does not seem to have a significant impact on the surrounding (regional) flow.

The high resolution 3D numerical model established here was possible thanks to the increased power of modern computers and meshing algorithms. The mesh contained about 27 million tetrahedral elements, versus less than 300 000 in previous studies (West et al. 2003, Thériault 2004, Lange and Van Geel 2011). Results from a previous 2D study were upscaled and were in the same order of magnitude than with the 3D model. However, some limitations remain, and it was not possible to construct a mesh with a maximum element size less than 0.25 m in the permeable envelope, even if this parameter has a direct impact on back-filled inflow.

The permeable envelope seems to hydraulically decouple the tailings from the surrounding fractured rock (in the tested conditions). Global domain flow was governed by the permeable envelope, independently of the tailings properties. This observation needs to be verified for other envelope properties such as width or hydraulic conductivity, and for other pit shapes, to determine if it is a general behavior or only a special case for a conic-shaped pit.

Finally, results presented here are preliminary and represented a simple pit in an idealized orthogonal fractured environment. Further work will focus on (1) using a more realistic fracture network, (2) considering back-filled tailings anisotropy, (3) considering near-pit variation of fracture density to investigate rock's natural permeable envelope effect (Ednie 2002), and (4) optimizing waste-rock permeable envelope geometry.

5 ACKNOWLEDGMENT

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