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Blast damaged zone influence on water and solute exchange between backfilled open-pit and the environment

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ABSTRACT
In-pit disposal of mine wastes is a promising alternative management approach to conventional disposal facilities. However, wastes disposed of in pits are in direct contact with the surrounding rock, and regional groundwater could flow in the wastes and contribute to contaminant dispersion in the environment. Blasting operations result in the creation of new fractures close to pit walls, which can provide preferential flow paths and divert flow around backfilled masses, thus reducing contamination risks. The present study aimed to investigate the influence of the blast damage zone (BDZ) on water and solute exchanges using 3D numerical modelling. Results highlighted the BDZ potential beneficial effect which could reduce the flow rate though backfilled tailings by 40% and decrease contaminants release rate in the environment by around 30%. This paper presents the BDZ simulation approaches and discusses the main results obtained.

RÉSUMÉ
La déposition de rejets miniers dans les fosses est une alternative prometteuse aux approches de gestion conventionnelles. Cependant, les rejets déposés dans les fosses sont en contact direct avec le roc, permettant ainsi à l'eau souterraine de s'écouler dans les rejets, et contribuant à la dispersion des contaminants dans l'environnement. Les opérations de sautage entrainent la création de nouvelles fractures autour de la fosse, formant ainsi des chemins préférentiels pouvant contribuer à dévier l'eau autour des rejets remblayés et réduisant ainsi les risques de contamination. La présente étude avait pour objectif d'investiguer l'influence de la zone endommagée par sautage (ZES) sur les flux d'eau et de contaminant au moyen de modèles numériques 3D. Les résultats ont montré le potentiel effet bénéfique de la ZES laquelle pourrait permettre de réduire jusqu'à 40 % le débit dans les rejets remblayés et d'environ 30 % le flux de soluté. Cet article présente le modèle de la ZES et discute des principaux résultats obtenus.

1 INTRODUCTION

Mining operations generate large quantities of solid wastes whose storage is a major challenge for the industry (Aubertin et al. 2002). Pit backfilling is an alternative disposal approach to conventional waste storage facilities (such as tailings impoundments and waste rock piles) which has many advantages, including the elimination of potential accidental release of solids in the environment, the reduction of long-term waste management maintenance, the stabilization of pit walls, an improved social acceptability and better site aesthetics at closure (MEND 2015). However, wastes disposed in pits are in direct contact with the surrounding rock, and influx of dissolved oxygen or ferric ions from groundwater could contribute to acid mine drainage generation (AMD) (Blowes et al. 2014). Contaminants contained in the waste pore water (e.g. process water) can also be dispersed in the environment. Thus, interaction between the waste and the environment need to be controlled.

Several techniques have been proposed to isolate backfilled mine wastes, such as the pervious surround method which consists in surrounding the wastes with a more permeable material to divert groundwater streamlines (Matich and Tao 1986, Salama et al. 2002, West et al. 2003, Thériault 2004, Lange and Van Geel 2011, Rousseau and Pabst 2018). The surrounding rock, if permeable enough, could also provide preferential paths for the groundwater (natural pervious surround) (Misfeldt et al. 1999, MEND 2015). Blasting during operations results in the creation of new shock-wave-induced fractures, and the extension of the existing discontinuities around the open-pit. The extend of the disturbed fractured rock is called the "blast damage zone" (BDZ) and its thickness can exceed 15 meters in some cases (Morth et al. 1972, MEND 1995). Connected fractures increase the permeability of the rock and can create a natural pervious surround. However, the effect of BDZ on flow diversion and solute transport has not been quantified yet.

he objective of this study was therefore to assess the hydraulic properties of the BDZ and its effect on groundwater flow and solute transport in a backfilled open-pit. Three-dimensional numerical simulations of a simplified pit were therefore carried out, and the influence of the BDZ on flow and transport was analyzed. In particular, the effect of the mean fracture size, BDZ thickness, and fracture trace length influence were assessed.

2 METHODOLOGY

2.1 Blast damaged zone (BDZ) model

2.1.1 Conceptual model

Fracture networks are generally characterized by fracture density, size, aperture and orientation distributions. In this study, fractures were defined as two parallel disks of constant radius noted R and separated by a constant aperture noted b. Fracture density usually decreases as the distance from the pit wall increases (Poulsen et al. 2017), and can be expressed according to the following exponential distribution law (Figure 1) (adapted from Mourzenko et al. 2011a, 2012)

$$\rho(z) = {}^{4B_{21}}\!/_{\pi^2 R^2} \exp\left({}^{-z}\!/_{l_0}\right) \quad [1]$$

With B_{21} the blast damage fracture cumulative trace length [L^{-1}], which corresponds to the total length of fractures divided by the pit wall surface area (Tuckey 2012, Tuckey and Stead 2016), z the distance from the pit wall [L], and l_0 the fracture attenuation length which characterizes the thickness of the damage zone [L]. The form of equation 1 was validated both experimentally – for excavated damaged zones around tunnels (Thovert et al. 2011, Mourzenko et al. 2012) – and numerically – for blast energy propagation (Siamaki et al. 2018).

Fracture orientation was considered isotropic in this study, which means fractures do not have a preferential orientation.

2.1.2 BDZ equivalent permeability

BDZ fracture network equivalent permeability was calculated as follows (Mourzenko et al. 2012):

$$\begin{aligned} \rho'(z) &= \pi^2 R^3 \rho(z) \\ k_f(\rho') &= {}^{b^3}\!/_{12R}\, k'(\rho') \end{aligned} \quad [2]$$

Where $\rho(z)$ is the fracture density [L^{-3}] at distance z from the pit wall, R the fracture radius [L], $k_f(\rho')$ the equivalent permeability of the fracture network [L^2] and b the fracture aperture [L]. Permeability and hydraulic conductivity can be expressed by $K = kDg/\mu$ where D is the water density [$M.L^{-3}$], g the gravity [LT^{-2}] and μ the water dynamic viscosity [$ML^{-1}T^{-1}$]. In standard conditions, the factor Dg/μ is approximately equal to 10^7 $m^{-1}\,s^{-1}$.

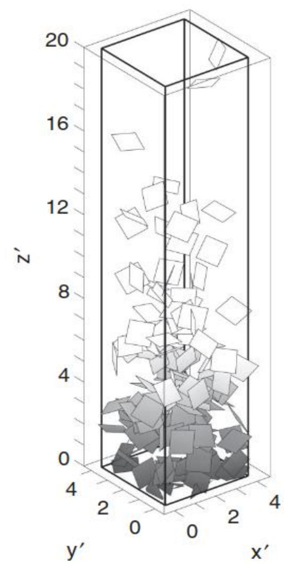

Figure 1. Conceptual model of the BDZ with square shaped fractures (circular fractures were considered in the present study). The (Ox'y') plane represents the pit wall and z' axis represents the distance from the pit wall. Fractures are colored in grey levels according to their z position (darker color indicates fractures closer to the pit wall). Adapted from Mourzenko et al. (2012)/

The dimensionless permeability of the fracture network $k'(\rho')$ can be approximated by the following heuristic model (Mourzenko et al. 2011b):

$$k'(\rho') = {}^{\alpha(\rho' - \rho'_c)}\!\Big/_{1 + \beta(\rho' - \rho'_c)} \quad [3]$$

Where α = 0.037, β = 0.155 and ρ'_c is the dimensionless fracture density at percolation threshold [-]. For circular fractures, ρ'_c = 2.4 (Mourzenko et al. 2005).

Equivalent permeability k_{eq} [L^2] for the fracture network and the rock matrix were defined as the sum of the permeability of each medium. This method, however, does not consider any coupling between the fracture network and the rock matrix and can thus underestimate the *in-situ* permeability (Mourzenko et al. 2012).

The BDZ permeability function was then expressed as a function of the distance to the pit wall by combining equations (1) to (3):

$$\begin{aligned} k_{eq}(\Delta\rho) &= k_m + {}^{b^3 \alpha\, \Delta\rho^2}\!\Big/_{12R\,(1 + \beta\,\Delta\rho)} \\ \Delta\rho(z) &= 4B_{21} R\, e^{-z/l_0} - \rho'_c \end{aligned} \quad [4]$$

Permeability of the BDZ fracture network is a decreasing function of z. Initial permeability k_0 [L²] denotes the maximum permeability of the BDZ at the pit wall, i.e. $k_0 = k_{eq}(z = 0)$.

2.2 Studied case

The studied case represented a circular open pit of 150 m radius at top, 75 m at bottom, 75 m deep, with a wall inclination of 45 degrees (Figure 2) in a rectangular domain of 2000×2000×750 m size in x, y and z direction. Pit was located at the center of the model and backfilled with tailings characterized by a hydraulic conductivity $k_w = 5\times10^{-7}$ m/s and a porosity n = 0.3 (based on typical tailings properties as reported by Bussière 2007). The regional fracture network was modeled using the equivalent porous medium approach. Such approach is usually considered valid for a well-connected fracture network (Berkowitz 2002). The hydraulic conductivity of the fracture network equivalent continuum was $k_r = 1\times10^{-8}$ m/s and its porosity n = 0.1 (Table 2). A 0.01 hydraulic gradient was applied in the x direction. Simulations were carried out in fully saturated and steady-state conditions.

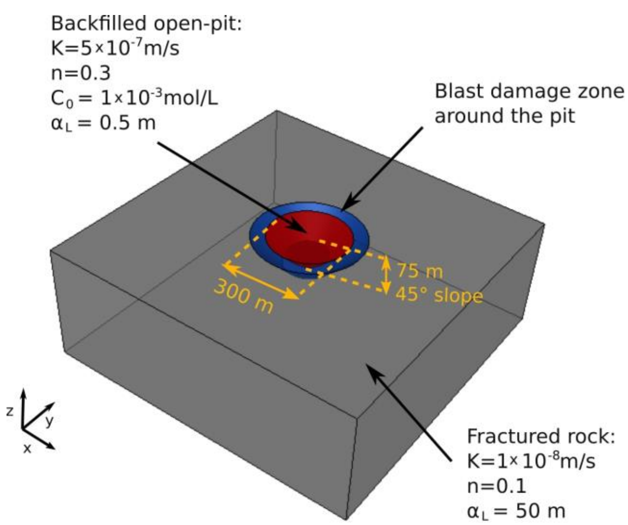

Figure 2. Conceptual model of the studied pit. Grey color represents the fractured rock, blue color shows the extent of the BDZ and red color represents the backfilled pit (tailings).

Solute transport was modelled using the advection dispersion equation (ADE). Only the contribution of the hydromechanical dispersion was considered and the free diffusion mechanism was neglected. Dispersivity tensor was considered isotropic, and dispersivity coefficient was equal to 50 m in the fractured rock and the BDZ, and 0.5 m in the tailings. An initial concentration of 1×10^{-3} mol/L of (unspecified) contaminants was considered in the tailings, and 1×10^{-9} mol/L elsewhere.

Numerical simulations were conducted using the open-source code PFLOTRAN to simulate flow and transport (Hammond et al. 2012). PFLOTRAN uses the finite volume method to discretize Richard's law and the advection-dispersion equation (ADE). Time is discretized using the fully implicit backward Euler method. Non-linear system of equations is solved using the Newton-Raphson method.

Model geometry was defined using Salome open source software (Ribes and Caremoli 2007), and discretized using a centroidal Voronoi tessellation composed of over 350 000 control volumes with refinements in the BDZ (typical size at the interface between the tailing and the BDZ = 0.1 m). Domain and mesh sizes were selected so that they did not have an influence on the simulation results. Only half the geometry was simulated (planar symmetry perpendicular to the y-axis) to reduce computational time, but all results presented thereafter were corrected for the full geometry.

2.3 BDZ influence assessment approach

2.3.1 Flow simulations

A parametric study was carried out to evaluate the impact of the initial fracture density, the fracture attenuation length and fracture radius on the flow through the backfilled material. Most parameters were determined based on literature (Table 1). Fracture attenuation length was estimated between 2.5 and 7.5 m, assuming 30 m benches (Tuckey, 2012) and well-controlled blasts (Hoek and Karzulovic 2000, Hoek 2012). Typical values of B_{21} are comprised between 1 and 10 m⁻¹ (Tuckey 2012, Tuckey and Stead 2016). Discontinuity radius R can be difficult to assess in practice, since observations are limited to boreholes and wall mapping, and was estimated between 0.5 and 5 m (Lupogo et al. 2014). Fracture aperture was considered constant and equal to 100 µm in this study, as observed by Ishibashi et al. (2015).

Table 1. Blast damaged zone (BDZ) parameters

Parameters	Range of variation	Source
Attenuation length l_0	2.5 to 7.5 m	(Hoek and Karzulovic 2000, Hoek 2012)
Trace length B_{21}	1 to 10 m⁻¹	(Tuckey 2012, Tuckey and Stead 2016)
Fracture radius (R)	0.5 to 5 m	(Lupogo et al. 2014)
Fracture aperture	100 µm	(Ishibashi et al. 2015)

The diverted flow index (DFI) was determined to quantify and compare the volume of water which was diverted from the backfilled pit by the BDZ compared to a reference simulation neglecting it:

$$DFI = 1 - {Q_{with}}/{Q_{without}} \quad [5]$$

Where Q_{with} is the flowrate entering the pit considering the BDZ in steady state conditions and $Q_{without}$ the flowrate in the hypothetical case without. A positive DFI indicates the BDZ effectively diverts groundwater from the backfilled materials, while a negative DFI indicates that the BDZ contributes to increase the volume of water which enters the pit.

A total of 1000 simulations were carried out and DFI was calculated for each case.

2.3.2 Solute transport

The influence of the BDZ on solute transport was assessed by simulating the dispersion of a contaminant initially contained in the tailings pore water in the environment.

Three different cases were simulated with different BDZ parameters:

- DFI = 0.37: B_{21} = 8 m^{-1}, R = 4 m and l_0 = 5 m
- DFI = 0: B_{21} = 1 m^{-1}, R = 4.5 m and l_0 = 5 m
- DFI = -0.07: B_{21} = 3 m^{-1}, R = 1.5 m and l_0 = 5 m

Simulated contaminants release rate and retention time (defined as the time when 95% of the contaminant initially in the pit is dispersed in the environment) were compared to a reference transport simulation neglecting the BDZ.

3 RESULTS

3.1 BDZ influence on flow

The diversion of water by the BDZ (expressed by the DFI – equation 5) depended on the trace length B_{21}, the fracture attenuation length l_0 and the fracture radius R. In general, greater fracture radius, trace and attenuation length increased DFI (Figure 3). DFI could be negative, especially for low trace length, indicating that, in these cases, BDZ contributed to increasing water flux entering the tailings (therefore increasing the risk of contamination). Maximum DFI was 47% (i.e. 47% of flow was deviated from the backfilled pit in the BDZ) and was obtained for an attenuation length l_0 = 7.5 m, a trace length B_{21} = 10 m and a fracture radius R = 5 m, i.e. for the thickest and most fractured BDZ simulated.

Generally, higher trace length resulted in higher DFI. For example, DFI could reach 0.47 for a trace length of 10 m, but did not exceed 0.23 for a trace length of 5 m (Figure 3a). In other words, the more fractures are visible at the pit wall, the more the BDZ diverts groundwater from the backfilled tailings. The DFI was relatively independent of the attenuation length for small trace lengths (Figure 3a and 3d). For example, increasing the attenuation length l_0 from 2.5 to 7.5 m for a trace length B_{21} < 5 m only resulted in 5% increase of the DFI (Figure 3d). BDZ flow behavior

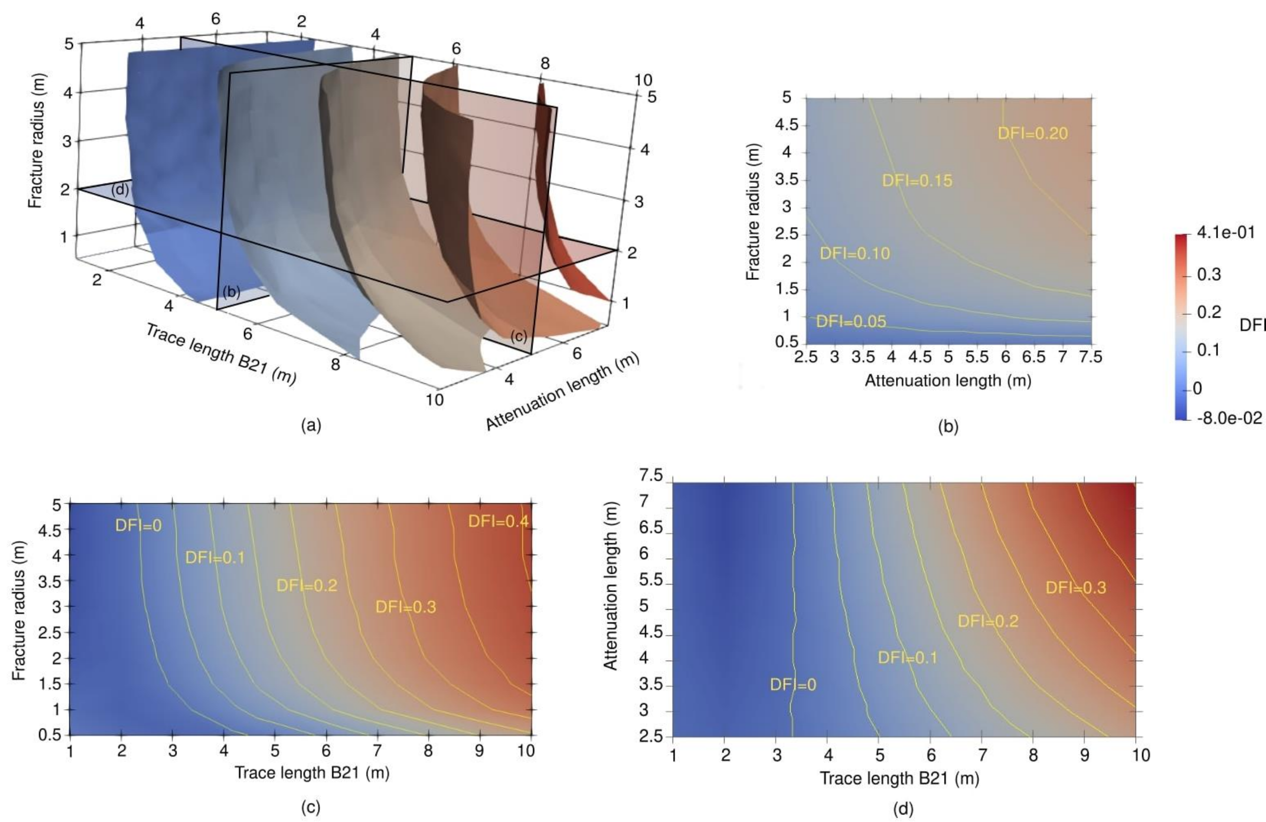

Figure 3. (a) 3D plot of the DFI with iso-surface from DFI = 0 (in blue) to DFI = 0.4 (in red) with 0.1 steps (DFI = 0.1: light blue, DFI = 0.2: grey and DFI = 0.3: orange) as a function of attenuation length, fracture radius and trace length. (b) DFI as a function of attenuation length and fracture radius for a constant trace length B_{21} =5 m. (c) DFI as a function of trace length and fracture radius for a constant attenuation length l_0 = 5 m. (d) DFI as a function of trace length and attenuation length for a constant radius R = 2 m.

thus did not depend on its thickness when the pit wall was lightly fractured.

Fracture radius in the BDZ influenced significantly the diversion of groundwater from the backfilled tailings (Figure 3a to 3c). This effect was particularly marked for R < 3 m, but tended to decrease for larger radii. For example, for a constant trace length l_0 = 5 m, an increase of fracture radius from 1 m to 3 m, increased DFI from 0.05 to 0.15 (i.e. +0.10), while an increase of fracture radius from 3 to 5 m induced an increase of DFI of less than 0.05 (Figure 3b). Larger discontinuity size in the BDZ did not increase flow diversion in the BDZ.

Initial permeability k_0 and attenuation length l_0 were used to characterize the BDZ flow influence (Figure 4). In general, the more permeable was the BDZ at the pit wall, the more the BDZ would reduce groundwater flow in backfilled tailings, and the thicker the BDZ was, the more it contributed to diverting groundwater from the backfilled wastes. For example, for an initial permeability $k_0 = 3\times10^{-13}$ m², DFI was around 0.08 for an attenuation length l_0 = 2.5 m, and around 0.16 for l_0 = 7.5m, while DFI reached 0.26 and 0.44 respectively at an initial permeability $k_0 = 7\times10^{-13}$ m². The effect of fracture radius on function DFI = f(k_0) was negligible, since a reduction of fracture radius by one order of magnitude at constant initial permeability k_0 and attenuation length l_0 led to a reduction of 4% of the DFI (Figure 4).

DFI was negative if the BDZ initial permeability k_0 was lower than three times the tailings permeability k_w, and minimum DFI was reached when the BDZ initial permeability k_0 equalled the permeability of the backfilled tailings. Therefore, determination of the BDZ initial permeability (with a permeability test conducted on the pit wall for example) could be used to predict the flow behavior of the BDZ. These two threshold initial permeabilities corresponding to k_w (minimum DFI) and 3 k_w (DFI < 0) were relatively independent of the BDZ thickness (attenuation length) and fracture radius (Figure 4).

Influence of fracture aperture on the DFI was also investigated. The same permeability distribution in the BDZ could be obtained by either scaling the initial aperture b_0 by a γ factor, or by considering $B'_{21} = \gamma^3 B_{21}$ and $R' = R/\gamma^3$. In this case, initial permeability k'_0 also writes $k'_0 \approx \gamma^3 k_0$. Doubling the fracture aperture have thus the same effect as both reducing the fracture radius and increasing the trace length by a factor of 8. Influence of fracture aperture on the BDZ flow behavior was thus significant: a two-time increase of the aperture resulted in approximately an eight-time increase of the initial permeability, which could correspond to an increase of DFI of up to 50% for the thickest BDZ (l_0 = 7.5m) considered in this study (Figure 4).

3.2 BDZ influence on contaminants transport

Contaminant fluxes for the four cases simulated (see above) decreased during the first 100 years, and until a constant flux was reached, lasting approximately 5000 years (Figure 5). After 5000 years, a decrease toward zero occurred, meaning all the solute initially present in the pit was dispersed in the environment. The initial contaminant release rate in the reference case neglecting the BDZ effect on flow was around 1100 mol/y, and decreased to approximatively 100 mol/y for 5000 years. 95% of the contaminant was dispersed in the environment after 7300 years.

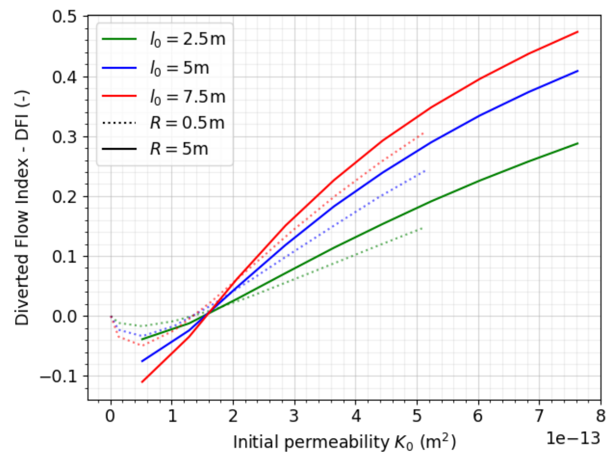

Figure 4. DFI as a function of initial permeability at pit wall for different attenuation length (l_0 = 2.5 m (green), 5 m (blue) and 7.5 m (red)) and for a high (R = 5 m; solid line), and small fracture radius (R = 0.5 m; dotted lines)

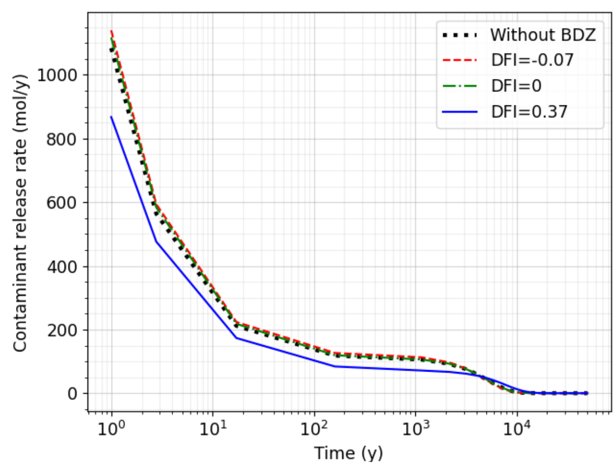

Figure 5. Contaminant release rate function of time for the reference hypothetical case without the BDZ (dark dotted curve), and for three different BDZ parameters sets including a negative (-0.07), null and a positive DFI (+0.37)

Contaminant release rate in the case DFI = 0 were comparable to those obtained in the reference case (i.e. neglecting DBZ). Only a small increase of 3% of the initial flux was observed when considering the DFI = 0 simulation. Differences in contaminant release became negligible after 100 years and retention time was not significantly impacted by the BDZ when DFI = 0. This indicated even if the BDZ have no influence on flow, contaminant release could increase slightly at early time.

Solute transport in the case DFI = -0.07 (negative DFI, i.e. BDZ contributes to increase by 7% flowrate entering the backfilled tailings) resulted in a 5% increase of contaminants release rate. 95% of the contaminant was dispersed in the environment after 6900 years. In other words, a negative DFI reduces the retention time of contaminant.

Finally, in the case DFI=+0.37, contaminant release rate was reduced by 20% compared to the case neglecting BDZ (850 vs 1100 mol/y) for the first 100 years, and by up to 30% between 100 and 5000 years (70 vs 100 mol/y). 95% of the contaminant was dispersed in the environment after 10,000 years. This represented a 30% increase of the contaminant retention time in the backfilled pit compared to the reference case. Therefore, if the BDZ diverts effectively the groundwater from the backfilled tailings, it can also decrease the release rate of contaminants and increase retention time in the pit.

4 RESULTS ANALYSIS AND DISCUSSION

Volume of flow diverted by the BDZ, contaminant release rate and retention time in the pit were closely linked. The three transport simulations revealed the greater was the DFI, the lower was the contaminant release and the greater was the retention time. A decrease of 37% of the flowrate through the pit resulted in 30% lower fluxes (simulation DFI = 0.37) and 30% greater retention. Inversely, a 7% increase of flowrate conducted to 5% greater fluxes (simulation DFI = 0.07) and 5% lower retention. Considering BDZ in pit backfilling simulations can therefore significantly impact the estimation of contamination release rate to the environment.

Release rate of contaminants simulated in this study showed a similar trend than previously reported by West et al. (2003) when studying backfilled pits with a pervious surround. Solute transport is initially controlled by diffusion mechanism, and later, the convection mechanism becomes predominant. Contaminant release rate therefore decreases quickly while the diffusive potential (i.e. concentration gradient between the backfilled waste and the surrounding rock) decreases until a constant flux is reached, corresponding to solute convective flux (Salama et al. 2002, West et al. 2003). Such results (Figure 5) indicate that the BDZ acted as a pervious surround and contributed to retaining contaminants in the pit longer by reducing convective fluxes of solute in the backfilled tailings, like a pervious surround does (Salama et al. 2002, West et al. 2003, Lange and Van Geel 2011). Addition of a pervious surround in backfilled pits could result in an increase of the initial flux because of greater volume of fresh water flowing near the waste, which increased concentration gradients at the interface between the waste and the pervious surround (Salama et al. 2002, West et al. 2003). This effect was also observed with null and positive DFI transport simulations. Initial flux with positive DFI was smaller than the initial flux without BDZ, but there was still a 10% increase of the diffusive flux (Figure 5).

Solute transport simulations were very sensitive to the dispersivity coefficient of the backfilled waste, as already reported by Salama et al. (2002). Changing dispersivity coefficient balance the relative importance of diffusion and convection transport mechanisms: high value of dispersivity can for example make the diffusion predominant even after 100 years (Figure 5). This parameter is also difficult to assess and is scale-dependent (Schulze-Makuch 2005). Also, the hydromechanical dispersion tensor was considered isotropic in this study because of numerical constraints imposed by the finite volume method (Moukalled et al. 2016). However, dispersion tensor is anisotropic and characterized by 3 dispersivity coefficients in practice, and should therefore be further investigated.

5 CONCLUSION

A blast damage zone (BDZ) permeability model was proposed in this study. The model considered an exponential fracture density dependence with distance to the pit wall, and permeability was derived according to four parameters: the cumulative trace length of fractures at the pit wall B_{21}, the fracture attenuation length l_0, the aperture b and the fracture radius R.

A parametric study was carried out to assess the influence of the cumulative trace length, fracture attenuation length and radius on groundwater flow around the backfilled wastes. Generally, the greater the three parameters tested were (i.e. the more was the BDZ thick and fractured), the greater the volume of groundwater diverted from the backfilled waste was. The maximum volume of water diverted considering the BDZ was around 47% compared to the same simulation neglecting the BDZ, thus highlighting its beneficial effect. The BDZ could also have a negative influence on the flowrate (more water can enter the wastes), when the pit wall is little fractured (i.e. at low trace length B_{21}).

Initial permeability k_0 measured at pit walls appeared to have a strong impact on the flow simulations. For example, a necessary condition for the BDZ to divert groundwater was that its initial permeability should be greater than three times the permeability of the backfilled wastes. The maximal negative influence was also reached when the initial permeability at pit walls was equal to those of the backfilled waste.

Solute transport simulations also showed if the BDZ reduced the flowrate through the backfilled waste, it also reduced the rate of solute released from the pit to the environment and contributed to increasing contaminants retention in the tailings pore water.

Further works will include the evaluation of the influence of the fracture orientation anisotropy on flow and transport which could increase water diversion. Additional parametric studies will also be carried out to analyze the influence of BDZ for various (and more realistic) pit geometries.

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