Modeling coupled hydro-geomechanical-geochemical behavior of leaching pads

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Abstract

Heap leach pads constitute a common practice in the mining industry. In short, heap leach pads are used to recover an ore rich solution that will be used to obtain the ore through metallurgical recovery methods in a process plant. The process consists of placing amounts of ore over a geomembrane and a drainage system, adding a leaching solution on the top via drip systems (a solution that dissolves the ore from the mineral) and recollecting the “pregnant leach solution” (PLS) at the bottom of the “leach pad”.

Coupled hydro-geomechanical-geochemical processes are of paramount importance in the design of heap leach pads for two main reasons: (1) they determine the physical stability of the pad and; (2) they are keys for the metallurgical efficiency, especially in the mid to long term.

As an example of the relevance of such a complex coupled phenomena it may be mentioned that geotechnical stability of the heap is related to the distribution of liquid pressures which, at the same time, is related to the permeability through Darcy’s law. In its turn, permeability will be affected by porosity changes, which depend on the consolidation state and the dissolution/precipitation of minerals. Obviously, hydrometallurgical performance of the heap ore is also strongly linked with the above mentioned coupled processes.

In this work, we present a numerical model able to solve the coupled hydro-geomechanical-geochemical processes in a copper leach pad. The model is numerically solved by using COMSOL-PHREEQC, a java interface developed for combining COMSOL Multiphysics – a well-known commercial FEM platform – with PHREEQC, the open-software geochemical simulator developed at USGS and used worldwide.

The resulting numerical tool is able to solve simultaneously unsaturated liquid flow, soil effective stress and chemical dissolution and precipitation. Geochemical changes affecting porosity and permeability are coupled explicitly in the hydraulic and geomechanical calculations.

In this paper we provide a demonstrative simulation of a synthetic heap leach pad case in order to show the importance of the coupling and the capabilities of the numerical tool.

Introduction

Heap leaching is a mineral processing technology widely used in the world due to its cost-benefit, whereby large heaps of crushed or run-of-mine rocks are leached with various solutions that extract the valuable minerals. The largest facilities in terms of both land area and annual tonnage are associated with
copper mines, where copper-containing minerals are irrigated with a weak sulfuric acid solution (Thiel et al., 2004).

During the process of construction, irrigation and leaching there are many physical, biological and chemical processes important for the stability and the efficiency in the mid-long term of the heap. However, such coupled phenomena used to be modeled uncoupled or just partially coupled due to its intrinsic complexity (i.e. hydrodynamics and solute transport (Tyler et al., 1999) or geomechanics and hydrodynamics approaches (Pacheco et al., 2011)). The coupling among these physical and chemical processes is shown in Figure 1.

![Figure 1: Flowchart for couplings present in a heap leach pad](image)

Note: Biological effects are included in the chemical chart

The main objective of this work is to improve the understanding of a heap leach pad by using a coupled hydro-geomechanical and chemical model. Capabilities of this coupling are shown in a demonstration model simulation set up with arbitrary parameters, thus, results obtained could not correspond to any real heap leach pad situation case. Thermal effects and explicit biological reactions (they are implicitly present in the used kinetic rates) have not been considered, although they can be relevant in some cases, we decided to keep the problem focused on the previously commented coupling.

The simulation is carried out by the coupling of two standalone codes: COMSOL Multiphysics (which develops the geomechanical, the hydraulic part and the conservative solute transport part) and PHREEQC (which performs the geochemical reactive simulations). Comsol Multiphysics is a commercial Finite Element code, widely used in many different scientific fields for the modeling of processes based on partial/ordinary differential equations and algebraic differential equations which can derive in different coupled and non-linear systems (COMSOL®, 1997-2012). The second code is the well-known geochemical software Phreeqc (v2.0) (Parkhurst et al., 1999), a freely available computer program for simulating chemical reactions and transport processes in water. It is perhaps the most widely used geochemical code in the scientific community and is distributed free of charge by the US Geological Survey. The program is based on equilibrium chemistry (mass action law) of aqueous solutions interacting with minerals, gases, solid solutions, exchangers, and sorption surfaces, but also includes the capability to model kinetic reactions that are completely user-specified in the form of basic statements.

**Mathematical description**

In this section we provide a detailed description of the mathematical expressions used in the simulation case in order to make possible the reproducibility of the results.
**Soil mechanics**

The fundamental equation for mechanical physics is the force equilibrium equation (Zienkiewicz et al., 1989):

\[ \nabla \cdot \sigma + [(1 - \phi) \rho_s + \phi \rho_f] g = 0 \]  

(1)

Where \( \sigma \) is the total stress tensor (N·m\(^{-2} \)), \( \rho_s \) is the soil density (kg·m\(^{-3} \)), \( \rho_f \) is the pore fluid density (kg·m\(^{-3} \)) and \( g \) is the acceleration of gravity vector (m·s\(^{-2} \)). In a variable saturated porous medium the effective stress \( \sigma' \) (N·m\(^{-2} \)) controls the mechanical behavior. In this context, it is possible to use a simplified approach where it is a function of the degree of saturation of the soil mass, reflecting the contribution of matric suction to effective stress:

\[ \sigma' = (\sigma - p_a I) + S_e (p_a - p_l) I \]  

(2)

Where \( p_a \) is the air pressure [Pa], \( p_l \) is the liquid pressure [Pa], \( I \) is the identity matrix (-) and \( S_e \) is the effective saturation (-) which is defined by:

\[ S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \]  

(3)

Where \( \theta \) is the volumetric liquid content, \( \theta_r \) is the residual volumetric liquid content (m\(^3\)·m\(^{-3} \)), and \( \theta_s \) is the saturated volumetric liquid content (m\(^3\)·m\(^{-3} \)). The volumetric liquid content is related with the porosity \( \phi \) (m\(^2\)·m\(^{-3} \)) and the liquid saturation \( S_l \) (m\(^3\)·m\(^{-3} \)) by:

\[ \theta = \phi S_l \]  

(4)

And we will use the following approximation for the pore fluid density

\[ \rho_f \approx S_l \rho_l \]  

(5)

Where \( \rho_l \) is the liquid density. The constitutive behavior of the soil usually takes the form of a relationship between stresses and strain:

\[ d\sigma' = [\mathbf{D}'] d\mathbf{\varepsilon} \]  

(6)

Where \([\mathbf{D}']\) is the constitutive relationship matrix relating the change in stress and strain (stiffness matrix N·m\(^{-2} \)), \( d\sigma' \) is the incremental stress vector (N·m\(^{-2} \)) and \( d\mathbf{\varepsilon} \) is the incremental deformation vector (-) (Potts, 1999).

**Water flow**

The mass balance equation for unsaturated soil can be written as (Bear, 1979):

\[ \partial_t (S_e \phi \rho_l) + \nabla \cdot (\rho_l \mathbf{q}_l) = 0 \]  

(7)

Where \( \mathbf{q}_l \) the Darcy flow vector (m\(^3\)·s\(^{-1}\)·m\(^{-2} \)). We can expand the storage term of this equation:

\[ \partial_t (S_e \phi \rho_l) = S_e (\phi \partial_t (\rho_l) + \rho_l \partial_t (\phi)) + \phi \rho_l \partial_t (S_e) \]  

(8)

Where changes on porosity over time can be related with mechanical deformation by the \( \partial_t (\phi) \) term:

\[ \partial_t (\phi) = b \partial_t \varepsilon_v + \frac{1}{N} \partial_t (p_l) \]  

(9)

In which \( \varepsilon_v \) is the volumetric strain, \( b \) is the Biot’s coefficient (-) and \( N \) is the Biot’s tangent modulus (-). They are defined by:

\[ b = 1 - \frac{K}{K_s} \quad \text{and} \quad \frac{1}{N} = \frac{b - \phi_0}{K_s} \]  

(10)
Where $K$ and $K_s$ are the bulk modulus of the matrix and the solids respectively and $\phi_0$ is the initial porosity. However, it is commonly assumed that $b$ and $\frac{1}{N}$ are equal to 1 and 0, respectively. Darcy flow vector ($m^3 \cdot s^{-1} \cdot m^{-2}$) is defined by:

$$
q_i = -\frac{k_{ic}}{\mu} (\nabla p_i - \rho_i g)
$$

(11)

Where $k$ is the intrinsic permeability tensor ($m^2$), $\mu$ is the dynamic viscosity (Pa·s), $p_i$ is the liquid pore pressure (Pa) and $k_c (-)$ denotes the relative permeability (between 0 and 1) which depends on the degree of saturation. In real soils and rocks, the permeability varies with porosity. (Lu, 2004)

$$
\kappa = \kappa_0 \left( \frac{\phi}{\phi_0} \right)^3
$$

(12)

Where $\kappa_0 (-)$ and $\phi_0 (-)$ are the initial permeability and porosity, respectively.

**Reactive solute transport**

The mass balance equation for a reactive chemical species is described by:

$$
\omega \partial_t (c) = L_t (c_a) + f_{ext}^w c_a^* + \omega r_{eq} + \omega r_{kin}
$$

(13)

$$
\omega = \phi S_l |\omega|^w
$$

(14)

Where $S_l$ is the liquid saturation (-), $|\omega|^w$ is the water mass fraction in liquid (kgw· kg$^{-1}$), $c$ is the concentration vector of species (mol·kgw$^{-1}$), $c_a^*$ is the external concentration vector of the aqueous species (mol·kgw$^{-1}$), $f_{ext}^w$ is an external supply of water (kgw·m$^{-2}$·s$^{-1}$), $r_{eq}$ is the reaction rate due to equilibrium reactions (mol·kgw$^{-1}$·s$^{-1}$) and $L_t (-)$ is a linear operator that accounts for advection and diffusion/dispersivity and non-chemical sink-source terms for the liquid phase:

$$
L_t (c) = -\rho_i |\omega|^w q_i |\nabla (c) - (c) | \nabla \cdot (\rho_i |\omega|^w D_i |\nabla (c) - (c) |) - (c) | \nabla \cdot (\rho_i |\omega|^w D_i |\nabla (c) - (c) |) - f_{ext}^w (c) - f_s^w (c)
$$

(15)

Where the mechanical dispersion tensor $D_t$ ($m^2 \cdot s^{-1}$) is defined as:

$$
D_t = \alpha_l |q_i| + (\alpha_t - \alpha_l) \frac{q_i q_i^j}{|q_i|}
$$

(16)

Where $\alpha_l$ and $\alpha_t$ are the longitudinal and transversal dispersivity (m). The Eq.14 consists on a system of equations of chemical species size ($N_c$), however, it can be reduced to a system of number of chemical components size ($N_c$). Chemical components are defined as a linear combination of species whose mass is not affected by equilibrium reactions (Smith et al., 1982) (Lichtner, 1985) (Steefel et al., 1996) (Saaltink et al., 1998).

$$
\omega \partial_t (u) = L_t (u_a) + f_{ext}^w u_a^* + \omega r_{kin}
$$

(17)

Where $u$ is the vector of components (mol·kgw$^{-1}$). This vector of components $u$ can be decomposed in subcomponents $u_p$, $u_m$, $u_a$ and $u_d$ which contain the chemical species of the component present in the gas, mineral, aqueous and sorbed phases respectively. Notice that $u = u_p + u_m + u_a + u_d$.

Changes in porosity due to mineral precipitation are taken into account after chemical speciation by the following expression:

$$
\phi^{k+1} = \phi^k + \omega \sum_{m=1}^{N_m} V_m c_m^{k+1}
$$

(18)

Where $k$ is the previous calculated time step, $k+1$ is the current time step, $V_m$ is molar volume (m$^3$·mol$^{-1}$) and $c_m^{k+1}$ is the mineral concentration at the current calculation time (mol·kgw$^{-1}$).
**Couplings procedure**

The Partial Differential Equation (PDE) system of Eq.17 is highly nonlinear. This is the reason why it is commonly solved using an operator-splitting (OS) approach, where solute transport (Eq. 19) and geochemical reactions (Eq. 20) are evaluated separately.

\[
\omega \partial_t (u_a) = L_t (u_a) + f_{ext}^{\omega} u_a^* \\
d_t (u_g + u_m + u_s + u_d) = r_{kin}
\]  

(19)  

(20)

This OS approach can derive on an iterative (SNIA) or non-iterative (SIA) scheme, depending if the system iterates until a desired level of convergence tolerance. More details on the different coupling strategies can be found elsewhere (Saaltink et al., 2001).

In this work, a sequential non-iterative approach (SNIA) has been used. The advantage of the SNIA is its fast computation, since no iteration is performed. The reactive step affects the transport only in lagged mode, thus, accurate results require a control of the time step size. The flow diagram of the SNIA is shown in Figure 2.

![Flow diagram of the sequential non-iterative approach](image)

**Figure 2: Flow diagram of the sequential non-iterative approach**

Equation 2, Eq.7 and Eq.19 are the set of PDE equations which form the multiphysics problem. They are solved over the unknowns \( \mathbf{v}, p_t \) and \( u_a \) respectively. Phreeqc solves Eq. 20 over \( u_a, u_m, u_g, u_d \) but also solves the necessary equations to resolve the \( c, r_{kin}, r_{eq} \) values. From the calculated \( c_m \) value the interface updates the porosity (\( \phi \)) that will be returned to Comsol for next time calculation.

**Application case: Heap leach pad**

This section presents an application case of a copper heap leach pad. Here we will analyze basically the influence of geochemical processes into the mechanical and hydrodynamics behavior. Time analysis of the processes has been carried out for about a year.
Conceptual model

Figure 3 shows a sketch of the conceptual model, accounting for an ore layer, a drain layer and a basement rock. The solution collection system composed by polyethylene network pipes and drainage gravel has been simplified to a drain layer domain.

Geometry and dimensions try to reproduce a typical heap leach pad facility. In order to keep the problem focused on the importance of the different physical couplings only the simulation of the first layer of the pad has been considered. Furthermore, isotropic properties for all the materials have been assumed.

The model simulated has a 2% drain layer slope and a constant net recharge rate (which accounts for the real amount of water which is infiltrated, taking into account i.e the evaporation rate) applied on the top surface \( Q = 15 \, \text{l/h/m}^2 \).

Figure 3: Sketch of the single layer heap leach pad conceptual model

Parameters used in the model can be found in Table 2. It is worth noting that the parameter values adopted have been taken from different information sources, such as laboratory tests, in situ tests and average field measurements for similar materials. The combination of all of them, however, could not correspond to a real case since they have been taken from different places.

The elastic–perfect plastic Mohr-Coulomb criterion and plane strain conditions are assumed for simulating the geomechanical behavior. Initial conditions are zero strains \( \varepsilon_0 \) and stresses \( \sigma_0 \) for each domain. Detailed information about boundary conditions and material properties are indicated in Table 1 and Table 2 respectively.

With respect to the hydraulic assumptions, the bottom right boundary condition constitutes the only outflow of the system. Saturated initial conditions are assumed for the rock domain and unsaturated for the drain and the ore. The Van Genuchten retention curves (Van Genuchten, 1980) have been calculated by using the retention parameters provided by laboratory test information (Pacheco et al., 2011).

Table 1: Summary of boundary conditions for each phenomenon, where \( \mathbf{n} \) is the normal vector, \( \mathbf{q} \) is the flux vector and \( \mathbf{u} \) is the displacement vector

<table>
<thead>
<tr>
<th>Boundary condition</th>
<th>Soil mechanics</th>
<th>Water flow</th>
<th>Reactive solute transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB - IJ</td>
<td>( v_x = 0 )</td>
<td>( q \cdot \mathbf{n} = 0 )</td>
<td>outflow</td>
</tr>
<tr>
<td>AJ</td>
<td>( v_x = v_y = 0 )</td>
<td>( q \cdot \mathbf{n} = 0 )</td>
<td>outflow</td>
</tr>
<tr>
<td>BCDE</td>
<td>Free</td>
<td>( q \cdot \mathbf{n} = 0 )</td>
<td>outflow</td>
</tr>
<tr>
<td>EF</td>
<td>Free</td>
<td>( q \cdot \mathbf{n} = Q )</td>
<td>If ( q \cdot \mathbf{n} &lt; 0 ) ( Q_{in} = q(u_a - u_a') \cdot \mathbf{n} )</td>
</tr>
<tr>
<td>FG</td>
<td>Free</td>
<td>( q \cdot \mathbf{n} = 0 )</td>
<td>outflow</td>
</tr>
<tr>
<td>GH</td>
<td>Free</td>
<td>( p - p_0 = 0 )</td>
<td>outflow</td>
</tr>
<tr>
<td>HI</td>
<td>Free</td>
<td>( q \cdot \mathbf{n} = 0 )</td>
<td>outflow</td>
</tr>
</tbody>
</table>
Table 2: Summary of mechanical, water flow and reactive transport parameter values

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Rock</th>
<th>Drain</th>
<th>Ore</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid density $\rho_s$</td>
<td>(kg·m$^{-3}$)</td>
<td>2,700</td>
<td>2,300</td>
<td>2,300</td>
</tr>
<tr>
<td>Cohesion $c'$</td>
<td>(kPa)</td>
<td>200</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Angle of friction $\phi$</td>
<td>(°)</td>
<td>30</td>
<td>35</td>
<td>37</td>
</tr>
<tr>
<td>Young’s modulus $E$</td>
<td>(MPa)</td>
<td>4,000</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$</td>
<td>(-)</td>
<td>0.25</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Hydrodynamics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial permeability $K$</td>
<td>(m$^2$)</td>
<td>1e-15</td>
<td>1e-9</td>
<td>1e-11</td>
</tr>
<tr>
<td>Initial porosity $\phi_0$</td>
<td>(%)</td>
<td>30</td>
<td>33</td>
<td>35</td>
</tr>
<tr>
<td>Saturated liquid volume $\theta_S$</td>
<td>(%)</td>
<td>porosity</td>
<td>porosity</td>
<td>porosity</td>
</tr>
<tr>
<td>Residual liquid volume $\theta_r$</td>
<td>(%)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Storage $S$</td>
<td>(-)</td>
<td>1e-5</td>
<td>1e-5</td>
<td>1e-5</td>
</tr>
<tr>
<td>Dynamic viscosity $\mu$</td>
<td>(Pa·s)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>(kPa$^{-1}$)</td>
<td>1.030</td>
<td>1.030</td>
<td>1.030</td>
</tr>
<tr>
<td>$n$</td>
<td>(-)</td>
<td>1.195</td>
<td>1.195</td>
<td>1.195</td>
</tr>
<tr>
<td>$l$</td>
<td>(-)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Reactive Transport</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal dispersivity $\alpha_l$</td>
<td>(m)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Transversal dispersivity $\alpha_t$</td>
<td>(m)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Initial water ($u_a^0$) and boundary (infiltration) water ($u_a^*$) concentrations used for the reactive solute transport are shown in Table 3. The chemical reactions considered in the conceptual geochemical model are described in the Table 4. It is worth mentioning that geochemical processes of mineral dissolution and precipitation affect the porosity values in the whole simulated domain.

Table 3: Chemical composition of pore water and leaching solution

*Note*: Concentrations are given in mol/l

<table>
<thead>
<tr>
<th>$u_a^0$</th>
<th>$u_a^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pore water</td>
</tr>
<tr>
<td><strong>Temp(°C)</strong></td>
<td>25</td>
</tr>
<tr>
<td>pH</td>
<td>5.95</td>
</tr>
<tr>
<td>Eh (mV)</td>
<td>738</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water species</th>
<th>$u_a^0$</th>
<th>$u_a^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.30 x 10$^{-2}$</td>
<td>1.04 x 10$^{-3}$</td>
</tr>
<tr>
<td>Ca</td>
<td>2.70 x 10$^{-2}$</td>
<td>2.70 x 10$^{-3}$</td>
</tr>
<tr>
<td>Cl</td>
<td>8.80 x 10$^{-3}$</td>
<td>9.63 x 10$^{-2}$</td>
</tr>
<tr>
<td>K</td>
<td>2.09 x 10$^{-2}$</td>
<td>6.30 x 10$^{-4}$</td>
</tr>
<tr>
<td>Fe</td>
<td>2.62 x 10$^{-7}$</td>
<td>7.50 x 10$^{-6}$</td>
</tr>
<tr>
<td>Mg</td>
<td>1.04 x 10$^{-5}$</td>
<td>1.30 x 10$^{-5}$</td>
</tr>
<tr>
<td>Na</td>
<td>6.50 x 10$^{-5}$</td>
<td>6.10 x 10$^{-4}$</td>
</tr>
<tr>
<td>S</td>
<td>3.08 x 10$^{-5}$</td>
<td>4.50 x 10$^{-2}$</td>
</tr>
<tr>
<td>Si</td>
<td>9.90 x 10$^{-9}$</td>
<td>3.20 x 10$^{-4}$</td>
</tr>
</tbody>
</table>
Table 4: Summary of chemical reactions

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Volume fraction</th>
<th>Type of reaction</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jarosite-K</td>
<td>Initial condition = 0</td>
<td>Equilibrium conditions</td>
<td>-</td>
</tr>
<tr>
<td>Jurbanite</td>
<td>Initial condition = 0</td>
<td>Equilibrium conditions</td>
<td>-</td>
</tr>
<tr>
<td>Basaluminite</td>
<td>Initial condition = 0</td>
<td>Equilibrium conditions</td>
<td>-</td>
</tr>
<tr>
<td>Fe(OH)₃(a)</td>
<td>Initial condition = 0</td>
<td>Equilibrium conditions</td>
<td>-</td>
</tr>
<tr>
<td>Schwertmannite</td>
<td>Initial condition = 0</td>
<td>Equilibrium conditions</td>
<td>-</td>
</tr>
<tr>
<td>Pyrite</td>
<td>1.08 x 10⁻²⁷</td>
<td>Kinetic dissolution</td>
<td>Williamson and Rimstidt, 1994</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>5.36 x 10⁻⁴⁵</td>
<td>Kinetic dissolution</td>
<td>Saaltink et al., 2002</td>
</tr>
<tr>
<td>K-Feldspar</td>
<td>1.58 x 10⁻¹⁴</td>
<td>Kinetic dissolution</td>
<td>Palandri USGS, 2004</td>
</tr>
<tr>
<td>Albite</td>
<td>1.47 x 10⁻¹⁴</td>
<td>Kinetic dissolution</td>
<td>Palandri USGS, 2004</td>
</tr>
</tbody>
</table>

* These parameter values were chosen arbitrarily

Simulations result

The range of horizontal displacements is shown in Figure 4.a; notice that the left slope (upstream) has less displacement than the right one (downstream). Figure 4.b draws the variation of horizontal displacements for the first and last simulation day for the cross section A-A’. This change is mainly caused by the water saturation and the increase of porosity. Figure 4.c and 4.d represent the same type of information than 4.a and 4.b, respectively, but for the vertical displacement. Since the weight of the whole pad has been applied in a single step the vertical displacements obtained do not correspond to real field observations.

![Figure 4: Distribution of horizontal a) and vertical c) displacement due to self-weight. Horizontal b) and vertical d) displacement for the cross section A-A’ for 1 and 350 days](image-url)
The hydrodynamics behavior is conditioned by the time that takes the inflow water to saturate the heap ore in the path to the drainage system. The transitory flow system, from unsaturated to almost fully saturated, is shown in Figure 5. After the transient, a steady state is achieved; in our case this state arrives after about 50 days of constant irrigation (Figure 5.c).

Figure 5: Degree of saturation and water level for 1 day a), 15 days b) and 350 days c)

Figure 6.a shows the concentrations of selected dissolved species at the output of the drainage system. The evolution of pH shows the arrival of the acidic solution irrigated on the top boundary in a very short time (around 50 days). Kinetic dissolution of chalcopyrite is triggered by the infiltration of the acidic solution and, as a result, an increase of Cu concentrations is observed in the outlet flow (Figure 6.b). The chemical evolution of Si and Al concentrations (Figure 6.c and 6.d) clearly shows that under this low pH conditions kinetic dissolution of aluminosilicates is also favored. This process is highly dependent of the pH and, over a long period of time, porosity can be significantly modified.

Figure 6: a) pH evolution through time, b) Metal recuperation and c) Dissolution of aluminosilicates
Figure 6: Chemical evolution of pH a), Copper concentration b), Silicon concentration c) and Aluminum concentration d) respect to time in the drainage system outflow

In Figure 7.a) and 7.b), the changes of porosity over time due to the mineral dissolution and consolidation in the ore domain can be observed. Note that porosity changes due to consolidation are very small because we just simulate a single layer (in a single step). The only change over time which affects the volumetric strain is the increase of liquid pressure which only changes by the overpressure created by infiltrated water. This process is not relevant enough to provoke big displacements.

Figure 7: Temporal evolution of Porosity a), porosity average evolution on the ore domain b)
Conclusion

Coupled physical and geochemical processes have been simulated in this paper. The main aim of investigating such a complex hydrodynamics-geomechanical-geochemical problem is to develop a quantitative tool able to simulate the behavior of a heap leach pad. Although the simulation case has been restricted to a single heap ore layer, simulation time has been short (one year) and parameter values used have been chosen arbitrarily, the illustrative example reported in this paper shows that it is feasible to simulate the behavior of the ore leaching in a leach pad taking into account such coupled phenomena.

Our results show that under the prescribed conditions, a pseudo-steady-state of water pressures is achieved after about 50 days, with the development of a water table of about 2.5 m. The numerical model also illustrates that significant changes in porosity, due to mineral dissolution and precipitation, can cause significant changes in the mechanical and hydrodynamics performance of the heap leaching and therefore compromise its long-term stability. The simulated example shows that the porosity of the ore layer increases (up to 3%) mainly due to the dissolution of silicates.

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References


