MATCHING THEORY AND PRACTICE IN HEAP LEACHING PROCESSES

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ABSTRACT

As usually occurs in technology development, heap leaching knowledge has been built upon two parallel lanes, theory developed on fundamentals but relatively far from industrial applications and on the other hand, operational know how generated from empirical trial and error.

As contribution to close the gap between the above-mentioned lanes, the De Re Metallica process consulting group has been developing and applying fundamental-based modeling tools for industrial process design and process optimization of existing plants along the last ten years. As result, a library of models is now available with application to the whole production chain from blasting to electrowinning.

This presentation is centered in heap leaching and several real study cases are developed, showing how paradigms are broken when fundamentals are applied.
INTRODUCTION

Eventhough its huge development as business, heap leaching is still a non consolidated technology, with many practices based on experience rather than knowledge. Many paradigms hold nowadays engineering projects and industrial operation without a fundamental-sound basis. A major challenge is the lack of comprehension on the fluid dynamics through industrial pads, especially when rich-clay ores are beneficiated.

Significant advances in the understanding of flow through artificial soils have been made along the last twenty years, especially by adapting existing knowledge in the agriculture field and environment contamination to copper heap leaching.

Oxide copper leach models are described through the advective-dispersive transport equations conveniently combined with a leach chemical kinetics law [1-4]. Others consider continuity and momentum equations for the liquid phase, coupled to solute transport equations, often assuming mobil-immobil liquid phases [5-8]. Heat and oxygen balances are also included in bacterial heap leaching models as well as detailed description of bioleaching kinetics [9-13].

Many mathematical models and computer codes are available today to describe transport phenomena throughout heaps or dumps, but there are relatively few applications in design process and project engineering and operational optimization of existing plants. Keeping the fundamental approach, but deeply oriented to applications, Menacho and his group at De Re Metallica in Chile, have developed and applied a lot of metallurgical models to the whole hydrometallurgy production chain [14-17].

Hydrodynamical and metallurgical applications in engineering projects and optimization of large-scale heap leaching operations have been performed by De Re Metallica at Collahuasi – Anglo American (2002); Radomiro Tomic - Codelco Chile (2003); PTMP-Codelco Chile (2005-2006); El Abra - Phelps Dodge (2005-2006); Cerro Colorado – BHP Billiton (2005-2006); Escondida – BHP Billiton (2006); and Nueva Victoria - SQM (2006). The last mentioned is a nitrate-iodine caliche heap leach operation.

Some selected examples of application are presented in the following sections.

CASE STUDY 1: How future copper budget must be correctly planned

Problem set up

Future copper production at most of the mining operations is calculated from the Mine Program, which gives tonnage $m$, grade $L$ and the corresponding mean recovery $R$ on a month or year basis. Assuming annual values, expected production $P_{\text{Budget}}$ is given by:
This simple and logical sound expression is conceptually and practically incorrect. From the viewpoint of the plant operator, real production is continuously built from the PLS flowrate \( Q(t) \), its copper concentration \( C(t) \) and the SX copper transfer efficiency \( \eta(C(t)) \), that is:

\[
P_{\text{Real}} = \int_0^{365} Q(t) C(t) \eta(C(t)) \, dt \quad \text{t Cu/year} \tag{2}
\]

The decreasing non linear nature of the copper recovery along the time for the leach semi batch process drives to

\[
\dot{m} L R = \int_0^{365} Q(t) C(t) \eta(C(t)) \, dt + \varepsilon \tag{3}
\]

Where \( \varepsilon \in \mathbb{R}^+ \). Magnitude of \( \varepsilon \) is proportional to instantaneous variability of \( Q(t) \), \( C(t) \) and \( \eta(C(t)) \). In practice \( C(t) \) is the main variation source, which moves according to variability of the Mine grades. Net result is

\[
P_{\text{Budget}} = \dot{m} L R \geq \int_0^{365} Q(t) C(t) \eta(C(t)) \, dt = P_{\text{real}} \tag{4}
\]

Inequality 4 is a permanent sword pending over the operator head. He is continuously fighting to reach the target without understanding why it is so hard, but in reality, he often is fighting against an incorrect planning.

**Conceptual Solution**

A realistic planning process must consider plant variability, ideally instantaneous. Consequently, a calculation tool where variability is explicitly included is necessary to compute \( P_{\text{Real}} \). Under this framework, a process simulator with the following features has been developed:

- Dynamic balances on daily basis.
- Differential continuity and momentum equation system for the liquid phase (Darcy in variable-saturated porous media), coupled as the classical Richards equation [18].

For the unidimensional case it is:

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ k(h) \left( \frac{\partial h}{\partial z} + 1 \right) \right] \tag{5}
\]
Where $\theta$ is the volume liquid content, $h$ is the pore liquid pressure relative to atmosphere. Due to capilarity $h < 0$ for $\theta < \theta_{\text{saturated}}$. This equation is solved under the initial condition $\theta(z,0) = 0$ and the Neumann boundary condition

$$k(h) \left( \frac{\partial h}{\partial z} + 1 \right)_{z=0} = q_0(0,t) \quad (6)$$

- Copper dispersion-advection transport equation. For the unidimensional case the boundary condition is $c(0,t) = c_0(t)$, where $c_0(t)$ is recursively computed when closing the circuit day by day.

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial z} \left( \theta D \frac{\partial c}{\partial z} - q c \right) + \rho \frac{\partial c_s}{\partial t} \quad (7)$$

$D$ is the dispersion coefficient and $c_s$ is the actual copper grade in the ore.

- Kinetic model for copper extraction, sensitive to the main process variables [19], with initial and boundary conditions $c_s = c_{s0}$ for $t = 0$ and $c_s = c_{SM}$ for $t \to \infty$. $\rho$ is the apparent density of the heap and $\lambda_0, \Lambda$ are characteristic parameters.

$$\frac{\partial c_s}{\partial t} = - (\lambda_0 + \Lambda \frac{q}{\rho \Lambda})(c_s - c_{SM}) \quad (8)$$

- SX-EW models (linearized McCabe Thiele and Faraday law).
- Closed circuit balances, that is, all plant entrances and exits are considered.

**Application example**

Flowsheet of the plant in analysis is shown in Figure 1. Part of raffinate solution irrigates the ripio dump, which discharges into pond 1. Another external effluent also feeds same pond 1. The more fresh pads are irrigated with solution pumped from pond 1, while the older pads are irrigated with the remaining raffinate solution. Effluents from all pads are collected together in pond 2, which feed pond 3, where also solution from pond 1 and the electrolyte purge are joined to finally form the PLS solution closing the circuit with the SX stage.
Real variability in copper Mine grade is illustrated in Figure 2. It includes daily data along three months of operation. Average grade is 1.60% total copper ± 0.52% as standard deviation.

Figure 3 contains a single Mine program for the next 12 months on a daily basis, but using data per year, per month and per day. The first two were supplied by the Mine and last one was generated by stochastic simulation according to data in Figure 2.
Figure 3 – Copper budget for next twelve months specified on a year, month and daily basis

Production vectors computed for the three alternatives are shown in Figure 4. The annual-mean Mine program is exactly the same, but 8,539 t Cu/year are not really produced when daily Mine program is used instead of the year-mean Mine program!

Figure 4 – Monthly production vector computed with the three options of same Mine year-program
CASE STUDY 2:  How to estimate the optimum pad height to leach a clayish copper ore

Problem set up

Heap leaching of rich-clay copper ores is becoming ordinary practice at many sites. Valuable empirical knowledge has been accumulated at Chilean plants like El Tesoro, Codelco Norte, Cerro Colorado and Minera Escondida, among others, but it is generally accepted the lack of understanding on transport phenomena driving the final hydrometallurgical result.

In practice there are at least two ways to face beneficiation of clayish ores: (i) to operate with a size profile compatible with the desired irrigation rate and/or (ii) to handle low-height pads. The first one can be neared by restricting the comminution degree from blasting to crushing. Also the fraction of clayish ore in the blend can be restricted at the Mine, but this is not always possible in practice. Also the clayish ore can be blended with existing stocked high permeability ores, such that, hydrodynamic properties are moved over the limit compatible with the expected irrigation rate. The thin pad option takes advantage of a better initial condition for irrigation, that is, low compaction, low size segregation and a shorter irrigation cycle, thus reducing pore blinding along the time.

Conceptual solution

Present modeling framework is similar to that described in Case Study 1. The key aspect here is the experimental support. This should provide information not only on copper extraction, acid consumption and other metallurgical indices, but also on detailed hydrodynamic parameters. Last ones primarily include matrical suction curve and saturated hydraulic conductivity. When dealing with clays it is also relevant to characterize axial and side dispersion phenomena, surface ponding, hanged and bottom tables and similar. If possible, it is always convenient to run semi industrial or industrial tests to assure similarity in critical phenomena.

On the above-described framework, the following general procedure was developed:

- Measurement or estimation of matrical suction curve and saturated hydraulic conductivity for most representative materials and conditions.
- Correlations between hydrodynamic parameters and physical properties are developed on the basis of the available data (pedotransfer functions).
- Fine tuning of parameters by using a variable saturation porous bed simulator is performed. This can be 1D, 2D or 3D according to specific requirements. The basic simulation is to reproduce the more representative experiments, preferably the industrial or semi industrial data if available.
• Predicting other available experiments starting from the basic simulation above mentioned in order to validate the model.
• Systematic simulation of sceneries is then performed. Variables to be studied in this case are ore composition and size distribution, pad height and irrigation rate. Storage, effluent flowrate and critical flow phenomena occurrence are main responses to be evaluated.
• Results from the above simulations allow to identify the feasible operational window for the specific problem under study.
• Risk analysis and technical economical selection is finally performed.

Application example

80 millions tons of a secondary clayish material bearing 0.45% total copper are stocked close to the Mine site. In previous trials this material was agglomerated in drums, stacked and irrigated in 500,000 tons and 15 m pads. Pad 1 and Pad 2 were leached for about 300 days. On-off flowrate were measured on a daily basis as well as the evaporation rate and topographic pad height. Also information was supplied by tensiometer, piezometer and moisture sensor devices installed within the pads. Apparent density vertical profiles were determined by drilling technique at the end of irrigation cycle. Flowrate was handled within a range, such to avoid significant internal saturation and surface ponding.

From the experimentation it was deduced these pads could only support 1.0 L/h/m² to 1.5 L/h/m², which was not economical. It was then decided to mix this clayish material with a high permeability material bearing 0.07% total copper and evaluate the metallurgical and hydrodynamical response. An industrial trial with a 1:1 mix was then performed in a new 500,000 tons pad and 15 m height. It was then required to determine optimum design parameter on the basis of the 1:1 mix industrial test.

Matrical suction curve for the mix was first determined. Results were modeled with the van Genuchten equations [20]. Flow response of the industrial test with the mix was then reproduced by adjusting the saturated hydraulic conductivity. A numerical 2D code was used in this case. Similar initial and boundary conditions to Case Study 1 were applied. The modeling step was completed by setting correlations between physical properties of individual and mixed components and hydrodynamic parameters.

Parameters of the van Genuchten model applied to the 1:1 mix are presented in Table 1, together with parameters for the single clayish ore. Subsequent simulated and experimental PLS flowrates are shown in Figure 5.
Table 1 – Parameters of the van Genuchten model. Clayish ore pure and 1:1 mix with a highly permeable material

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Pure Material</th>
<th>1:1 Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_s$</td>
<td>m/s</td>
<td>$1.351 \times 10^{-6}$</td>
<td>$3.995 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>m$^3$/m$^3$</td>
<td>0.043</td>
<td>0.040</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>m$^3$/m$^3$</td>
<td>0.26</td>
<td>0.23</td>
</tr>
<tr>
<td>$\alpha$</td>
<td></td>
<td>0.14</td>
<td>0.11</td>
</tr>
<tr>
<td>$n$</td>
<td></td>
<td>1.0</td>
<td>2.2</td>
</tr>
<tr>
<td>$l$</td>
<td></td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 5 – Experimental and fitted effluent exiting the 500,000 tons pad loaded with the mix 1:1

Same model was then used to predict industrial results from the other industrial pads loaded with 100% the clayish ore. Parameters were those indicated in Table 1 and the irrigation calendar was the real one in each case. Predicted effluent rates compare very well to the real ones, as shown in Figure 6.
Saturation and moisture vertical profiles were obtained from same numerical simulations. Figure 8 shows instantaneous results at 100 days of irrigation of the 1:1 mix pad. Raffinate solution was applied for 12 h at 6 L/h/m² followed by 12 h repose.

Maximum saturation was 70% in the 1:1 mix pad, appropriate value for design. Iso-saturation curves were then generated by simulating same irrigation calendar (6 L/h/m² instantaneous irrigation rate, 1:1 intermittence, 300 days) for different fines content and pad height combinations.
Figure 9 clearly indicates the original project 100% clayish ore is out of the feasible region when 15 m pads are used and granulometry is 19.5% minus 200# Tyler. The 1:1 mix option is still under a restrictive condition for 15 m height, but if this is reduced to 6 m then acceptable variability is enlarged and hence the risk of the project is significantly reduced.

Iso-saturation curves in Figure 9 are valid for the specific materials here studied and new hydrodynamic parameters are to be included in other similar problems.

![Iso-saturation curves](image)

Figure 9 – Iso-saturation curves for different fine content and height combinations

Both materials will be randomly fed to the plant in a 1:1 mass ratio. The minus 200# for each material is given by x and y, respectively. For independent random variables the probability $P$ to simultaneously have $x > a$ and $y > b$ is given by the bidimensional probability density function

$$
P(x>a, y>b) = \int_a^\infty \int_b^\infty f(x,y) \, dx \, dy \quad (9)
$$

Geostatistical information on the two stock materials to be mixed indicates fines variability according to Figure 10. Probability to violate the hydrodynamic constrain $\theta < 0.70$, is shown in Figure 11. Critical conditions are expected to be overpassed 20% to 35% of the times if 20 m to 25 m height pads are used, but it reduces to less than 2% when 6 m height pads are used. The last one is clearly the optimum technical choice.
Industrial practice revised from the fundamental point of view always drives to improve process design in engineering phases, as well as in operational practices, providing better optimization and control tools. Other interesting applications developed by De Re Metallica include determination of optimum leaching application rates and dripper spacing, design of agglomerates to improve hydrodynamics and recovery, optimization of crushing
plants to improve recovery, studies of optimum leach cycles including variable application rates, leach industrial process design assisted by dynamic simulation, environmental risk analysis of existing and new leach operations, among others. This rigorous approach has often driven to new judge elements not revealed from the classical engineering tools.

REFERENCES


16. Menacho J.M., B. Merino, “Hydrometallurgical Scale Up from 1 m and 6 m Columns to 6 m Industrial Pads”, Report DRM 012/05, Santiago, Chile, 2005.


