Enhanced Heap Leaching – I. Insights

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Abstract

Flow in heaps and dumps is essentially a two-phase flow phenomenon, though for many applications it could be simplified as unsaturated flow. Unlike saturated flow (typical of groundwater flow) where permeability is independent of other hydraulic parameters, unsaturated flow permeability depends on the degree of saturation and/or on capillary pressure. Several recent field studies suggest that flows in heaps and dumps tend to concentrate in preferred pathways, bypassing much of the ore. Different preferential flow phenomena are triggered, promoted, and influenced by different heap structures, by pretreatment, by the composition of the leach solution, and by application rates and schedules. The structure of heaps and dumps is determined and affected by each and every stage of their construction – from blasting to crushing to conveying and stacking of the material. History of heap construction and operation combined with monitoring, mapping, and certain field tests can reveal patterns of flow and transport in a given heap, and can shed light on the physical mechanisms behind it. Such insight can provide a first cut on heap leaching enhancement by either eliminating or bypassing physical barriers to flow and leaching. Based on the understanding of the heap structure, advanced flow and transport models can be constructed and further enhance the insight. This insight is essential for understanding cause and effect, and can provide a basis for decision making. Further, based on the physically-based models, an intelligent control agent such as MRDS\(^1\) can learn and build a self-learning representation (or a model) of the complex heap leaching system, followed by optimization and planning of heap leaching and heap rinsing.

Introduction

Flow in heaps and dumps is essentially two-phase flow of liquid and air in porous media, though for isothermal applications it could be simplified as unsaturated flow by neglecting flow of air. Unlike saturated flow (typical of groundwater flow) where permeability is independent of other hydraulic parameters, unsaturated flow permeability depends on the degree of saturation and/or on capillary pressure. Therefore, one cannot characterize a heap or a dump by a single permeability value, but rather define relationships between permeability, saturation, and capillary pressure throughout the heap.

Unsaturated flow in porous media is a complex phenomenon that has been studied extensively for the last 60 years in the areas of soil science and hydrology. Two- and three- phase flows are typical of oil reservoirs, and have been studied extensively in the field of petroleum engineering. This suggests that we can use the knowledge, experience, and physical intuition accumulated in hydrological sciences and petroleum engineering to simulate, optimize, and improve current heap leaching operations today. Concurrently, additional planning (discussed later in the text) based on field and laboratory experiments combined with theoretical, conceptual, and numerical models is needed to improve ore leaching.

\(^1\) MRDS stands for Multiple Resolution Decision-Support System (e.g., Meystel et al., 2001).
One of the consequences of two-phase/unsaturated flow is preferential flow. In a recent investigation of the Aitik waste rock heaps (of copper-bearing mineralized rocks) in Sweden, Eriksson and Destouni (1997) concluded that the only possible explanation for low copper concentrations in the drained solution was flow heterogeneity in the form of preferential flow. Several other field investigations around the world have suggested that bypassing of ore by leach solution is a common phenomenon. Preferential flow phenomena are common in natural soils, as can be seen in Figure 1.

Figure 1. Preferential flow in natural soils (Adapted from Selker et al., 1999)

Due to its great implications on contaminant transport and agriculture, preferential flow has been subject of numerous investigations in hydrology and environmental sciences. As expected, similar channeling effects have been observed in dissected heaps after leaching in different sites around the globe (e.g., field experiments by Girilambone Copper Company - B. James, personal com., 1998), and implied by geophysical imaging (Uhrie, 1998).

Maximizing solution contact and minimizing channeling (or preferential flow) is crucial for enhancing leaching efficiency and ore recovery. Different preferential flow phenomena are triggered, promoted, and influenced by different heap structures, by pretreatment, by the composition of the leach solution, and by application rates and schedules. The structure of heaps and dumps is determined and affected by each and every stage of their construction – from blasting to crushing to conveying and stacking of the material.

The first paper in this series will briefly review some of the mechanisms that govern unsaturated flow, and their importance for heap leaching, heap rinsing, and closure, with special attention to
preferential flow phenomena and ways to minimize it. The second article will demonstrate the ability of advanced modeling techniques to simulate flow and transport of leach solution in heaps, to predict metal recovery, and to link that recovery to heap construction and application methods and rates. Besides construction and operation history, an essential input for these models includes data obtained from hydrologic, chemical, and geophysical monitoring. Obviously, the models would vary from site to site. Once a model of flow and transport in a particular heap is constructed, operators could use its predictive power and flexibility to simulate multiple scenarios at high speed and low cost, to design new heaps, and to enhance leaching in an existing heaps by determining best solution application methods and rates over time.

In the following review, we interchange between the terms “permeability” and “hydraulic conductivity”, “saturation” and “water content”, and “capillary pressure” and “suction”, though they are not necessarily identical.

**Flows in Heaps - Permeability and Pressure as Functions of Saturation**

In unsaturated porous media, the driving force is a vector sum of gravity and capillary forces (or capillary pressure, or suction). The capillary pressure, in turn, is dependent on surface tension of liquid and wettability of the rock fragments and grains. On a microscopic scale, surface tension is a result of cohesion between the liquid molecules (relative to liquid-gas attraction), while wettability is a result of adhesive forces between liquid molecules and solid surfaces. The important effects of organic carbon in the leach solution and surfactant additives on these forces will be discussed later in the text.

An unsaturated porous medium is often conceptualized as a twisted bundle of capillary tubes; as liquid saturation is lowered, larger capillary tubes are emptied while finer tubes with higher suction dominate the flow. This conceptual model implies dependence of permeability and suction on liquid saturation. The permeability (or hydraulic conductivity) of an unsaturated porous medium is highly and non-linearly dependent on liquid saturation, increasing by orders of magnitude from very low values at low saturation to high values at higher saturation, up to the saturated conductivity (the upper limit) under complete saturation. The saturation-capillary pressure relationship for a given porous medium is described by a “characteristic curve” or a “retention curve”, as shown in Figure 2a. It reflects the pore size distribution of the medium, and often exhibits hysteresis (i.e., the “wetting” curve differs from the “drying” curve). A close look at Figure 2a reveals a strong non-linear dependency of capillary pressure (or suction) on saturation. Similarly, Figure 2b reveals high dependency of hydraulic conductivity on capillary pressure. The relative permeability as a function of saturation (or as a function of capillary pressure) together with the characteristic curve and bulk porosity, completely describe the macroscopic hydraulic properties of an unsaturated porous medium.
By introducing Darcian flow (i.e., flow that obeys Darcy’s law, where flux is proportional to the product of hydraulic conductivity and head gradient) and by considering mass balance everywhere, typically in the form of a partial differential equation (for each fluid, in the case of multiphase flow), together with the pressure-suction-conductivity relationships (described above) and with initial and boundary conditions, we finally obtain a complete model of unsaturated (or two-phase) flow. That is, once the properties of the medium and the initial and boundary conditions are known, one can solve for (or predict) pressure distribution and fluxes over time everywhere within the domain. In other words, “modeling” and “simulations” of flow and transport in unsaturated porous media mean computational solutions of mass balance equations. [In the case of non-isothermal conditions, energy balance equations are added.] Due to the complexity of the equations, they are commonly solved using numerical methods such as finite differences or finite elements, and become “numerical models”.

By linking flow to reactive transport and including the geochemistry involved, this becomes a complete hydrogeochemical or reactive transport model. In principle, such a model can predict variations in grade, pH, acid consumption, etc. throughout a heap. In other words, such a model could simulate a three-dimensional and/or two-dimensional cross sections of heap leaching over time. The next step, then, would be to optimize heap construction and solution applications at a particular site, but first, let us gain more insight.

The conductivity-saturation (or conductivity-capillary pressure) and saturation-capillary pressure relationships (or functions, or curves) with or without hysteresis are nonlinear and highly dependent on pore size distribution, and therefore on fragment size distribution. This can be seen in Figure 2a, where the two curves describe different particle sizes of dune sand – coarse ($K_c$) and fine ($K_f$). These
nonlinearities render the flow highly sensitive to fragment size distribution and placement of the ore, as well as to water content, application methods, and application rates (boundary conditions). This sensitivity is reflected by high dependency of model predictions on the parameters (or coefficients) that embody these nonlinear relationships (or functions). Therefore, each step in the planning, construction, and operation of heaps is crucial – from the choice of fragment sizes and their mixed distribution to conveying, to stacking, to pretreatment, and to solution applications. This is why it is so important to be rigorous and careful in all stages of heap leaching operation – at every step, an operator can influence the leaching efficiency, depending on the way things are done. By the same token, the sensitivity to operational practices could also work in favor of the operators: by changing initial conditions (e.g., by adjusting initial water content) and boundary conditions (e.g., by changing application rates and/or application methods), an operator could generate changes in flow regimes and flow paths, and thereby, improve leaching efficiency. The better the heap construction is, the easier it is to control flow and leaching efficiency. With the aid of proper monitoring and numerical modeling, operators can predict how such changes will affect production, and act accordingly.

**Preferential Flow Phenomena**

**Funnel Flow**

The constitutive relationships between hydraulic conductivity, saturation, and capillary pressure differ from one medium (or fragment distribution) to another; curves that describe these relationships for different textures not only differ in shape but also may intersect each other, as shown in Figure 2b. Consequently, as can be seen in Figure 2b, a coarse-grain layer (e.g., sand) which is highly permeable under saturated conditions (low suction), becomes less conductive than a fine-grain layer (e.g., clay) under low saturation (high suction), where capillary forces dominate the flow. This is why a coarse grain lens can act as a barrier to flow under unsaturated conditions typical of heap leaching (as opposed to saturated flow, where coarse materials act as good sinks and drains (see, for example, a videotape by Bell and Steenhuis, 1992). This so-called “funnel flow” is counterintuitive and causes confusion and misconception among professionals who are used to thinking in terms of saturated flow. This is one reason why layers of different textures within heaps could severely reduce sweeping and leaching efficiency. On the other hand, this type of layering is ideal for heap closure, where much of the flow is passively diverted away from the heap. The capillary barrier effect and flow diversion can be seen in Figures 3 (after Ju and Kung, 1997), and in Figures 4 and 5 (simulated by FEFLOW – a saturated-unsaturated finite-elements code). Figure 4 shows the effect of covering a coarse-grained stockpile by a fine-grained soil cover (note: the lines are flow lines), while Figure 5 shows a similar effect obtained by a two-layer soil cover (consisting of coarse and fine material) for fine-grained tailings.
Figure 3, 4, and 5, and our heap flow simulations (presented in the 2nd article) also demonstrate the ability of computer models to capture this important bypassing phenomenon by using highly refined grids. These simulations reproduced the same funnel flows observed in laboratory and field studies; the simulations confirm strong dependence of water flow patterns on the combination of water application rate and textural discontinuities. The implication for leaching efficiency is clear. The way rock fragments segregate while being shoveled, conveyed, or dumped would have a direct impact on leach flow and sweeping efficiencies. Likewise, stacking of pads (one on top of the other) and agglomeration of fine material before stacking, can affect flow in different ways; while stacking could adversely affect sweeping by creating “layers” of different flow properties, agglomeration is expected to improve sweeping by eliminating layering of fine material (see also “Fingering”, below).
Figure 3. Vector plot of numerically simulated flux that shows funnel-type preferential flow paths in two-dimensional 12m wide by 6m deep hypothetical profiles with randomly distributed 35 lenses [A], 25 lenses [B], and 15 lenses [C] of coarse sand (After Ju and Kung, 1997).
Flow Lines

**Figure 4.** Flow lines in a Capillary Barrier consisting of a layer of fine material on top of coarse material
Figure 5. Flow in a Capillary Barrier consists of alternating fine and coarse layers on top of fine material (tailing)
Macropore Flow and Changing Flow Paths

Let us once again consider the bundle of capillary tubes analogy. Under increasing saturation, the larger capillary tubes and the gravitational forces associated with them start to dominate the flow, while the overall capillary suction decreases. This implies that by controlling saturation (e.g., by controlling application rates), one could change flow paths in heaps, thereby increasing overall leaching. According to the Hagen-Poiseuille equation, discharge through capillary tubes depends on the fourth power of the tube’s radius. Indeed, it has been found in laboratory experiments with soil samples that as saturation increases, the larger pores “take over”, and almost all of the flow (say, above 96%) occurs preferentially within “macropores” larger than approximately 0.2 mm in diameter (Scotter, 1978) or pores associated with zero to -15 cm of capillary suction head (Watson and Luxmoore, 1986).

The effect of macropore and other preferential flow phenomena on leaching of salts from agricultural soils has been demonstrated in numerous studies. Keller and Alfaro (1966) in their laboratory investigation, and Miller et al. (1965) in field studies showed that by water management practices, a control of solute movement and leaching could be achieved (see also Bressler, 1967). In each study, decreasing flow rate and moisture content by lowering water application rate or using intermittent applications resulted in higher leaching efficiency. These observations are consistent with Scotter’s experiments which demonstrated the dependence of flow paths on saturation (van-Genuchten, 1991), and with our numerical simulations (described in our 2nd paper). Moreover, numerical simulations of transport in homogeneous porous media (Soicher, 1996) demonstrated the almost identical effect of intermittent (or pulsed) irrigation and reduced irrigation rates on solute transport in the subsurface as soon as it reaches some (shallow) depth below the surface, while the dominant factor is the cumulative applied volume of water, regardless the pulse (or irrigation) period. Based on the above field experiments and on field experiments by Wierrenga (personal communication), this similarity between intermittent and low flow rate is expected to prevail in heterogeneous media as well. The implication to heap leaching is clear: variations in application rates and/or reduced application rates on heaps and dumps could increase leaching efficiency. This was experienced in San Manuel (a copper mine in Arizona) where reducing the application rate resulted in increased leaching (i.e., total copper recovery; Al Liguori, pers. com.).

Another example from the mining industry is a recent attempt to rinse cyanide from heaps of leached gold. By comparing intermittent and continuous rinsing of samples in test columns, Bakshi and Nelson (1995) found that the total cyanide mass in the rinsed liquid under intermittent rinsing was higher than the cyanide removed under continuous rinsing. Practically speaking, however, optimization of leaching efficiency at a particular site as a function of application rate and application method would be a time consuming process unless a simulation tool is used. By using a numerical model that can simulate two-phase (or at least unsaturated) flow and transport in porous media, a large number of scenarios can be tested, and only the most promising ones would be field-tested.

Wetting Front Instability and Fingering

Another mechanism of preferential flow is instability of wetting fronts. When one fluid displaces another fluid of different density and/or different viscosity, an unstable front or interface may develop, which leads to propagation of discrete fingers rather than a uniform surface, as demonstrated in Figure 6.
This is a major problem which has been intensively studied in Physics, Soil Sciences, Hydrology, and Petroleum Engineering (e.g., Taylor, 1950; Saffman and Taylor, 1958; Scheidegger, 1960; Hill and Parlange, 1972; Philip, 1975; Parlange and Hill, 1976; Glass et al., 1988; Selker et al., 1991a, 1991b; Steenhuis and Parlange, 1991). Needless to say, leaching efficiency is reduced significantly under unstable (fingered) flow.

In Petroleum Engineering (particularly, Enhanced Oil Recovery), the “non-wetting” oil is usually displaced by the “wetting” water (some recent methods use other fluids which are also non-wetting but of different viscosity). In soils and heaps, water or leach solution (the wetting fluid) displaces air (non-wetting) and usually becomes unstable when (i) a downward moving wetting front encounters a compression of air ahead of it, (ii) in water-repellent porous media, (iii) in heterogeneous soils and heaps under relatively high application rates and/or under ponding, and (iv) where hydraulic conductivity increases with depth. Roughly speaking, gravitational forces and certain types of heterogeneities (such as sequences of low and high conductivity layers) promote instability, while capillary and viscous forces have a stabilizing effect on a downward moving wetting front. The effect of heterogeneity on instability and fingering was reviewed by Chen et al. (1995), and was formulated probabilistically and modeled numerically by Chen and Neuman (1996).

On a larger scale, unstable flow and fingering most commonly develop beneath the interface between a layer of fine material and a coarse-grain layer when ponding occurs above the fine layer (e.g., Bell and Steenhuis’s, 1992). According to Chen et al. (1995), ponding of water above a coarse-grain layer could cause fingering even without the existence of an overlaying fine-material layer. Different investigations (e.g., Glass, 1991, Wierrenga, personal communication) have shown that after infiltration ceased and the profile drained, the subsequent infiltration followed the same finger-like pathways which were developed in the initial infiltration (see also Hillel, 1980, and Stephens, 1995).

Ghodrati and Jury (1990) investigated the effect of irrigation method on fingering in a field site in California. After irrigating eight soil plots with an addition of a dye tracer, they excavated them down to 1 meter. The observed vertical and horizontal distribution of dye clearly indicated that fingering took place in each plot. However, fingering was less pronounced under sprinkling than under flooding in undisturbed plots. It was most pronounced where flood irrigation occurred over disturbed surfaces (Chen et al., 1995).

In the following, we discuss a few physical factors that induce instability and fingering.

**Repellent Soils**

Theoretical studies (e.g., Raats, 1973) and field studies (van Dam et al., 1990; Hendricks and Dekker, 1991; Hendricks et al., 1993; Ritsema et al., 1993; Ritsema and Dekker, 1994) show that infiltration in dry water-repellent soils results in unstable wetting fronts (Stephens, 1995; Chen et al., 1995). Direct relationships between repellency and instability were found recently by Steenhuis et al. (1996) in a laboratory study which revealed that the more repellent the soil is, the faster is the growth of fingers; under extreme repellency, only one finger was formed. Qualitatively, the inverse of repellency is “sorptivity”, which can be measured in the field; in a recent field study (presented in the 1996 GSA meeting), it was found that for smaller sorptivity values the flow becomes unstable and the growth of fingers accelerates.
Since repellency is created by a repeated contact of solid surfaces with organic compounds, it is likely to be affected by kerosene residues in the leach solution, by microorganisms that grow on rock fragments, and by surfactant additives.

**Grain Size Distribution**

Another study (1996 GSA meeting) compared soils with different textures and thereby different characteristic curves and different hysteresis; in soils with characteristic curves that imply uniform grain size distribution, the flow was unstable, while in soils with characteristic curves that imply nonuniform grain size distribution, flow was mostly stable. These findings are consistent with earlier experiments by Diment and Watson (1985), and Selker et al. (1992), where water was ponded on initially dry, uniform sands.

The effect of grain size distribution on flow has some striking implications for heap construction, such as the benefit of crushing (of ore) into a uniform fragment size compared to blasting into multiple fragment sizes. It also highlights the importance of lateral stacking of material on heaps vs. dumping it down slope, and the importance of heap’s height. Dumping multiple fragment sizes alongside a high heap would create segregation between finer material near the top and coarser material near bottom, which leads to an increasing hydraulic conductivity with depth, which, in turn, promotes wetting front instability and fingering.

**Initial Wetting**

It has been shown in many studies (see above, and Chen et al., 1995) and in our flow and transport simulations (below) that preferential flow, particularly instability and fingering, develops more readily in dry porous media, while wet initial conditions inhibit preferential flow.

**The Effect of Saturation on Anisotropy**

Another peculiar phenomenon is the apparent magnification of slight anisotropy in hill slopes under unsaturated flow, which causes downward vertical flow to divert into flow parallel to the natural slopes. Theoretical studies by Zaslavski and Sinai (1981), field studies in sand dunes by McCord and Stephens (1987), laboratory experiments by Frederick (1988), and numerical simulations by McCord et al. (1991) revealed saturation-dependent anisotropy, particularly increased anisotropy as the moisture content decreases.

The apparent anisotropy that results from layering of particles in slightly different ways or particles of slightly different sizes during the genesis of the dunes (or during heap construction, in our case) is probably a large-scale manifestation of multiple small-scale funnel flows. In terms of heap construction, this means that variations in the methods used, such as the routes trucks may take while driving on a heap, or slight variations in material types during construction could cause leaching deficiency deeper below the heap slopes. Here, a separate optimization of solution application rates is needed. Moreover, heap or dump construction by dumping the material (from trucks) in successive inclined layers, particularly when they consist of slightly different material, would create anisotropy and flow diversion along the sloping beds, bypassing much of the ore. Segregation, which leads to fingered flow (as described above) would further worsen the situation.
Film Flow

Film flow on rock surfaces is another unsaturated flow phenomenon that has to be addressed. It is intimately related to physical absorption of fluids on surfaces and to wettability.

Tukanaga and Wan (1997) found that film flow on fracture surfaces is a considerable fast preferential flow mechanism in unsaturated fractured rocks. In another study by Xing-He et al. (1987) of molecular dynamics of water near uncharged silicate surface, they found the diffusion in thin water films to be anisotropic, regardless the anisotropy of the crystal surface. It seems that upscaling and modeling of such phenomena on our scale of interest has not yet been developed. In particular, more study should be done on linking film flow to wetting, capillary action, and chemical reactions in heaps, where the leach solution interacts with different rock surfaces and different minerals, particularly clays (this is mainly a problem of up-scaling from microscopic to macroscopic scales).

The Effect of Precipitation, Dissolution, and Sediment Transport

Finally, pore sizes, and hence pore size distribution and flow paths may change over time due to chemical precipitation and dissolution of minerals (e.g., gypsum), as well as weathering of rock surfaces and subsequent transport of fine material (colloidal and larger). Much more work is needed in order to quantify such changes, i.e., to translate them to changes in relative permeability and characteristic curves.

Conclusion

The insight obtained by all of the above studies points to opportunities for improvement of heap design and construction. We defer our recommendations for such a design to future discussions, and we concentrate here on leaching enhancement in existing operating heaps.

Perhaps the most important information for leaching enhancement purposes is contained in records from all stages of heap construction and leaching. This includes blasting, ore delivery, placement, stacking or dumping, pretreatment or curing, solution applications – methods, schedules, and rates, and solution composition. This is why it is so important to keep such records throughout the life and closure of heaps and dumps. In order to enhance leaching and rinsing of an existing heap, one should start reviewing and compiling records of heap construction and operation over the years, and then synthesize the data to form a conceptual model of that heap. By combining the conceptual model with hydrologic and geochemical characterization, one could construct a numerical model of flow and transport for the heap. The heap characterization should include geophysical mapping, measurements of flow characteristics, compilation of basic geochemical information, and where possible, geochemical analyses. Obviously, both heap characteristics and the constructed model are site-specific.

It is highly recommended to design and install a monitoring system before starting with pretreatment and/or leaching – otherwise it should be done as early as possible. The most informative and cost-effective way to monitor transport of leach solution in heaps is via geophysical methods, particularly high-resolution resistivity (HRR) mapping, and to a lesser extent, ground penetrating radar (GPR). HRR mapping done on heaps by hydroGeophysics, Inc. proved successful in identifying and delineating unleached zones. Recently developed 3D imaging technology enables experienced geophysicists to construct three-dimensional electrical resistivity tomography based on resistivity contrasts detected by sensors installed on the heap surfaces (J. Fink, personal communication). The mapping produced by
such methods delineates solution distribution and pathways within the heap during leaching. Based on such mapping and hydrologic modeling, operators can direct solution flow through unleached zones by changing application rates, application distribution, and application method, including invasive methods.

In the following paper we show some examples of 2D modeling of cross-sections of flow and transport in heaps. We will show how such models can be used to simulate flow and transport patterns in heaps as well as leaching process. Based on such models, an intelligent control agent (MRDS; e.g., Meystel et al., 2001) can learn and plan optimal metal recovery, heap rinsing/decommissioning, and ways to enhance both.

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