OPTIMAL STRATEGIES FOR LEACH PAD INJECTION OPERATIONS

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Abstract

Cripple Creek and Victor Gold Mining Co. is developing a full-scale pad injection program as part of the overall operational plan for the Valley Leach Facility. As part of the development process the mechanics of the injection methodology are evaluated in the context of physical injection measurements, outcome from geophysical monitoring, and gold leaching theory. The results indicate that hydraulic fracturing analogies advanced heretofore do not accurately describe injection phenomena in unconsolidated and noncohesive material typical of leach pads. A new interpretation is presented and extended to define operational strategies for maximizing gold production.

Introduction

In 2010 Cripple Creek and Victor Gold Mining Co. (CC&V) conducted a trial program testing the utility of enhancing gold production from the Valley Leach Facility (VLF) through subsurface solution injections [1, 2]. Nine injection wells were installed in a mature area of the VLF and treated over a twelve-week period. The trial program proved very successful as measured by the hastened recovery of over 4,300 ounces of gold and the program was expanded to other areas of the VLF. Over fifty additional wells have now been installed and treated. The results from these wells have demonstrated that the utility of the program extends well beyond simply targeting suspected under-leached zones within the heap and CC&V is now developing a full-scale pad injection program as part of the overall operational plan for the VLF.

Complete discussion of the motivations and expectations for the full-scale program are beyond the scope of this work and the claimed benefits afforded by injections are well-advertised [3, 4]. However, one of the foremost considerations in defining the scope of the program is determining the optimal well spacing and injection protocols. The paucity of material results in published literature to this end leaves many technical questions unanswered and the operational experience at CC&V suggests that proposed mechanistic theories are incomplete or inaccurate or both. Resolving these questions is paramount to maximizing the utility of the injection program at CC&V.

In the discussion below the mechanics of injection in unconsolidated media are surveyed. Theoretical predictions from the analysis are evaluated in the context of physical injection measurements, results from geophysical monitoring, and basic heap leaching principles. The results are then extended to propose an innovative operational strategy as a first step toward optimizing injection operations on the VLF and to heap leaching operations in general.

'Fracture' of Unconsolidated Media

In the published accounts of leach pad injection advanced to date, the asserted motivation is to break up hydraulic barriers in the heap arising from compaction, inadequate surface ripping, migration of fines, etc., and create highly conductive flow channels that facilitate direct transport of lixiviant to unleached or underleached material [3, 4]. The process is likened to the hydraulic fracturing techniques currently employed in the oil and gas industry and the new flow channels are reportedly established by 'fracturing' the heap material when the solution pressure exceeds the compressive stress at the injection zone. In the theoretical treatment accompanying these accounts, models developed to describe fracturing hard rock are extended to provide predictions on the critical injection pressures as well as the geometry and orientation of the fractures [5]. However, the validity of these claims has not been thoroughly appraised and, interestingly, assertions that the 'breakdown' pressure was reached during an injection are never accompanied by discussion of the proximity of the measured to predicted values.

Flow rate and pressure trends qualitatively similar to those typical of actual hard rock fracturing operations observed during a small number of injections in leach pads provide casual support for the hydraulic fracturing analogy. However, the similarity breaks down rapidly thereafter. Unlike hard rock, noncohesive and unconsolidated materials are already 'fractured' and cannot bear a tensile load. Hence, the central tenet of fracture mechanics, *i.e.* that fracture occurs when the strain energy at the crack tip is greater than the energy required to form new surfaces [6], is never applicable. A pressure-driven fracture mechanism cannot accurately describe injection phenomena in unconsolidated media.

Classical theory holds that when a viscous fluid is injected within unconsolidated and noncohesive particulate matter, the flow regime will depend on the ratio of inertial to viscous forces as described by the Reynolds number, Re, defined as:

$$Re = \frac{Dv}{\upsilon} \quad (1)$$

where D [L], is the average pore or grain diameter; v [$L \cdot T^{-1}$], the apparent fluid velocity; and υ [$L^2 \cdot T^{-1}$] the kinematic viscosity of the fluid. At low Reynolds numbers, typically less than one, the flow can be described by Darcy’s Law with the hydraulic gradient, i, given by:

$$i = -av \quad (2)$$

where a [$T \cdot L^{-1}$], is the hydraulic resistivity (reciprocal of conductivity). In this regime inertial forces are negligible compared to viscous forces and the flow is laminar. As the Reynolds number increases, however, the occurrence of turbulent eddies dissipates fluid energy and the hydraulic potential gradient becomes less effective in inducing flow [7, 8]. In this region Darcy's law no longer holds and the hydraulic gradient scales nonlinearly with the flow velocity. An empirical fitting parameter, m, is required to quantitatively describe the relationship between the gradient, velocity, and hydraulic resistance according to:

$$i = -av^m \quad (3)$$

In this region drag forces on the media are still lower than the confining stresses on the particles, and the pore pressure inside the material quickly reaches a stable state. However, if the Reynolds number is increased further the drag force exerted on the particles increases as well and eventually becomes sufficiently large to overcome the confining stresses. At this critical strain value the particle-fluid mixture becomes fluidized and the flow regime changes dramatically.

Wu [9] showed that this drag-force-induced fluidization is responsible for 'fracture' in unconsolidated media and that the process is more aptly described as fluidization of a cavity in the particulate assembly. In this framework the critical velocity for cavity formation is dependent on the viscosity of the injection fluid. At low fluid viscosities energy dissipation in the fluid is mainly due to turbulence and cavity growth, is governed by the confining stress state. As the viscosity of the fluid increases, shear forces within the fluid eventually becomes the primary mode of energy dissipation. In this regime the cavity propagation is restricted and proceeds along a slipping boundaries nearer to the injection point.

Results and Observations

Predictions from Wu's model agree with experimental observations in lab-scale injection experiments. These studies indicate that viscous fluids are more likely to drive discrete fractures into the host material along shear bands near the injection site while less viscous fluids typically permeate the host material uniformly with breakdown only occurring at high injection velocities [10, 11]. In these experiments the 'fractures' could be observed directly. Direct observation is not possible in the case of full-scale injections in a leach pad, but indirect observations including geophysical monitoring and top hole flow and pressure data suggest that the predictions hold at the leach-pad-scale as well.

During the 2010 trial, injection at each zone started by allowing solution to flow down the well under line pressure with no pumping. This was done primarily to fill the drop pipe and void space at the injection zone in order to back pressure the pump, but the initial (stable) flow rate and pressure were also perceived to be an indication of the conditions at the injection zone. Once the fluid pressure stabilized, the pump was started and progressively throttled to the maximum sustainable speed. Maximum flow rates ranged from 800 to 1,200 gpm (3.0 to 4.5 m^3/min) with pump discharge pressures (top hole) between 250 and 300 psi (17 and 20 bar). During most injections the flow was periodically interrupted and the pump header manifold was reconfigured to accept 6,000-gallon (23-m^3) loads of 30% lime slurry. The lime slurry was offloaded from the transport truck by gravity and pumped down the well at low speeds to keep the injection pump from cavitating. Full pumping was resumed once the lime slurry had been offloaded. At the end of the injection cycle the pump speed was ramped down and switched off. The stable post-treatment flow rates and pressures were recorded as solution continued to flow down the hole under line pressure.

At nearly every injection zone treated in 2010, the flow rate without the aid of the pump following the injection cycle was several times higher - in some cases over ten time higher - than the initial flow. The large ratio of final to initial flow rate clearly indicates that the injections altered the particulate assembly near the injection zone and, at the time, was assumed to be indicative of the efficacy of the injections. However, deeper investigation suggests that the opposite may be true.

The specific injection flow rate at a normalized pressure per unit length of borehole is given by the Lugeon value, Lu [$L^2 \cdot T^{-1}$], calculated as:

$$Lu = \frac{q}{D}\frac{P_0}{P} \qquad (4)$$

where q [$L^3 \cdot T^{-1}$], is the injection flow rate; D [L], is the length of the injection zone; P_0 and P [$M \cdot L^{-1} \cdot T^{-2}$] are, respectively, the reference[1] and measured pressure. Lugeon measurements are used to estimate the relative hydraulic conductivity of formations for hydrogeologic and engineering applications. Trends in the Lugeon values observed when the pressure and flow rate are changed have been correlated to specific phenomena occurring during the injection [12-14]. Figure 1 shows Lugeon values computed from the free-flow pressures and rates before and after, as well as for the maximum pressure and flow rate combination measured during the injection cycle for three zones from the 2010 trial. The data are typical of trends observed during the project. The drop in the Lugeon value between the initial and intermediate measurements is characteristic of a turbulent flow regime. The overall increase in the Lugeon value at the end of the injection indicates that permanent and irrecoverable changes

[1] Lugeon values are traditionally defined in SI units 1 MPa specified as the reference pressure, P_0. A reference pressure of 145 psi is used in the imperial unit system with a proportionality constant included to ensure values are comparable.

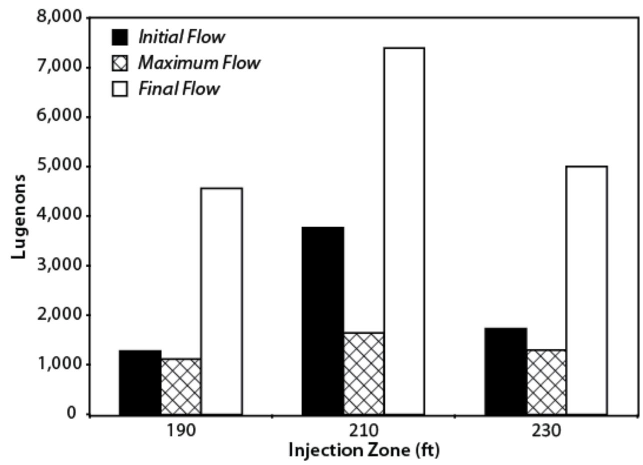

Figure 1 - Lugeon values computed from pressure and flow rate measurements before, during, and after the injection cycle on three zones from the 2010 injection trial. Injection zones are denoted by depth from the pad surface.

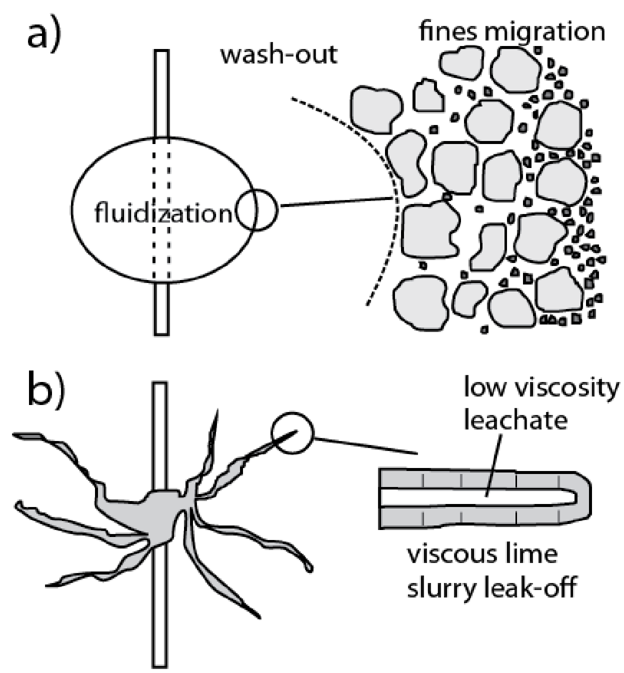

Figure 2. a) Schematic of injection process showing region around injection borehole with fluidization. Far from the cavity's center is an area of washout with little fines and a region of concentrated fines from migration. b) viscous fingering from lime slurry

occurred during the injection that dramatically increased the hydraulic conductivity at the injection site [12, 13]. These observations concur with predictions from the fluidization model and imply that fines near the injection zones have been 'washed-out' leaving a string of highly permeable regions along the lengths of the well bores. The illustration in Figure 2a shows a cross-section along a hypothetical well depicting the wash-out concept.

It is well known that creating lenses of low permeability, through poor stacking methods, inadequate ripping, poor agglomeration etc., disrupts solution flow within the pad and ultimately impacts overall recovery [15-18]. Unsurprisingly, the ability to forcefully break up compacted layers within the heap, allegedly promoting recovery of gold from underleached ore below, is perhaps the most advertised aspect of leach pad injection. The operational objectives during the 2010 trial program were defined and executed with this approach in mind. However, when the overall impact of fluidization at the injection zone is considered, it is clear that this approach is specious and shortsighted. 'Washing-out' the fines at the injection zones and concentrating them at the edge of the fluidized cavity actually creates secondary hydraulic discontinuities within the injection zone and likely reduces the amount of gold that can ultimately be recovered from the injection efforts. Recovery of gold from the fines will be protracted because the comparatively low hydraulic conductivity of the densely-packed areas will limit solution infiltration and drainage [19] making it harder to both supply the material with fresh lixiviant and rinse the dissolved gold. The lack of fines near the well bore also ensures that the residual coarse material will drain to a lower residual wetness with less lixiviant to drive gold dissolution and, hence, gold recovery will be protracted in the coarse fraction as well. Moreover, the hydraulic discontinuities resulting from the washing-out of fines are exactly those that have been shown to produce unstable flow, fingering, and short circuiting within the heap [16, 20, 21]. All of these issues will also undermine the efficiency of secondary injections or surface-based rinsing.

Injection zones in the heap cannot be observed directly, and precisely determining the size of the wash-out zone is impossible. However, geophysical monitoring results provide insight to the movement of solution near the wellbore and provide additional support for the fluidization model. During the 2010 trial, CC&V contracted with hydroGEOPHYSICS (HGI) to support the program using electrical resistivity monitoring to observe the propagation of wetting fronts during the injections. In the cases with no lime injection, marked changes in the contact resistance on borehole electrodes caused by infiltration of wetting fronts established that leachate solution migrated radially outward 60-80 ft (18-24 m) from the well bore. The affected size and velocity of the wetting front was dependent on the rate and depth of injection. Wetting fronts would typically arrive at electrodes just below the elevation of the injection zone, in some cases less than fifteen minutes after the injections started. It is isn't clear if the fluidized zone extended to the contacted electrodes, but the velocity of the wetting fronts and the changes in the hydraulic conductivity suggest the distance was appreciable.

Acceding to Wu's predictions about solution viscosity, addition of viscous lime slurry resulted in significantly different flow regime. No wetting front arrivals were observed during lime slurry injections. The lime slurry was injected at a very low flow rate (pump idle) which likely wasn't sufficient to cause fluidization at the injection zone, leaving the bulk of the slurry amassed near the well bore. Huang identified several regimes of flow during highly pressurized injection in unconsolidated material [11]. Comparison with this work indicates that the propagation mode is likely described as a viscosity fingering-dominated regime. Figure 2b shows conceptually what may be happening in the heap. Hydraulic discontinuities created by fingers of concentrated fines from the slurry will also confound effective gold leaching in adjacent material. They also curb the utility of subsequent injections. When leaching of barren solution resumed following lime addition, the propagation behavior was significantly different than in cases with no lime injection. Wetting front arrivals were erratic and typically asymmetric. In some instances, the arrivals were observed at elevations above the injection zone with subsequent arrivals at electrodes that were not necessarily immediately below the first arrival. This likely results from the viscous mixture consuming the fluid energy and arresting cavity formation near the well bore thereby truncating the lateral spread of solution and creating a network of branching channels. Increasing the flow rate and pressure during the lime addition, or during the post-addition injections, may help push the lime slurry deeper into the pad and fluidize the viscous mixture. However, this approach would only redistribute the hydraulic discontinuities and would not address the root deficiencies of the method.

Refined Injection Strategy

The injection strategy currently employed at CC&V aims to avoid creating new hydraulic discontinuities inside the heap, promoting uniform solution contact and hold-up in the ore adjacent to the injection zones. Lime slurry injection has been discontinued entirely. Injections are limited solely to barren solution and the basic tenet of the strategy is to maintain the specific fluid velocity at the injection zones below the fluidization limit of the particulate matrix. However, this does not require limiting the overall flow rate and does not decrease the lateral coverage. Improved hydraulic understanding and a reconfigured injection setup actually permit injecting at flow rates well above any reported to date and establish a basis from which to maximize the utility of the injections.

The foundation for the revised injection mode stems from observations made during the commissioning of a new injection setup in 2011. The setup was deployed to treat twenty-two new wells installed on an area of the VLF two benches below the site of the 2010 trial. As before CC&V enlisted HGI to conduct a resistivity monitoring survey during the initial injections. A network of surface and subsurface electrodes were installed around the target wells. Electrical monitoring was continuous and lasted two weeks, allowing the tracking of wetting fronts within the heap for multiple injection scenarios, pressures, and rates [22]. Injection flow rates during the monitoring campaign ranged from 500 to 915 gpm (113 to 204 m^3/hr) with pressures between 160 and 380 psi at the well head (11 and 26 bar) depending on the depth of the injection zone. The 30% reduction in the flow rate compared to the 2010 campaign resulted from high frictional head losses in an undersized packer mechanism. The substantially reduced the fluid velocity within the injection zone led also to a dramatically different flow regime relative to those observed during the 2010 trial.

Comparisons of pre- and post-injection Lugeon values suggest that very little breakdown occurred during the 2011 injections and, whereas in 2010 several wetting front arrivals were recorded at electrodes coincident with the injection zones, in 2011 arrivals were typically only observed at electrodes well below the injection zones. The lateral coverage below each zone typically reached levels comparable to those observed in 2010, but only one coincident front arrival was recorded and only two arrivals were recorded at electrodes 20 ft below the injection depth. The lack of coincident arrivals can easily be dismissed as a consequence of the lower injection flow rates, but this does not address the question as to why a few arrivals were recorded or explain why the coverage area eventually equaled levels from 2010 despite the absence of breakdown in the heap. Deeper analysis shows that arrivals at the

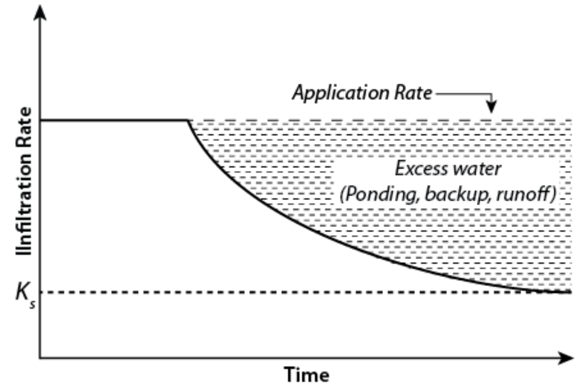

Figure 3 - Time dependence of infiltration rate und a constant application rate higher than the saturated hydraulic conductivity of the matrix. (After Hillel [19].)

uppermost electrodes only occurred after the injections had been running for upwards of two hours. This time dependence arises as a consequence of the changing infiltrateability of soils under steady infiltration rates [19]. Figure 3 illustrates this concept showing that if the solution application rate exceeds the saturated hydraulic conductivity then excess solution will eventually accumulate in the soil matrix. Hence, even though the fluid velocity during the injections was well below the fluidization limit, the same overall coverage could be achieved because the infiltration rate was greater than the infiltrateability of the crushed ore allowing solution to back up and spread laterally away from the injection site. From this perspective, maximizing the flow rate while maintaining the specific fluid velocity below the fluidization limit will maximize the radial coverage achieved during an injection without causing irreversible damage to the host matrix.

Figure 4 shows the Lugeon profile for the injection on the 230-ft zone of an injection well treated following a reconfiguration of the injection setup at CC&V to minimize the frictional head loss and reduce the specific fluid velocity through the well bore perforations. The data in Figure 4 were collected by recording the initial and final injection pressure and flow rate, as well as those observed while cycling the pump drive motor from 1,000 rpm to a maximum of 2,200 rpm and then back down in 100 rpm increments. Injection flow rates ranged between 1,080 and 1,540 gpm (261 and 350 m^3/hr) with tophole pressures of 120 to 200 psi (9 to 14 bar). The difference in the shape of the Lugeon profile compared to those in Figure 1 confirms that the revised injection protocol produces a substantially different flow regime. The nearly symmetric profile is

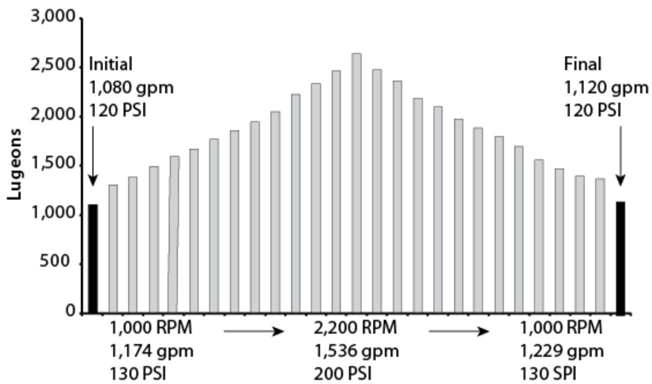

Figure 4 - Lugeon profile for 230-ft zone observed under the revised injection mode. Symmetry about the point of maximum pressure and flow is characteristic of hydrojacking behavior and is typical of ongoing injections at CC&V.

indicative of a phenomenon known as 'hydrojacking' [12, 23], wherein contact forces in the material are decreased at elevated pressure and flow rate allowing the material to become more permeable, but the increased permeability is not accompanied by permanent damage to the material from wash-out.

The slight asymmetry of the profile in Figure 4 may indicate that some wash-out occurred near the well bore, but could also be due to material expanding with increasing pressure and flow and then returning to a state of slightly less compaction as the injection is slowed. If this is true then it should be possible to controllably loosen impermeable zones by cycling flows and pressures during the injection or by injecting areas multiple times with intermittent rest periods. In any case, the revised injection method clearly reduces the disruption to the particulate assembly near the well bore. The lack of hydraulic discontinuities should improve gold production from the injected area as well by minimizing the chances for fingering or short-circuiting of solution and maximizing the fraction of the injected solution remaining in contact with the ore as residual wetness. Moreover, because there are no high-conductivity paths radiating from the well bores, the potential for solution back flow into the casing at lower elevations, bypassing much of the ore entirely, is greatly reduced.

Discussion and Future Work

The Lugeon profile in Figure 4 is typical of ongoing injections at CC&V. The pressure and flow rate are not normally cycled during routine injections, but the overall character holds even when the maximum flow rate exceeds 2,000 gpm. Flows are typically limited to 1,200 gpm (270 m^3/hr) for convenience in maintaining practical solution balances and managing distribution systems. Injection pressures are allowed to equilibrate freely (rarely exceeding 180 psi) and injections generally run for three hours at each zone.

The revised injection method has been used successfully on over 50 injection wells with no detrimental impacts. There is manifest evidence that the injections have accelerated gold recovery from the VLF and plans are currently being formulated to implement a full-scale pad injection program as part of the overall operational plan for the VLF. However, there is no basis to conclude that any of the injection parameters are optimal and the relationships between injection flow rate, duration and radial coverage have not been fully characterized. Straightforward reasoning suggests that the number of wells required to totally cover a certain area will be minimized, from the simple perspective of wetted area , if the injection flow rate and duration are maximized. However, the fraction of the total volume of injected solution that remains in the heap, and is available to dissolve residual gold, should be highest at low flow rates and short durations. Correctly specifying the interwell spacing for the pad-wide operations planned for the VLF will require additional investigation into the relationship between these two competing considerations.

An additional resistivity monitoring campaign is planned for summer 2013. The program is being designed to further validate the findings presented above and to explore the relationship between injection flow rate and duration aiming to identify protocols that will maximize overall production using the minimum number of wells.

Conclusion

Success from a trial program conducted in 2010 and subsequent pad injection efforts have prompted the development of full-scale injection program as part of the overall operational plan for the VLF at CC&V. Investigation into the mechanics of process indicates that hydraulic fracturing analogies advanced heretofore do not accurately describe injection phenomena in unconsolidated material typical of leach pads. From a gold recovery standpoint the optimal strategy is to maximize the injection flow rate while maintaining the specific fluid velocity below the fluidization limit of the host ore. Additional work is needed to define the optimal flow rate and duration.

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