HEAP CHARACTERIZATION AND MONITORING WITH ELECTRICAL RESISTIVITY FOR OPTIMIZING SECONDARY LEACHING

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ABSTRACT

Electrical resistivity geophysics has been applied on a heap to characterize and monitor changes in saturation after primary and secondary leaching applications. The characterization effort mapped the distribution of high and low resistivity, which can be correlated to low and high moisture content, respectively. Regions of low moisture and high resistivity were assumed to be ineffectively leached during the primary leaching cycle, and were targeted by a secondary leaching application with Hydro-Jex. Hydro-Jex involves the injection of lixiviant at high pressures in a cased well. During the injection, the electrical resistivity was used to monitor the decrease in resistivity. The decrease is directly related to increased saturation. The electrical resistivity monitoring showed how the fluid injected into the heap moved away from the injection well, and demonstrated the effectiveness of the Hydro-Jex technology to reach dry and unleached areas within the heap.

INTRODUCTION

Heap construction and effective leaching is greatly impacted by the types of geologic materials used in the construction. The ineffective leaching within the heap is typically the result of finer-grained material to agglomerate into confining layers, which create the two main concerns of pooling and shading. The pooling effect is created when solution accumulates above the confining layer, where the hydraulic conductivity is sufficiently low that percolation through the layer occurs at very large time scales. The pooling will then cause additional water to flow around the pooled solution and create a shading effect immediately below the confining layer. The shaded zone remains relatively dry reducing the total volume of leached ore. Large confining zones will therefore reduce the total effectiveness of the heap and leave large metal inventories in the heap.

The Hydro-Jex technology was developed for the secondary stimulation of heap leach pads to augment the extraction of the metal inventory [Seal, 1994; Seal, 2007]. The Hydro-Jex process consists of drilling and casing holes within a heap, perforating the casing at specific depths, and injecting lixiviant at each depth using a straddle packer. This secondary leaching application is extremely effective if the drilling targets are the areas left dry by ineffective primary leaching. Lixiviant volumes and injection pressures of the Hydro-Jex system have been based on cylindrical models and refined by field testing. Actual flow paths of lixiviant within a heap are strongly dependent on the directional hydraulic conductivity of the heap which is, in turn, dependent on the heap construction and variability in particle sizes within the pad. The variability in particle size generally ranges from crushed material (3/4” minus) to run-of-mine (ROM [6” plus]).

Any cost-effective characterization technology that will offer insight into the heterogeneity of the heap and locate the dry areas would optimize the Hydro-Jex technology and ensure an even distribution of lixiviant in the zone of stimulation. The characterization technology should be capable of sensing large volumes over broad areas and be non-obtrusive to the drilling and pumping operations. Borehole-based sensors, such as pressure transducers, water content probes, or logging tools, are handicapped in this regard based on 1) disturbance of the zone near the borehole, and 2) the sensing volume is a relatively narrow band near the borehole. Interpolation between boreholes from these small-volume measurements can be misleading.

Electrical resistivity geophysics has previously been demonstrated in a number of mining operations to aid in defining heap characteristics [Versteeg *et al*., 2005]. The dry zones are electrically resistive and are assumed to represent volumes of minimally leached ore-grade material. Fortunately, these dry zones can be imaged inexpensively and non-invasively from the surface of the heap. In addition to characterization, the resistivity technique can be used to monitor time-dependent processes such as the solution migration during Hydro-Jex stimulation. As the saturation of the pore space increases, the electrical resistivity of the material decreases and the effect can be monitored to ensure complete saturation of the desired area.

We demonstrate a field application of electrical resistivity to characterize the confining zones and preferential flow paths of lixiviant in a heap after primary leaching from the surface. The characterization effort was then used to help locate wells for secondary stimulation by Hydro-Jex. During injection of lixiviant, the resistivity system was used to monitor the fluid migration away from the Hydro-Jex well in real-time. The electrical monitoring of fluid movement allowed field-based decisions to be made regarding the order of stimulation and the potential for optimizing the process for increasing production.

METHODOLOGY

Electrical Resistivity Characterization

Electrical resistivity surveying is conducted by measuring the voltage on a pair of stainless steel electrodes in direct contact with the earth while electrical current is passed on an adjacent pair of electrodes. The measured voltage is affected by the electrical properties of the subsurface. To completely image the subsurface, a line of electrodes are placed at a set interval and each electrode pair is used in the voltage measurement. The current electrode pair is changed and the cycle of voltage measurement is repeated. An inversion procedure is then used to calculate the electrical properties needed to match the voltage measurements. Electrical properties are affected by the moisture content (or degree of saturation), porewater ionic strength, and soil type.

After the primary leaching cycle was completed on the pad, electrical resistivity was deployed along 12 parallel lines. A SuperSting R8 resistivity meter (Advanced Geosciences, Inc. – Austin, TX) was used to conduct the measurements using a gradient and Schlumberger array. Each line was approximately 1370 feet long and comprised of 140 electrodes spaced every 10 feet. The lines were separated by approximately 55 feet. Figure 1 shows the layout across the top of the heap. With the 1680 electrodes, the number of voltage measurements exceeded 81,000.

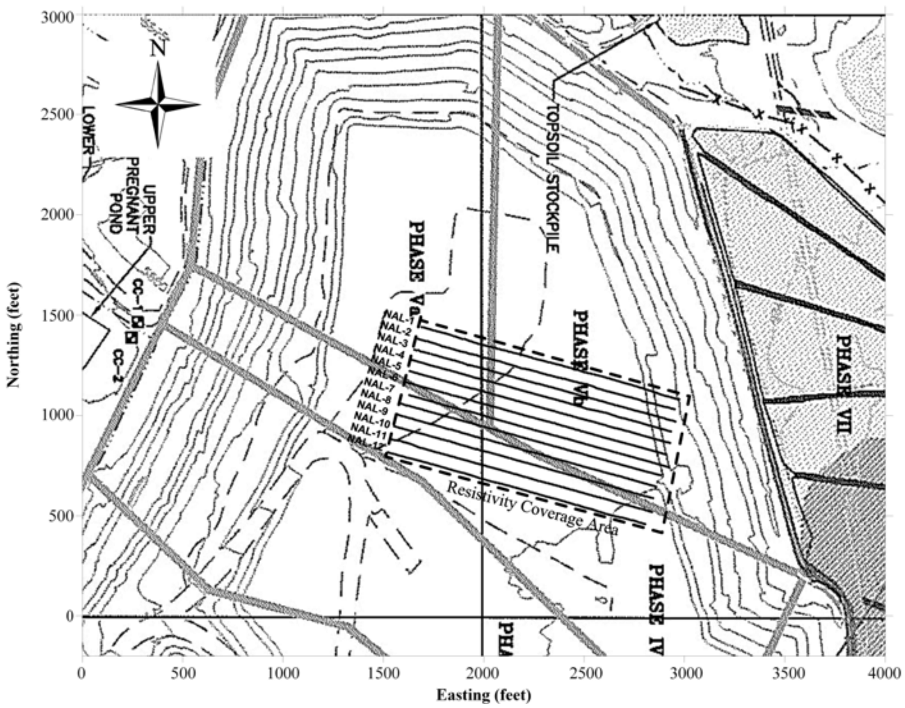

Figure 1: Electrical resistivity survey lines over the top of the heap.

The electrical resistivity software EarthImager3DCL (Advanced Geosciences, Inc. – Austin, TX) was used to invert the data. The capabilities of the code and enhancements over normal inversion codes was discussed in Rucker *et al.* [2008]. Figure 2 shows the spatial distribution of electrical resistivity beneath the survey lines. The figure segregates low and high resistivity to show moist (low resistivity) and dry (high resistivity) zones. The figure clearly shows areas that were ineffectively leached, with the eastern most region near the slope of the pad being drier than the western region. Additionally, the deeper regions appear to be wetter than the upper regions.

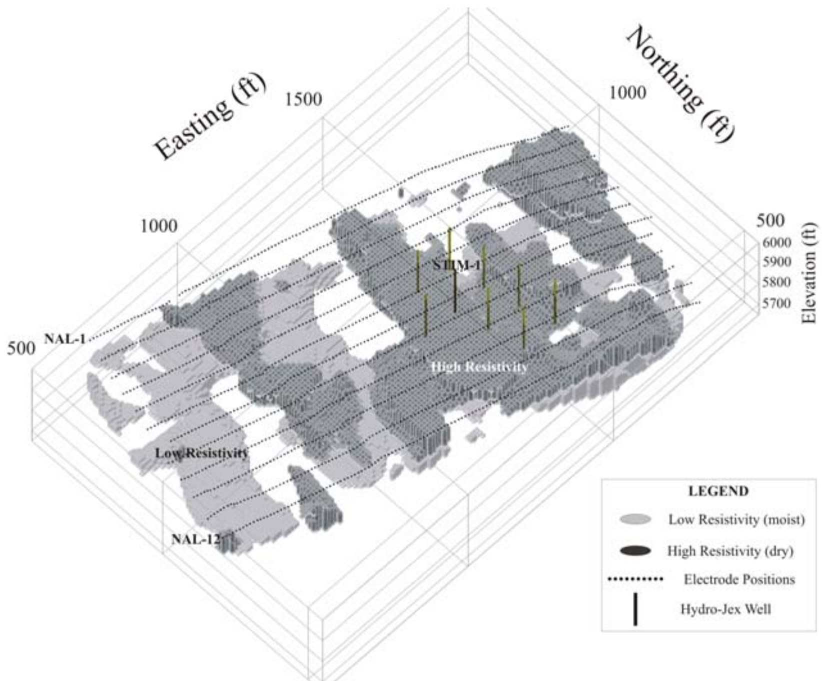

Figure 2: 3D characterization of a heap after primary leaching using resistivity.

The results of the characterization was used to help place the wells for secondary extraction using Hydro-Jex. The use of resistivity help optimize the location of the Hydro-Jex wells by preferentially citing them in areas that have not previously been effectively wetted. Nine wells were placed in the eastern region, within the zone of high resistivity. The wells were installed to a depth of 200 feet below the top of the pad. The wells are placed roughly 100 feet apart.

Electrical Resistivity Monitoring

During the Hydro-Jex stimulation of the heap, an electrical resistivity monitoring system was deployed to monitor the changes in saturation. Hydro-Jex stimulation occurs at every 20 feet from 190 to 30 feet below pad surface, and the stimulation within a single well occurs over a couple of days. Total volume of lixiviant injected into the heap can be in excess of 750,000 gallons. After cessation of the injection of the lixiviant, a rinse cycle of water is conducted over several days to move the lixiviant out of the pore space.

The electrical monitoring equipment was manufactured by hydroGEOPHYSICS, Inc (HGI), and includes a 96-channel data acquisition system. The system is capable of acquiring voltage data simultaneously on 95 electrode pairs while current is passed on one electrode pair. For a complete set of measurements, where each electrode has a turn at transmitting current while all others measure voltage (and assuming a 2-cycle, 1Hz measurement), the time to create a "snapshot" of the subsurface is approximately three minutes. When the subsurface is highly dynamic, such as when the Hydro-Jex system is pumping in high volumes of lixiviant, a low measurement time is extremely important. The subsurface can change rapidly over short time scales and capturing the state of the fluid's position before it changes significantly can only be accomplished with high channel systems.

Figure 3 shows the set up of the electrode grid used for monitoring Hydro-Jex. The electrodes are placed much closer to the stimulation well (STIM-1) to focus on local changes near the well. Three parallel lines of electrodes were comprised of 24 electrodes for each line, with lines separated by 100 feet. The remaining 24 channels were connected to the wells surrounding STIM-1, some of which are not shown in Figure 3. The resistivity monitoring on the wells will not be discussed in this paper.

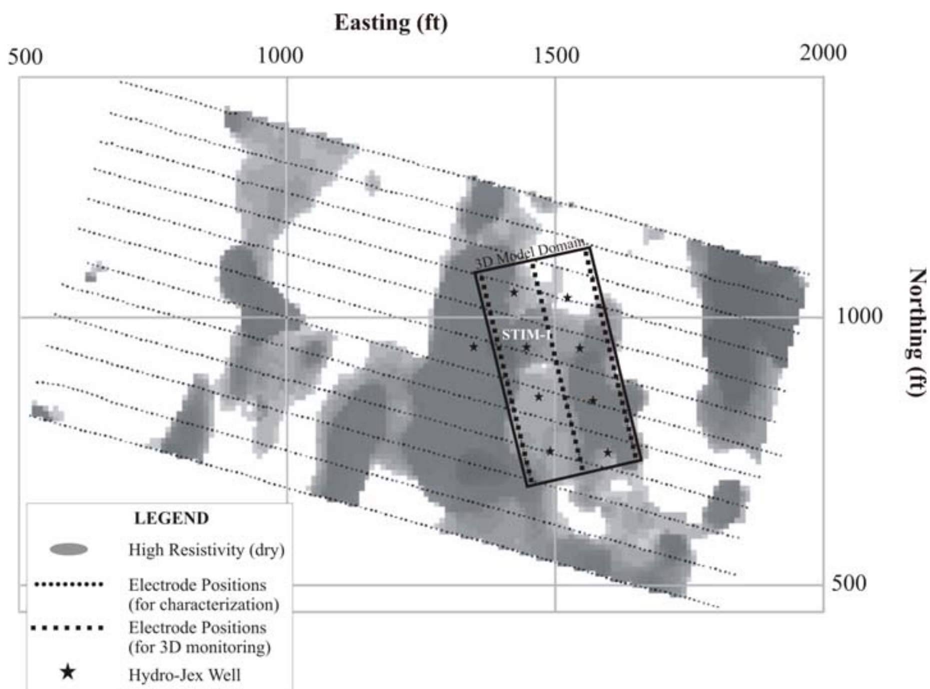

Figure 3: Electrical resistivity monitoring domain during Hydro-Jex stimulation on well STIM-1. Regions of high resistivity mapped from the characterization effort are shown for reference.

RESULTS AND DISCUSSION

Electrical resistivity monitoring occurred over a six day injection / rinse cycle in well STIM-1. Figure 4 shows the schedule of events that occurred during Hydro-Jex, including draindown (i.e., no injection or rinse), active injection with lixiviant and water rinse. Injection began on Day 1at 190 feet below pad surface. A malfunction in equipment shut down the operation temporarily, but injection started up again a short time later. Days 2 and 3 included injection on the remaining segments, with injections at each depth occurring over a 1.5 to 2 hour period. On Day 4, rinsing started and continued to the end of the monitoring campaign.

During the six day injection / rinse cycle on STIM-1, 117 snapshots of resistivity were gathered. Of these, six snapshots were pulled out for further analysis, and the times for these snapshots are display along the timeline of Figure 4. The baseline survey was conducted near midnight on the first day, and the baseline is used for comparison with all other snapshots. The remaining snapshots were obtained at the end of each preceding day, and through the end of Day 5.

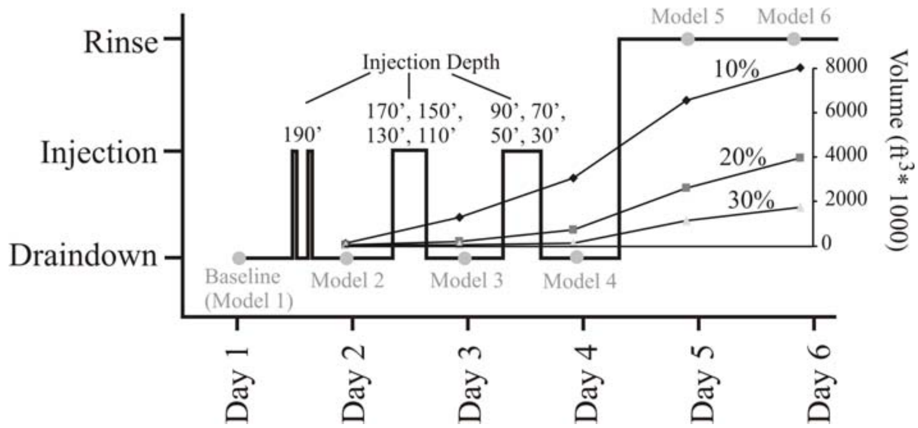

Figure 4: Injection schedule and volume affected by 10, 20, and 30 percent change in resistivity during Hydro-Jex on STIM-1.

The results of the resistivity imaging during the injection / rinse cycle on STIM-1 is shown in Figure 5. The data for Models 2 through 6 are shown as a percent decrease in resistivity compared to the baseline conditions, with three values of percent decrease shown. For reference, a change from 100 to 80 ohm-m in resistivity and 10 to 8 ohm-m are both equivalent to a 20% decrease in resistivity. A larger percent decrease would indicate a larger increase in saturation. The 15 cells in Figure 5 represent time horizontally and saturation intensity vertically.

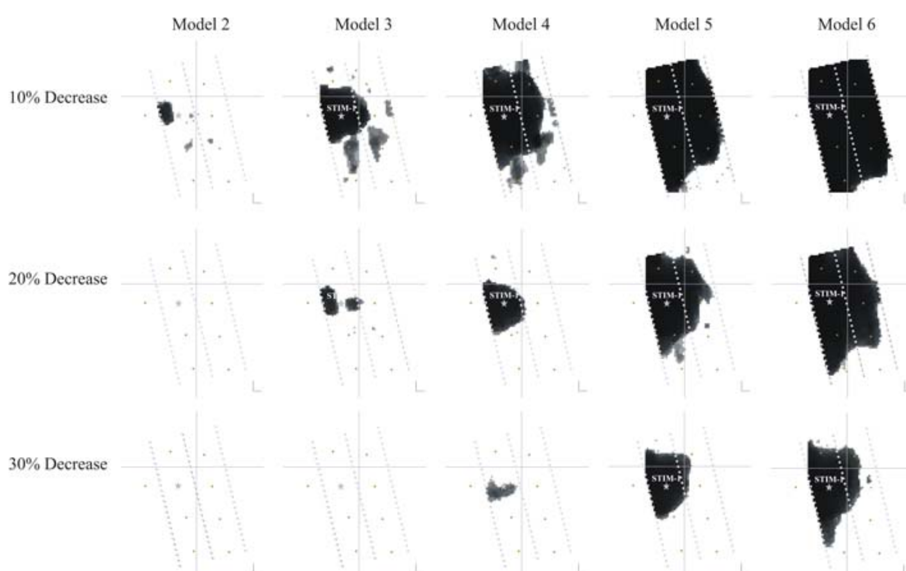

Figure 5: Electrical resistivity results presented as percent decrease in resistivity from baseline conditions.

Figure 5 shows how the fluid is moving in the heap during injection. Overall, the fluid appears to have a more north-south trend to the movement. Unfortunately, the positioning of the electrode grid was too close to see the full lateral effects of the fluid injection. However, local effects are shown and several notable hydrologic observations can be made:

- At the end of day 3, the affected area encompasses 150 foot radius at 10% decrease and very little at 20% decrease (and nothing for 30% decrease). This likely is the result of large pore spaces that has net reached saturation.
- With large pore spaces, gravity is dominating flow causing vertical movement of the fluid
- The spreading seen at the end of day 4 is likely occurring below the actual injection
- Rinsing is causing some lateral migration of fluid, pushing the lixiviant out away from the injection well. The rinsing is providing an inexpensive means for mobilizing the lixiviant.
- Although not seen here, it is predicted that with continued rinsing, the resistivity of the subsurface would increase. The increase in resistivity is due to the rinse water having a higher resistivity than the lixiviant. As the lixiviant in the porewater is replaced by rinse water, the overall effect will be an increase in bulk resistivity. This has been observed during monitoring of other areas, and can be used to determine the end of effective rinsing.

The volume of the heap affected by Hydro-Jex is shown quantitatively in Figure 4 along with the scheduled timeline. The three lines on the graphic represent the three groups of intensity in decreasing resistivity, as shown in Figure 5. The quantitative volumes for the 10, 20, and 30 percent decrease show a quick increase during the initial lixiviant injection through day 5. However by day 6, the *rate* of volume affected by rinsing starts to decrease, even though the total volume is still increasing. This is the beginning of rinse water and lixiviant mixing. Eventually, the replacement of lixiviant by rinse water will cause the curves of affected volume to decrease. At this point, rinsing is complete.

CONCLUSIONS

An electrical resistivity geophysical survey was used to characterize a heap after the end of the primary leaching cycle. The characterization survey included 12 parallel lines, approximately 1370 feet in length. The survey was used to determine areas of effective wetting, by assuming that low resistivity regions had a higher water content than high resistivity regions. The results showed regions of segregated and stratified low and high resistivity zones.

The high resistivity region towards the eastern side of the pad was targeted for secondary leaching with Hydro-Jex. The Newmont Mining Corporation developed the Hydro-Jex technology to enhance metal recovery, which involves the injection of high volumes of fluid at high pressures in cased wells. Injection occurs over 10-foot intervals spaced 20 feet apart. The five-foot injection intervals are maintained with inflatable packers. The characterization with electrical resistivity helped in the placement of the wells by targeting the region of high resistivity and low moisture.

To monitor the effectiveness of the Hydro-Jex technology, the electrical resistivity method was applied near an injection well. During the 6-day injection / rinse cycle, 117 snapshots of the spatial distribution of resistivity was obtained. The snapshots of resistivity at a particular time were compared to a baseline case to map the changes in resistivity. The change in resistivity is more uniquely related to moisture content, and values of 10%, 20%, and 30% decrease in resistivity was mapped over time. For reference, a reduction in resistivity from 100 to 80 ohm-m and 10 to 8 ohm-m result in a 20% decrease in resistivity.

The monitoring results show how the subsurface is affected during the high pressure injections. There appears to be an almost symmetrical flow away from the well at the onset of the injection. However, the relative change is quite low (i.e., low saturation), indicating large pore space. Large pore space is a consequence of large grained material, such as that from ROM. In addition to small changes in saturation, the large pore space is likely causing much of the fluid to travel vertically due to gravity drainage. Finally, water rinsing is shown to be effective at first dispersing the lixiviant then replacing the lixiviant in the heap.

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