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Liquid spread mechanisms in packed beds and heaps. The separation of length and time scales due to particle porosity

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ABSTRACT

The distribution of liquid within a heap is a key factor in the system performance as it has a strong effect on the transport of both reagents and leached species and thus the leaching rate. How liquid spreads from drippers and the subsequent development of flow paths and any associated channelling is thus important. In this paper a pseudo 2-D column was used to investigate the horizontal spread of liquid in the vicinity of dripper in columns packed with both narrowly sized particles and more realistic particle size distributions. Both systems had distinct separation of the time scales at which different saturation features developed. There was an initial rapid formation of flow paths in the inter-particle spaces with only local wetting of the intra-particle spaces, though this was associated with little spread. Over a much longer time period there was extensive horizontal spread of the liquid within the ore particles, though this was associated with virtually no vertical flow. The externally held liquid (liquid content between the particles) showed strong channelling behaviour, especially in the realistically sized particles, despite the care that was taken to ensure uniform packing. This effect can be reduced by changing initial bed conditions and employing dense drip emitter locations, but it cannot be completely eliminated as particle level heterogeneities in heap leaching systems affect external flow paths creation. Hysteresis in the amount of liquid spread was also demonstrated, with the total spread depending not only on the current flow rate, but also on the flow history.

1. Introduction

Although various mineral processing techniques are used to extract metals from run-of-mine (ROM) ore, most increase in cost and decrease in efficiency markedly as the grade decreases. Heap leaching, though, is far less sensitive to low grades than other mineral processing techniques. However, the recovery in heap leaching is generally relatively low compared to other separation techniques such as froth flotation and thus heap leaching leaves a lot of scope for improvement. Potential sources of improvement are not only in the chemistry and bio-chemistry of these systems, but also in the hydrodynamics of the heaps.

The fluid flow in these systems is unsaturated, consisting of both liquid, which is added at the top during irrigation, and air. The fluid flow in heap leaching is complicated not only due to it being unsaturated, but also because of the different length scale of the channels involved. The porosity of the packed particles has two distinct length scales, namely that of the channels between the particles (i.e. inter-particle space), which will typically have a length scale of order millimetres, and that within the particles (i.e. intra-particle space), which will typically have a length scales of order tens of microns or even smaller. The Bond number, which is the ratio of gravity to capillary forces, will be around 1 for the fluid flow between the particles, indicating that this flow is in the transition region between capillary and gravity dominated flow. However, the existing micro-pores within the particles will have Bond numbers that are many orders of magnitude less than 1, indicating capillary dominated flow (Ilankoon, 2012; Ilankoon and Neethling, 2013). These differences in length scale result in very different fluid flow behaviours.

In industrial heap leaching, solution application using drip emitters is very common and drip emitter lines are generally separated by about 50–100 cm with a spacing of about 50 cm between drippers on a particular line to cover a targeted wetted area of about 0.25–1 m^2 per dripper. Afewu (2009) suggested that a denser

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grid of drippers would result in more uniform wetting and ultimately better performance.

In order to achieve good leaching, particles in a heap should be in close proximity to actively flowing fluid. Transport of reagents and leached metal species by diffusion is a slow process and it decreases rapidly with distance as any flux requires concentration gradients. The liquid addition at the top of the heap is however not uniform in practice and the liquid trickles as preferential channels between particles from top to bottom (Petersen and Dixon, 2007). Bartlett (1992) demonstrated the relationship between superficial liquid velocity, intrinsic permeability, and hydraulic conductivity of porous media. He explained that Micro-flooding occurs in areas where the average velocity exceeds the local limiting velocity depending on the local hydraulic conductivity. Channelling and perched water tables form due to higher flows at the top of the heap. Short-circuiting through channels will be ineffective in transporting reagent and dissolved species and it would also dilute the grade of the pregnant solution (Bartlett, 1992).

The bulk density of the heap was observed to vary across the bed due to particle segregation (Howard, 1968; Roman, 1977; Yusuf, 1984; Bartlett, 1992). Areas of lower bulk density have higher permeability or less resistance to flow; these result in preferential flow through larger openings. The presence of significant quantities of clay results in localised compaction with low permeability. Often, high permeability channels surround these low permeability areas (Yusuf, 1984). The existence of preferential flow pathways instead of homogeneous flow is often observed and is generally referred to as channelling (Yusuf, 1984; Wu et al., 2009). Inhomogeneous wetting of particles is thus observed at various depths in the heap, which results in highly variable liquid content in different regions. Previous experimental studies have indicated this behaviour within both laboratory scale and large scale ore columns, heaps and dumps (eg. Howard, 1968; Armstrong et al., 1971; Murr, 1979; Cathles and Murr, 1980; Murr et al., 1981; Wu et al., 2007, 2009; Fagan et al., 2014).

While the fluid flow experiments indicate that differential flow and channelling is a very real effect in heaps, these previous studies do not show the mechanisms at work. Furthermore, large scale columns cannot be effectively used to study the underlying mechanisms (eg. Murr and co-workers), because the scale limits the extent to which the fluid flow behaviour can be directly observed and are thus of less use in the elucidation of the mechanisms at work. In order to understand the particle level mechanisms, experiments need to be conducted at a smaller scale where the impact of particle scale effects can be seen. Insights into these particle scale behaviours and mechanisms can then be used to better understand the behaviour of an industrial scale heap. The main objective of this study is thus to examine the wetting behaviour and liquid flow path development in laboratory scale narrow "2-D" ore systems using both narrow and realistic particle size distributions in order to better understand the mechanisms involved in liquid spread and channelling. The effects will be discussed in terms of actively flowing liquid channels, wetted area of the bed and channelling flow features. In addition, possible strategies to minimise these effects will also be discussed.

2. Experimental design and methods

In order to investigate both the horizontal and vertical liquid flow behaviour in ore mixtures, a rectangular Perspex column with a width of 800 mm and a height of 600 mm, and a depth of only 100 mm was designed (see Fig. 1) and hereafter referred to as the pseudo 2-D column. The 2-D column was suspended from two load cells so that the liquid content could be measured continuously with time. The system required careful calibration as the overall measurement is a combination of the two load cell measurements. The variation in liquid content is only a small proportion of the overall weight of the column (measured changes of a few grams of liquid in a packed column weighing about 100 kg) further adding to the requirement for accurate calibration. The calibration procedure and its validation against independent measures of liquid holdup has been described in previous papers (Ilankoon and Neethling, 2012, 2013).

The ore system used consisted of copper ore particles collected from Kennecott Utah Bingham Canyon Mine. The average water accessible porosity was measured by soaking the particles in water for 24 h and was found to be about 5%. The particle properties are described in more details in Ilankoon and Neethling (2013). The experimentally determined (based on load cell measurements) average external voidage (excluding internal porosity) was about 30.7% for the narrowly sized particles (20–26.5 mm) and around 18.7% for the more realistic size distribution (2–26.5 mm). Typically, about 75 kg of particles were required to randomly fill the 2-D column. The fluid flow experiments were performed with both a narrowly sized fraction of ore particles, namely 20–26.5 and more realistic ore size distribution, namely, 2–26.5 mm. Even though industrial heap leaching does not employ narrowly sized fractions, the 20–26.5 mm size fraction was selected to represent a typical particle size in a heap leaching system, with the similarities and differences in the behaviour of the narrowly sized and more realistic size distributions providing insights into the mechanisms involved. In order to prepare the 2–26.5 mm mixture a Gaudin Schumann (GS) distribution was employed with a gradient of 1.5. The distribution was created by mixing together the appropriate amounts of material from 7 particle size fractions (2–4, 4–8, 8–11.2, 11.2–13.2, 13.2–16, 16–20, 20–26.5 mm). The bottom plate

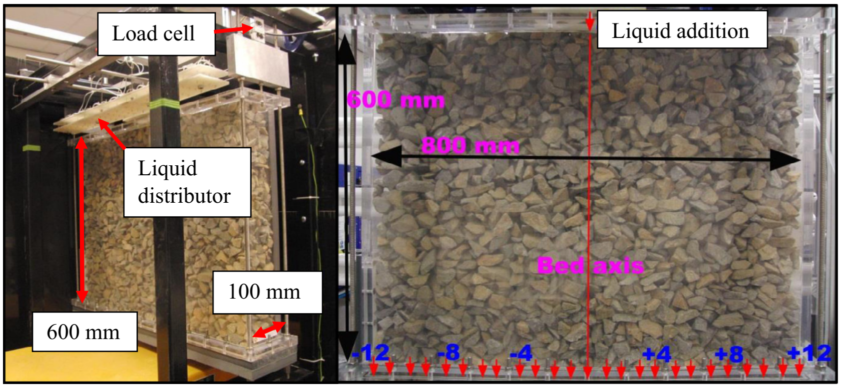

Fig. 1. 2-D column rig and its main components. In here the column is filled with the narrowly sized ore particles (20–26.5 mm) and the bed is initially dry.