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Computational modelling of unsaturated flow of liquid in heap leaching—using the results of column tests to calibrate the model

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Abstract

Unsaturated flow of liquid in a bed of uniform and spherical ore particles is studied numerically and experimentally. An unsteady and two-dimensional model is developed based on the mass conservation equations of liquid phase in the bed and in the particles. The model equations are solved using a fully implicit finite difference method giving the distribution of the degree of saturation in the particles and in the bed and the vertical velocity of flow in the bed, as well as, the effect of periodic infiltration on the above distributions. To calibrate the computational model, several column tests are performed using periodic infiltration of water on 40 cm high columns composed of ore having particles smaller than 25 mm. The numerical analysis shows that (a) the results obtained from numerical modelling under the same operating conditions as used for column tests, are in good agreement with those from experimental procedure, (b) the degree of saturation of the bed and the time required to reach steady state conditions depend on the inflow of water and intrinsic permeability of the bed and (c) the velocity fluctuations and the fluctuations of the degree of saturation in the bed depend on the inflow of water, period of infiltration, height and intrinsic permeability of the bed.

Keywords: Modelling; Unsaturated liquid flow; Heap leaching; Porous media; Column test

1. Introduction

A porous medium is defined as a matrix of solid particles with interconnected void spaces. The solid matrix is considered rigid or having small deformations. The interconnection of the pores allows the flow of one or more fluids through the medium. In a natural porous medium, the shape and size of pores are irregular. Thus, in microscopic scale, the flow quantities (velocity, pressure, etc.) will be non-uniform, but for studying the flow in a porous medium, usually space-averaged quantities are used [1]. Heap leaching is one of the industrial processes in which fluid flows through a porous medium. In this process, unsaturated lean liquor solution flows in the ore bed together with chemical reactions [2]. The perception of fluid flow through ore heaps is described primarily from soil mechanics, hydrogeology and chemical engineering theory supported by experimental

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Nomenclature

d	particle diameter
D	diffusivity
g	gravitational acceleration
h	pressure head
H	bed height
K_i	intrinsic permeability
K_r	relative permeability
K	hydraulic conductivity
m	exponent in Eq. (6)
n	shape parameter of SWRC
q	volumetric rate of production or consumption of liquid
r	radial distance
R	particle radius
S	degree of saturation ($=\varepsilon_l/\varepsilon$)
t	time
u	superficial velocity
z	depth from datum
α	shape parameter of SWRC
ε	porosity
Φ	potential
μ	dynamic viscosity
ρ	density
τ	time required reaching steady state

Subscripts and abbreviations

B	bed
e	effective
in	inlet
l	liquid
out	outlet
p	particle
r	residual
S	saturation
0	initial condition
SWRC	soil–water retention curve

information [3]. The solution in the bed is divided into two parts; the moving part that flows among the ore particles due to gravity and the stagnant part attached either to the pore walls of ore particles or to the particles external surfaces. The dissolution reactions of reactants are occurred in the stagnant part, and the diffusion of reagent and species between these two parts is done by mass transfer mechanism [4]. One way of improving this operation is periodic irrigation of leaching solution on top of the ore heap. As a result of this, one can reach to a relatively constant concentration of dissolved species in the pregnant solution and enhance the performance of the recovery plant [5].

The understanding of hydrodynamics of liquid (leaching solution) is an important factor during heap leaching operation. The purpose of this work is developing a computational model to analyze the flow of liquid through the bed of ore particles and the transport of liquid within the particles.

Martinez et al. [5] simulated the periodic infiltration of water in heap leaching based on mass conservation equation for liquid inside the bed as well as the liquid within the particles. They used the semi implicit finite difference technique (Crank Nicolson) to solve the set of descretized equations. Sheikhzadeh et al. [6] improved the Martinez et al. [5] computational model using a fully implicit finite difference technique [6]. Sheikhzadeh et al. used the same operating conditions as those used by Martinez et al. in order to be able to compare their fully implicit results with the semi implicit results obtained by Martinez et al. Although the results of two computational models are in good agreement, neither of them can be applied to other operating conditions, because the models are not calibrated based on experimental results. In this research, however, the authors performed a series of column tests using intermittent irrigation of water on top of 40 cm high columns composed of ore with particles smaller than 25 mm. They obtained the shape parameters for the characteristic curve of soil–water, experimentally and calibrated their computational model based on the experimental results. The model can now be used for other operating conditions.

2. Mathematical simulation of heap leaching

Modelling of processes occurring in heap leaching is done in two stages. The first stage is simulating the movement and diffusion of solution through the bed and within the particles. This stage consists of two models, one for diffusion of solution into the particle (particle model) and the other for diffusion and movement of solution among the particles (bed model). These two models are coupled due to equality of potential at the surface of particle (interface of particles and bed) and mass flux at the surface of particle. The first stage modelling gives (a) the local values of the degree of saturation at different times, (b) the local values of diffusion coefficient and hydraulic conductivity, and (c) the local values of vertical velocity of fluid. The degree of saturation and vertical velocity are necessary for second stage