Modelling unsaturated dual-phase flow through crushed ores for heap leaching

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Abstract

Heap leaching is used extensively for the processing of low-grade copper, gold, and uranium ores. The hydrodynamics is often the most important factor that limits the rate of metal recovery. Over the past decades the author has performed physical and hydraulic testing of a large number of ore samples considered for heap leaching. The data were reviewed to investigate the effect of physical properties such as particle size distribution (PSD) and bulk density on the hydrology. The unsaturated flow through the bed is traditionally modelled with soil science models such as Brooks-Corey (BC) and Van Genuchten-Mualem (VGM), which relate the hydraulic conductivity to the degree of saturation, also known as the hydraulic conductivity function (HCF). However, most authors found a disconnect between the saturated hydraulic conductivity (K_S) and the rest of the HCF, which is explained as resulting from a transition from capillary-to gravity-controlled flow. However, the author found no such transition, and found the flow to be governed by capillary flow throughout. Traditional BC or VGM fits were found to be appropriate, however it was necessary to modify the model to include a point of inflection, above which the hydraulic conductivity remains constant while the moisture content keeps on increasing. It was proposed that this is the result of unconnected or poorly connected pores, which fill with solution but do not create additional flow channels. The point of discontinuity was also found to correspond with the air entry point, measured independently from the air conductivity curves. On average, the air entry point corresponds to the experiential rule that the void saturation should remain below 65% for aerated heaps.

Keywords

heap leaching, modelling, solution flow, air conductivity

Introduction

Heap leaching accounts for approximately 17% of global gold production and 21% of global copper production (Marsden et al., 2017; Basov, 2015). Heap hydraulics are often the limiting factor, which determine the rate of metal dissolution. Poor solution permeability may limit the rate at which valuable metals can be flushed from the heap, whereas poor solution contact may result in uneven wetting and incomplete extraction. Over the years a number of operations have experienced problems with solution permeability, e.g., Benkala (Whiterow, 2013), Cerro Verde (Galdos et al., 2013), and Chuquicamata (Ramírez et al., 2019). Prior to heap leach design it is therefore necessary to perform physical and hydraulic testing of the crushed ores and agglomerates. This typically include compression tests to determine the bulk density profiles during compaction, as well as hydrodynamic column tests (Cherkaev, 2019; Pyper et al., 2015; Guzman et al., 2013; Milczarek et al., 2013; Robertson et al., 2013; Ilankoon and Neethling, 2012; Lupo, 2011; Afewu, 2009; Guzman et al., 2008). A number of benchmarks have been established by experience, for example, the bulk density should not exceed 1.9 t/m^3 (equivalent to 30% porosity) (Robertson et al., 2013; Guzman et al., 2013). Higher compactions will result in insufficient voidage available for solution flow, resulting in ponding or channeling. Furthermore, it was established that the degree of void saturation during percolation should not exceed 65% for aerated heaps, above which the heaps will not conduct air. For non-aerated heaps, the degree of saturation should not exceed 85% to maintain slope stability (Robertson et al., 2013; Milczarek et al., 2012). The saturated hydraulic conductivity (K_S) should be at least 100 × the target 'unsaturated' application rate (Pyper et al., 2015; Milczarek et al., 2013; Robertson et al., 2013).

Table I

Summary of correlations used

	Burdine	**Mualem**
HCF	$K_r = S_e^{\gamma}\left[\frac{\int_0^{S_e}\frac{dS_e}{h^b}}{\int_0^{1}\frac{dS_e}{h^b}}\right]^q$ [3]	
	$\gamma = 2, b = 2, q = 1$	$\gamma = 0.5, b = 1, q = 2$
	Brooks-Corey (BC)	**Van Genuchten-Mualem (VGM)**
WRC	$S_e = \left(\frac{h_c}{h}\right)^{\lambda}, h < h_c$ $S_e = 1 \quad , h \geq h_c$ [4]	$S_e = [1 + (\alpha h)^n]^{-m}$ [7]
HCF	$K_r = (S_e)^{n_p}$ [5]	$K_r = S_e^{\gamma}\left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2$ [8]
ACF	$K_g = K_{g\,max}(S_g)^{n_g}$ [6]	$K_g = K_{g\,max}(1 - S_g)^{\Upsilon}\left[1 - S_g^{\frac{1}{m}}\right]^{2m}$ [9]

The water retention curve (WRC) and the hydraulic conductivity function (HCF), which are rooted in pore-scale capillary and viscous flows, often form part of analytical and numerical models for flow and transport in unsaturated porous media. The WRC describes the relationship between soil matric potential (capillary head), h (m), and the soil water content, θ (m^3/m^3). The soil water content is typically represented as dimensionless effective saturation, S_e (Equation [1]), where θ_s and θ_r are the soil saturated and residual volumetric contents, respectively (Assouline and Or, 2013). The HCF is often expressed in terms of the relative hydraulic conductivity (K_r), which is scaled by dividing the hydraulic conductivity (K_w) of the solution by the saturated hydraulic conductivity, K_s (Equation [2]).

$$S_e = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right) \qquad [1]$$

$$K_r = \frac{K_w}{K_s} \qquad [2]$$

Hydraulic properties of unsaturated soils have been modelled by authors such as Burdine (1953) and Mualem (1976), who attribute to the soil a single unimodal pore size distribution governed by capillary action. Burdine's model (1953) defines the relative solution conductivity (K_r) in terms of the ratio between the square of the mean hydraulic radius (r_H) of the unsaturated soil at effective saturation (S_e) to the square of the mean hydraulic radius of the soil at full saturation ($S_e = 1$). Applying the capillary law ($r_H = C / h$), Burdine derived Equation [3] (Table I), where h is the capillary pressure, γ is the pore-size interaction term, and b and q are constants. For the Burdine model, $\gamma = 2$, $b = 2$ and $q = 1$. Mualem (1976) replaced the pore configuration with a pair of capillary elements whose lengths are proportional to their respective radii, and, by comparison of 45 soils, he found $\gamma = 0.5$ to provide the best fit when using measured K_s values as matching point. The Mualem model, also described by Equation [3], has $\gamma = 0.5$, $b = 1$ and $q = 2$.

Brooks and Corey (BC) (1964) observed that for a large number of experimental data sets, the WRC can be represented by Equation [4] (Table I), where λ is referred to as the pore-size distribution index and is usually in the range of 0.3 to 10 (Kosugi et al., 2002). The BC function is discontinuous, and has a distinct air-entry head, h_c, above which the soil is assumed to be saturated. Substituting the BC (Equation [4]) into Mualem's formula (Equation [3]) yields the HCF (Equation [5]), where n_p is a fitting parameter ($n_p = (2 + 3\lambda) / \lambda$).

A continuous WRC function (Equation [7]) was also proposed by Van Genuchten (1980), where m and n are fitting parameters, and a corresponds approximately to the inverse of the air entry value. Van Genuchten (1980) further proposed the relationship of $m = 1 - 1 / n$ ($n > 1$, $0 < m < 1$) and substituted Equation [7] into Mualem's formula (Equation [3]) to derive the Van Genuchten-Mualem (VGM) HCF (Equation [8]). The VGM model has found widespread application and has been applied to heap leaching. However, in most cases authors have only measured the WRC and Ks, and calculated the HCF from Equation [8]. Several authors have found a discontinuity between the HCF and the measured K_s value, which is attributed to a transition between capillary- and gravity-controlled flow regimes (Afewu, 2009; Mohanty et al., 1997; Luckner et al., 1989; Guzman et al., 2008, and Gerke and Van Genuchten, 1993).

The VGM model was further adapted by Parker et al. (1987) to describe the air conductivity function (ACF) (Equation [9]), where K_g is the air conductivity, and $K_{g\,max}$ is the air conductivity when only residual moisture is present (corresponding to $S_g = 0$). S_g is the relative degree of gaseous saturation, as defined by Equation [10], and θ_{aep} is the air entry point, or the maximum solution moisture content (corresponding to $S_g = 1$) at which the air conductivity drops off completely as the bed becomes saturated.

$$S_g = \left(\frac{\theta - \theta_r}{\theta_{aep} - \theta_r}\right) \qquad [10]$$

Experimental

Hydrodynamic column tests (HCT) are performed in a 15 or 20 cm diameter column (75 cm tall), loaded with agglomerates at a uniform target bulk density and irrigated at incremental solution application rates (Figure 1). From the solution balance tracked throughout the duration of the test follows the hydraulic conductivity, moisture content and degree of saturation. Also obtained from the HCT test are the air conductivity, the drain-

Figure 1—Hydrodynamic column test apparatus

down curve, and the total, micro- and macro-porosity. Once ponding occurs, the column is allowed to saturate, and the saturated hydraulic conductivity is measured by passing solution upwards through the column from a constant-head reservoir. Finally, the column is allowed to drain for 2 to 3 days to generate a drain-down curve. The air permeability is determined according to the method described by Milczarek et al. (2013) by measuring the pressure drop as a function of flux at each moisture content. Experience shows that for copper oxide leaching the maximum liquid saturation should be kept below 85% for geotechnical stability. For aerated heaps the bed should have an air permeability of at least 100 darcys and the degree of void saturation during percolation should not exceed 60% to 65% (Robertson et al., 2013).

Results and discussion

The unsaturated flow in the bed, measured in the hydrodynamic column tests, is modelled with traditional soil capillary models such as the Van Genuchten-Mualem (VGM) and Brooks Corey (BC), in order to derive the hydraulic conductivity function (HCF), which represents the relative hydraulic conductivity (K_r) against the dimensionless effective saturation (S_e), and the air conductivity function (ACF) (Equations [5], [8] and [9], and Table I). The hydraulic conductivity functions generated for the hydrodynamic column tests are mostly S-shaped curves if the measured K_s data point is included in the data set. This type of curve cannot be modelled by the conventional BC or VGM functions, except if K_s is made a fitting parameter (Mohanty et al., 1997; Luckner et al., 1989). However, instead of modelling the data as a continuous S- or J-curve, the author proposes a discontinuous J-curve to be the most realistic. The J-curve includes an inflection point, ($S_{e\,max}$), above which K_r remains equal to 1 (Equations [11] and [12]). Two examples of this approach are plotted in Figure 2. Also plotted in Figure 3 are the air conductivity curves. The modified VGM model (Equation [9]) was used to fit the air conductivity function (ACF), where $K_{g\,max}$ (air conductivity when only residual moisture is present) and θa_{ep} (the air entry point) are derived from the data. The fact that the moisture content keeps increasing above the point of discontinuity was ascribed to the presence of 'dead voids' or poorly connected pores, which fill up but do then generate additional flow channels.

$$K_{r\_BC} = \left(\frac{S_e}{S_{e\ max}}\right)^{n_p}, \; S_e < S_{e\ max} \qquad K_r = 1, \; S_e \geq S_{e\ max} \qquad [11]$$

$$K_{r\_VGM} = \left(\frac{S_e}{S_{e\ max}}\right)^{\Upsilon}\left[1-\left(1-\left(\frac{S_e}{S_{e\ max}}\right)^{\frac{1}{m}}\right)^{m}\right]^{2}, \qquad [12]$$

$$S_e < S_{e\ max} \qquad K_r = 1, \; S_e \geq S_{e\ max}$$

$$K_g = K_{g\ max}\left(1-S_g\right)^{\Upsilon}\left[1-S_g^{\frac{1}{m}}\right]^{2m} \qquad [13]$$

Figures 4 and 5 are plotted in order of increasing fines (-4.75 mm) content over the x-axis. The distribution of volumetric void fractions in the ore bed is plotted on the y-axis in Figure 4. The bed volume is divided into residual moisture (θ_r), the mobile moisture (defined as the increased moisture over and above the residual moisture) during irrigation governed by BC or VGM capillary flow (θ_{max} - θ_r), the volume fraction comprising 'dead voids' (θ_s - θ_{max}), and the volume fraction occupied by solids (1 - θ_s).

Also plotted on the y-axis is the air entry point (θ_{aep}) derived from the gas conductivity curves (Equation [9]). The close agreement between θ_{aep} and θ_{max} suggests that the air entry point occurs close to the point of discontinuity in the HCF. This may be explained by the fact that no new solution flow channels are expected to form once all the air flow channels are filled up with

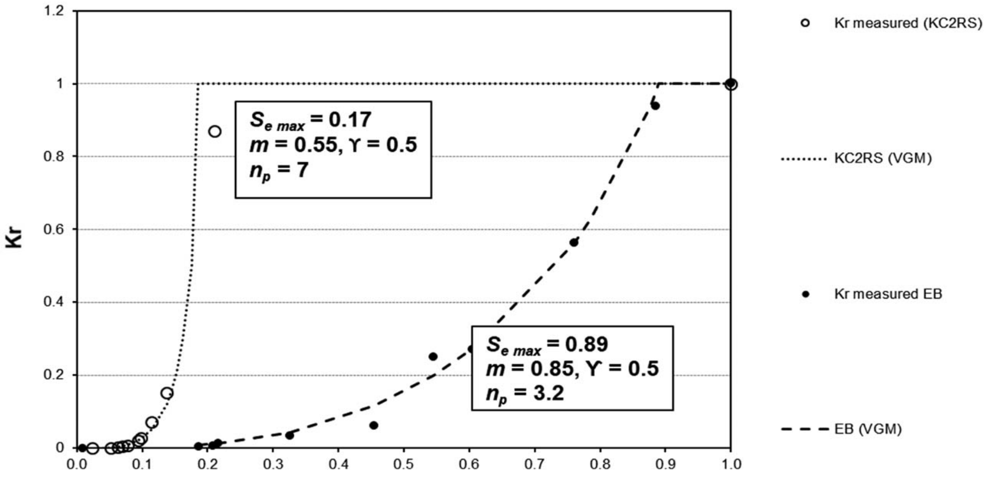

Figure 2—Hydraulic conductivity function (KC2RS, EB)

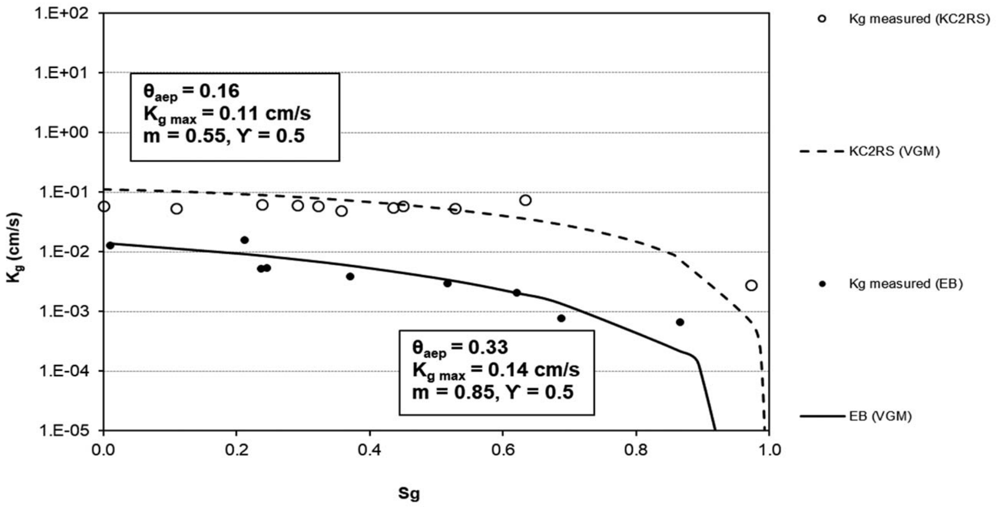

Figure 3—Air conductivity function (KC2RS, EB)

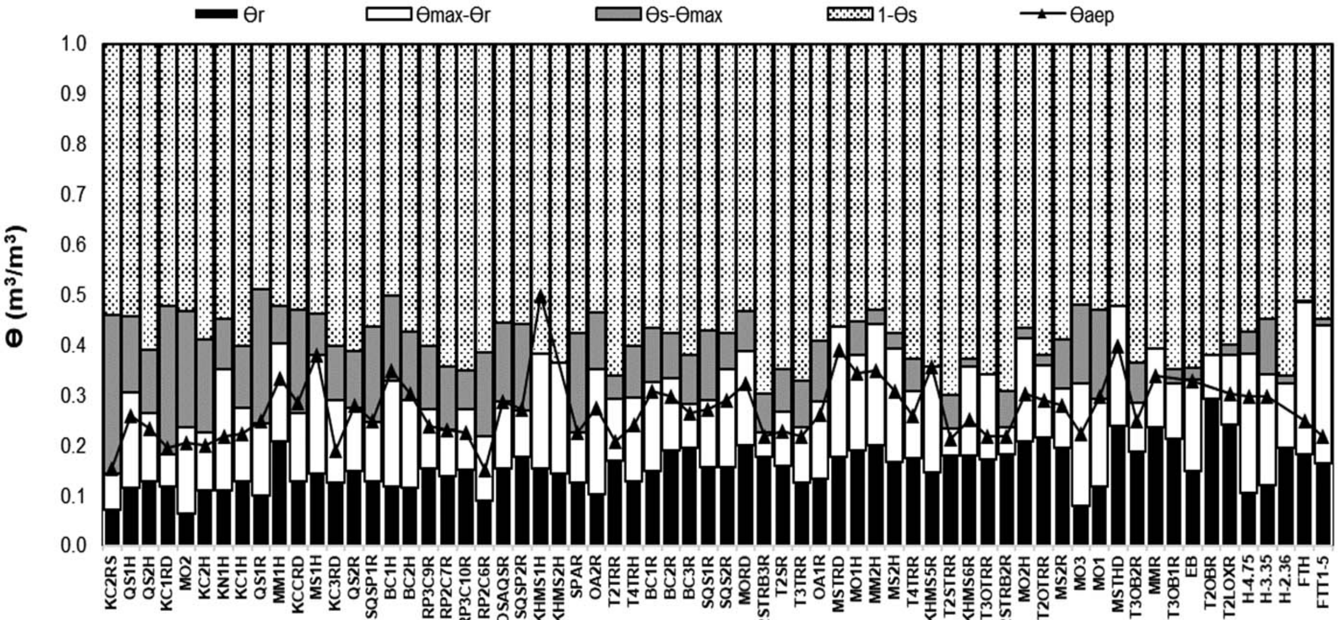

Figure 4—Volumetric void fractions and air entry point (Robertson et al., 2023)

solution (one would expect air flow channels to be converted into solution flow channels as the moisture content increases).

The normalized void fractions (i.e., excluding the volume fraction occupied by solids) are plotted in Figure 5, as this allows visual comparison with some of the design targets used in geomechanical (hydrology and physical) testing, which are also plotted on the same graph. The design targets include the requirement that 65% void saturation ($S \leq 0.65$) should not be exceeded in order to achieve proper aeration, and 85% void saturation ($S \leq 0.85$) should not be exceeded in order to maintain geotechnical stability (Robertson et al., 2013; Milczarek et al., 2012). The 65% saturation rule appears to provide a good design target for heap aeration, as it agrees visually with the air entry point on average. The average air entry point occurs at S = 0.66. In other words, 65% void saturation provides on average a good estimate of the air entry point (θ_{aep}) above which gas does not pass through the bed and above which the heap cannot be aerated.

An air entry point substantially below 65% may be indicative of poor pore interconnectivity, whereas an air entry point above 65% suggests pores with good interconnectivity. It can also be seen from Figure 5 that coarser samples generally have a lower air entry point and that the proportion of 'dead voids' (θ_s -θ_{max}) generally decreases as the fines content increases (from left to right over the x-axis). Coarser particles therefore contribute more to the formation of 'dead voids', which is counter-intuitive, as one would expect coarser rocks to generate larger macro-voids and hence larger flow channels. However, the formation of larger voids may not necessarily translate into larger flow channels, as the pores may not be well connected or may be blocked with finer material such as silt and clay.

The target for geotechnical stability ($S \leq 0.85$) occurs above the air entry point and the point of discontinuity in most cases. Hence the bed will become geotechnically unstable during the filling up of the 'dead voids' and starts to break apart since further increase in moisture cannot be directed towards creating new flow channels.

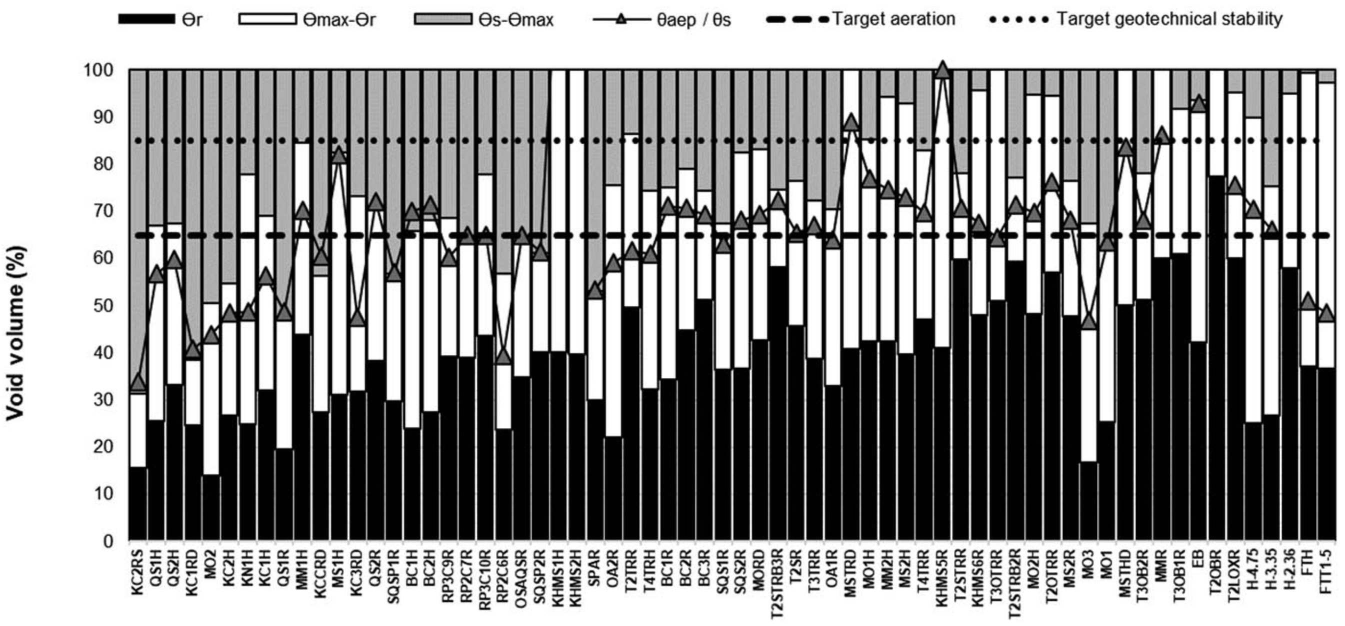

Figure 5—Normalized void fraction distribution (Robertson et al., 2023)

High saturation may occur in non-aerated heaps (e.g., copper oxides) at very high bulk densities or due to non-homogeneity, or if the bed contains a high silt and clay content, which increases the compressibility of the bed. Increased water content can reduce the stability of the rock slope by increasing the unit weight of the soil. The increased water pressure may cause instability if the increased load exceeds the shear strength of the slope. At low moisture contents, for example, the pore pressure is negative (suction), but this is converted into positive pore pressure at higher moisture contents, resulting in increased pressure exerted by the water downwards and sideways in the heap. If the material is dry or non-saturated, an increase in load compresses and compacts the mass and increases shear strength as grains and rock fragments come in closer contact with each other. However, increasing pore pressure with increased moisture content has a buoying effect, reducing the friction and shear strength.

Conclusions and recommendations

Whereas unsaturated flow models have been applied almost exclusively to material containing lower particle sizes (e.g., clay -0.002 mm, silt 0.002-0.075 mm, and sand 0.075-2 mm), typical heap leach material spans a wider range, with top sizes typically between 6 mm and 25 mm. It was shown that traditional capillary models, such as BC and VGM, may be applied to coarser heap leach samples at lower flowrates. The hydraulic conductivity function was however best described as a discontinuous J-curve, which allows the measured saturated hydraulic conductivity to be incorporated. The point of discontinuity coincided with the air entry point, measured independently. Hence it was proposed that at higher moisture content, 'unconnected' pores are filled up with moisture, without generating more flow paths. On average, the rule of thumb of <60% to 65% saturation required for forced aeration appears correct, however, the air entry point varied with fines content.

The VGM fit is popular since it provides a closed-form, continuous function suitable for mathematical models. Furthermore, most of the work publicised to date has been done on sand, where the effect of 'dead voids' will be less important. However, the results obtained in the laboratory do not suggest dual-porosity flow and indicate that flow is governed by capillary forces up to the air entry point (a single discontinuous VGM curve). However, the conventional approach to heap leach data, which comprises measuring the WRC and K_s, and then using the VGM model to predict the HCF curve, is unsatisfactory. The benefit of measuring both the HCF and the K_s was demonstrated in this work as well as the importance of performing hydrodynamic column tests.

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◆

Nomenclature

A		constant
A_i		
a		constant
B		constant
B_o		Bond number
C		constant
h	m	capillary head
h_c	m	air entry head
K_w	cm/s	hydraulic conductivity of solution
K_s	cm/s	saturated hydraulic conductivity
K_r		relative solution conductivity
K_g	cm/s	air conductivity
$K_{g\,max}$	cm/s	maximum air conductivity, air conductivity at residual moisture
b, q, m, n, n_p, n_g		fitting constants
r_H	m	hydraulic radius
S	m^3/m^3	degree of saturation
S_e		effective saturation
$S_{e\,max}$		effective saturation at air entry point
S_g		relative degree of gaseous saturation
γ		fitting constant
δ	kPa	stress
ε	m^3/m^3	bed porosity, voidage
λ		fitting constants
θ	m^3/m^3	moisture content
θ_r	m^3/m^3	residual moisture content
θ_s	m^3/m^3	saturated moisture content
θ_{aep}	m^3/m^3	air entry point
θ_{max}	m^3/m^3	moisture content at Se max
μ	kg/m/s	viscosity
ρ	kg/m^3	density