

PRELIMINARY RESULTS OF THE WATER FLOW MODELING IN AN ACID DRAINAGE GENERATING WASTE ROCK PILE LOCATED AT THE URANIUM MINING SITE OF POÇOS DE CALDAS – BRAZIL¹

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Abstract: The first uranium production center in Brazil began operation in 1982. After 13 years of a non-continuous operation, the mining activities were suspended definitively. Uranium was extracted by open pit mining. Operations gave rise to approximately $12.4 \times 10^6 \text{ m}^3$ of waste rock, while the mill process generated a volume of approximately $2.39 \times 10^6 \text{ m}^3$ of tailings. Regardless the fact that some studies developed in this area exist, a well defined plan of action, aimed at the remediation and rehabilitation of the site, has not been implemented yet.

The main sources of pollutants to the environment are the tailings dam, the waste rock piles and the open pit. Pyrite oxidation was found to be the driving force in the leaching of metal and radionuclides into environment. It was estimated that acid drainage generation will last for 600 and 200 years from the waste rock and tailings respectively. Accurate prediction of the release rate of metal and radionuclides from these sources and their transport in the subsurface is a critical factor to the assessment of environmental impact and to the development of effective remediation strategies. In prevailing practice, the source term is evaluated using the dissolution rate of waste form and the solubility of radionuclides. The fate of pollutants is addressed by the use of Kd-based “reactive” transport models. This standard practice has obvious shortcomings, mainly because it can not produce a realistic representation of the system under study. The alternative to overcome these shortages is using more sophisticated models that could represent real complex problems. Reactive transport codes are powerful tools in the evaluation of coupled thermal–hydrological–chemical processes and in the prediction of the long-term performance of remediation strategies. The difference between the predictions from these two approaches can be as high as several orders of magnitude. Generally, conventional approaches produce predicted values higher than the measured ones. On the other hand, the use of reactive transport model requires a good knowledge of the simulated hydrogeochemical system, along with the choice of appropriated algorithms that can represent the most important processes.

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Introduction

One of the most relevant tasks in the decommissioning of the first Brazilian uranium (U) mining site deals with the management of the acid drainage generated at two major waste-rock piles. It was estimated that acid drainage generation would last for more than 600 years (Fernandes and Franklin, 2001). Accurate prediction of the release rate of metals and radionuclides from the rock forming minerals, and the assessment of the environmental impacts into superficial and groundwater are critical factors to be addressed and will determine the remediation strategies that will be put in place.

Chen (2003) pointed out that reactive models, instead of K_d based ones, reflect more accurately the several concomitant reactions taking place in the waste-rock environment, while the K_d based models lack of the appropriate representation of these phenomena, because they assume an equilibrium condition that is hardly found in these systems in which the pollutant releases are dominated by kinetic and thermodynamic equilibrium reactions. In addition to this, K_d values vary spatially and temporarily. None of these characteristics can be simulated with a K_d -based model (Zhu, 2003). It has been demonstrated that the difference between the predictions from these two modeling approaches can be as high as several orders of magnitude (Yeh and Tripathi, 1991a). The drawback observed when reactive transport models are used relies on the fact that they require a good knowledge of the simulated hydrogeochemical system, along with the appropriate choice of algorithms that represent the most important processes.

The research project this paper is related to is aimed at supporting the decision-making process regarding the decommissioning process of the first U mining and milling facility in Brazil. In this paper the results of the flow profile inside one of these piles, which is the first step to be accomplished in this type of modeling work, is presented. The model used was the 2D finite-element hydrogeochemical transport model, HYDROGEOCHEM v.4, which describes flow and transport through variably saturated porous media. (Yeh and Tripathi, 1991a)

Study Area

The studied waste-rock pile is part of the Poços de Caldas mining and milling complex, located in the southeast region of Brazil (Fig. 1). Average rainfall rate is 1,700 mm/a, which causes serious problems in terms of water management. It has been estimated that about US\$ 200,000 are spent annually to treat the acid waters that originate in these waste-rock piles. Obviously the collect and treat strategy cannot be adopted as a permanent solution.

The cumulative U production was 1,242 tons of U_3O_8 . In the development of the mine 44.8 x 10^6 m³ of rock was removed. From this amount, 10 million tons were used as building material (roads, ponds, etc). The rest was disposed into two major rock piles, waste rock pile 8 (WRP-8) and 4 (WRP-4). Both piles are located at areas close to the mine pit. The WRP-4 was chosen for study because almost all the drainage coming from the pile is collected in only one holding pond, facilitating mass balance calculations. It is to be mentioned that a huge database from monitoring program carried out by the mine operator is available.

The WRP-4 was built in a valley near a stream bed. The construction method of the pile consisted of end-dumping, i.e., the waste-rock was dumped directly over the crest of the pile face from trucks. The bottom of the valley was previously prepared to receive the waste rock. Deep drains were constructed to allow drainage of the infiltrating waters and a liner of compacted soil

was placed to avoid percolation of water into the native land surface. The WRP-4 contains $12.4 \times 10^6 \text{ m}^3$ rocks, with a top area of 0.57 km^2 . Recently, four boreholes were drilled through the pile to allow groundwater sampling and the measurement of water levels. Periodic determinations of contaminant concentrations in the infiltration and out-flowing waters, as well as measurements of the discharge rates, are performed by the mine operator.

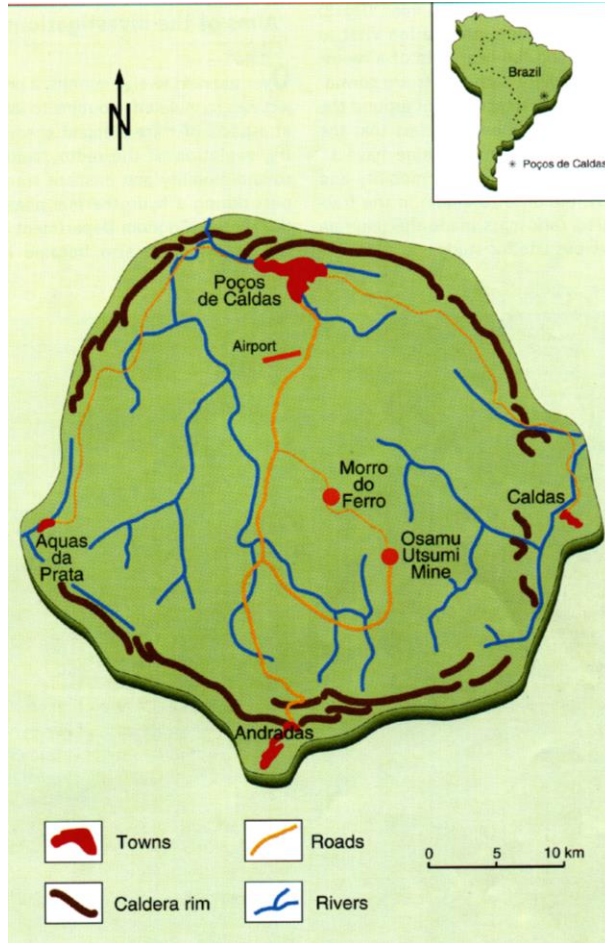


Figure 1 – Site location

Materials and Methods

Physical Characterization of the Pile

In a coupled reactive transport model, confidence on the final results will depend, in the first place, on the accuracy with which the model is able to simulate the flow within the pile. One of the main parameters to be known is the hydraulic conductivity within the pile. In principle, a single value of hydraulic conductivity cannot be used to represent the entire WRP-4 and a range of values should be expected as a consequence of variations in particle size, rock characteristics, and construction methods. Due to the lack of financial resources, the field program was conducted on the top and slope surfaces of the pile. The sampling points were designed to give the best possible representation of the hydrological processes occurring inside the pile. The sampling grid was set along a cross-section located over a portion of the ancient stream bed on

which the pile was built. The grid was composed by 12 sampling points. Six of them were fixed in order to form a transect, with 50 meter intervals between each of the sampling points. Three of these points were positioned at the top of the pile (P1, P2 and P3) and the others were located at the slope of the pile (B1, B2 and B3). In order to increase the consistency of the measurements at the top of the pile, two others points were positioned 10 m to the right and 10 m to the left of each one of these three points. The sampling grid is shown in the Fig. 2. For each sampling point, non-deformed samples were visually described and collected using a ring sampler 0.0599 m thick and 0.0537 m of internal diameter. These samples were sent to the laboratory for further analysis. They involved the determination of the basic hydrogeological properties of the samples such as porosity, specific gravity, soil-water characteristic curves, and saturated hydraulic conductivity. Due to the highly heterogeneous and unconsolidated nature of the material, non deformed blocks of waste-rock could not be collected for column tests in the laboratory. *In-situ* measurements of saturated hydraulic conductivity (K_{sat}), using the Guelph permeameter, were also taken.

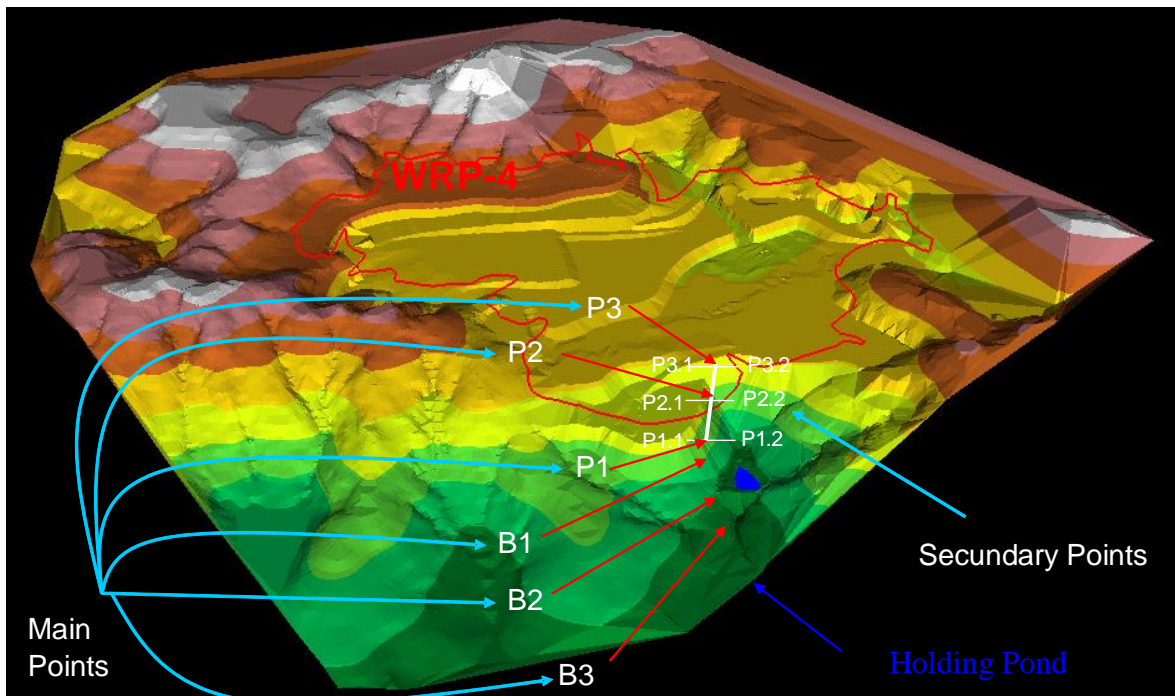


Figure 2 – Sampling grid. The sampling points (B1, B2, B3, P1, P2 and P3) are spaced in intervals of 50 m. The points (P1.1, P1.2, P2.1, P2.2, P3.1 and P3.2) are spaced 10 m of each of the main points.

Conceptual model of the WRP-4

The WRP-4 pile is located at a sloping land surface between a recharge (top of the pile) and a discharge area (where seepage water is collected into a holding pond). The primary source of water to the waste-rock pile is the precipitation. Part of the precipitation infiltrates the waste-rock and moves downward (in direction to the base of the pile). Another part can run off over the surface of the pile. The water balance for the WRP-4 was calculated based on historical data of rainfall and outflow records. The average rainfall rate considered was $1,700 \text{ mm a}^{-1}$. It was estimated that 30% and 12% of the precipitation corresponds to runoff and evaporation respectively. Based on these values, it was assumed that the infiltrating portion of the rainfall

creates a water table inside the pile. In fact, this assumption is supported by the measurements of the water level in the piezometers installed in the pile. Measurements of water level values in piezometer 01 (located at the ancient stream bed) showed variations less than 10% during the year, so that a saturated layer 10 mm thick is maintained inside the pile all through the year. This piece of information, associated with the small variation of the pile outflow (less than 10% between dry and wet season), suggests the existence of a mechanism that regulates the water level inside the pile.

Based on the above description the WRP-4 can be considered as a heterogeneous and unsaturated-saturated system containing waste rock layers which can steeply change in grain size. According to what is reported in the construction project of the pile the coarse grained material would be deposited in the base of the dump (with predominance of blocks of rock with diameter varying from 0.3m to 1.2m associated to the angle of slope (α) between 36° and 40°). The finer grained material is mostly found in the upper layers with (α) varying between 42° and 45° (IPT, 1984). The probable segregation of the material with the depth allows us to propose that the saturated hydraulic conductivity may be higher close to the base of the pile. Some authors point-out that end-dumping construction method results in a distribution of particle sizes grading from fine to progressively coarser proceeding from the level of the dump platform toward the base of the dump (MEND, 1991).

The field observations revealed three distinct particle size groupings, a fine upper zone, a very coarse toe zone and an intermediate zone between these two zones. The first layer consists of altered phonolitic rocks with different grain sizes including a fine matrix with significant fractions of silt and sand. The intermediate layer is composed of a combination of altered phonolitic and breccia rock with a narrower grain size range (3 to 15cm) with a small amount of fine grained matrix. Altered phonolitic rocks with a huge variation of grain sizes compose the base layer. It was possible to measure the existence of 2 cm wide channels between the blocks of rocks. The grain size segregation can be observed in the Fig. 3.

These layers are found adjacent to each other. This finding may suggest the possibility of preferential flow within the pile. Newman et al (1997) suggested that in unsaturated, layered systems such as waste rock piles, liquid water might be transported preferentially through the fine-grained material rather than the coarse-grained one. The authors recognize that this hypothesis contradicts conventional theory for flow in waste rock dumps. The importance of this idea is that this form of preferential flow may allow the waste rock pile to store water. In opposition to this idea, it is reported that high-permeability channeling is thought to be a primary control on water movement through waste-rock piles (MEND, 1991 –missing reference). Still the lack of field observation persists in the literature. However, it is clear that, despite the above mentioned difficulties in assessing moisture movement in waste rock piles, consideration must be given, among other issues, to the configuration and construction of the waste rock pile (Newman et al. 1997).

In summary it can be suggested that the entire base of the pile can be considered as a high-conductivity layer, rather than a discrete series of channels, and thus acting as the primary conduit for much of the water movement inside the pile and consequently, minimizing the elevation of the water table.

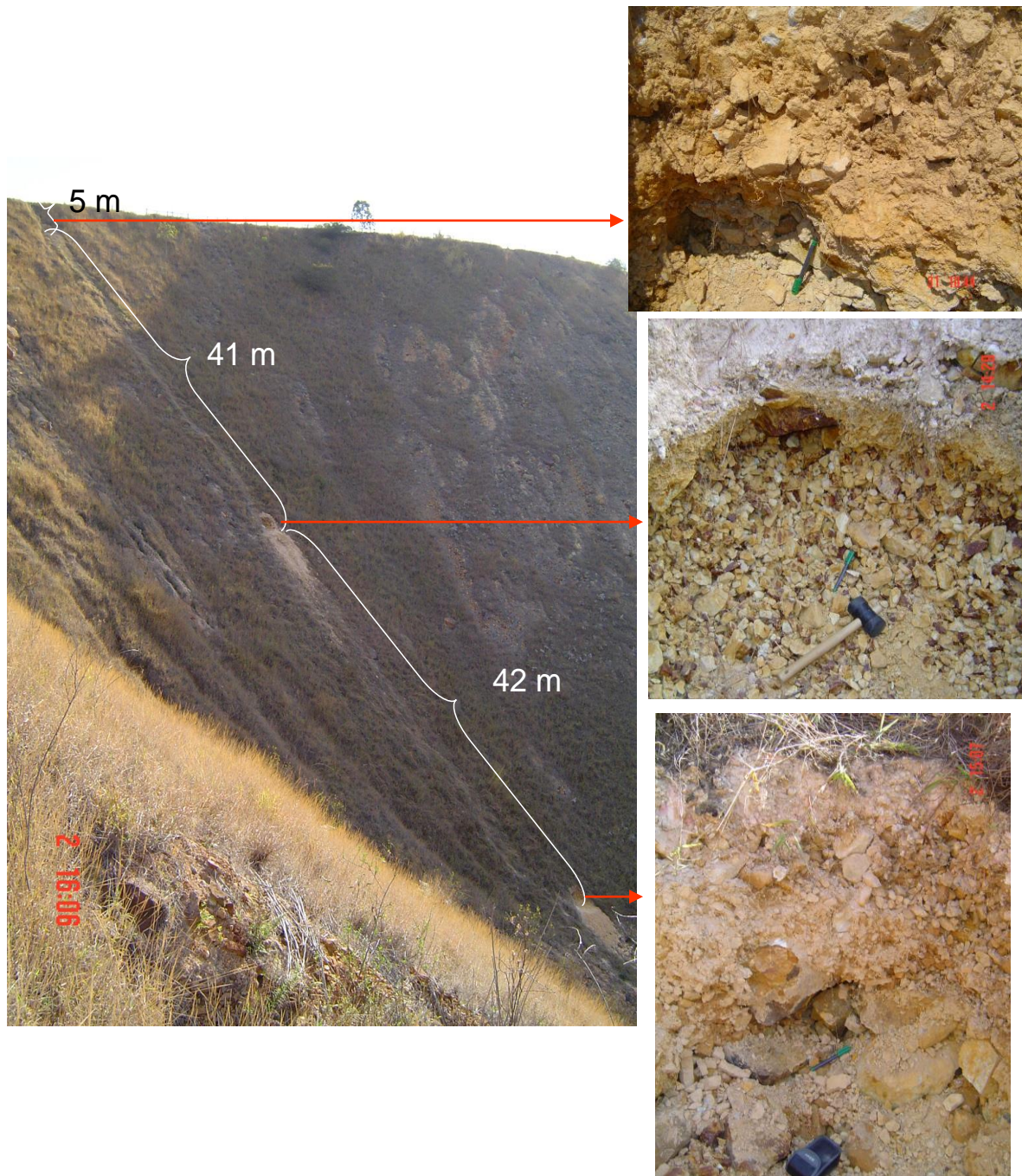


Figure 3 – Grain size segregation observed along the slope surface of the WRP-4 (Field program September; 2004)

For the sake of simplicity and in a pragmatic way, it was considered in the development of the conceptual model that the WRP-4 is composed by two types of homogeneous materials representing the two main hydraulic domains; one with low hydraulic conductivity and other one with high hydraulic conductivity. The model was based on a 2D vertical Cartesian cross-section

of the pile 700 m wide and 20 m high. The chosen section is intended to allow the best representation of the preferential of water flow inside the pile, because this section follows the topographical slope of the valley.

The conceptual model also assumes the follow conditions:

- (1) The flow system is in a steady-state, i.e., a constant rainfall rate is maintained at the pile surface during the entire duration of the simulation. This rate represents the measured average value of the rainfall rate at the site minus the runoff and the evaporation rates,
- (2) Porosity and permeability are not affected by pile consolidation, or by mineral precipitation or dissolution

Simulation of the WRP-4

The discretization of the waste rock pile (WRP) domain was made via a triangular finite element mesh, including a total of 30,828 elements and 16,969 nodes.

It was assumed that the initial distribution of the pressure head inside the WRP-4 was known. This condition was obtained by simulating the steady-state version of the Richards' equation subjected to time-invariant boundary conditions. Three different boundary conditions were imposed: (1) the base of the pile was considered impermeable; (2) the top and the slopes of the pile were subjected to the rainfall infiltration, evaporation and runoff; (3) a small boundary segment located at the toe of the pile was treated as groundwater outflow.

The environmental data used in the model as representative of the properties of the waste-rock were those obtained by field measurements and by laboratory assays.

Numerical simulations were performed for a period of 1 year to obtain a quantitative description of the system's time evolution in order to predict the spatial distribution of groundwater heads, moisture content, and velocity field.

Results

Field Observations

Data from the measurements with the Guelph permeameter showed that at the pile surface saturated hydraulic conductivity (K_{sat}) values varied by one order of magnitude (2.06×10^{-4} - 1.04×10^{-3} cm/s). Measurements of K_{sat} in the slope of the pile were only possible to be accomplished at sampling point B1. Due to the coarse-grained characteristics of the material, it was not possible to accomplish the measurements with the Guelph Permeater in sampling points B2 and B3. However, saturated hydraulic conductivity greater than 10^{-2} cm/s can be suggested as taking place at those locations because this is the highest of hydraulic conductivity that can be measured by the Guelph permeameter).

Few works are found in the literature discussing the variability of the hydraulic conductivity in waste-rock piles (MEND, 1991). One of them reported hydraulic conductivity values ranging from 10^{-2} to 10^{-5} cm/s Whiting (1981). Lefebvre et al (2001) reported values in the same range obtained in two mine sites; the South Dump of the Doyon mine site in Canada and the Nordhalde dump of the Ronnenberg mining district in Germany. The values of K_{sat} reported in this paper fall within this range.

Laboratory Analyses

Daniel (1984, 1994) reported that the values of hydraulic conductivity obtained in the laboratory are generally smaller when compared with those measured in the field. The comparison between field and laboratory values obtained in this work is presented in Table 1. The difference between the average values obtained in the field and in the laboratory was observed to be around 30%, being higher in the laboratory.

Table 1 – Values of the hydraulic conductivity obtained in field and in laboratory

Sampling Points	Hydraulic Conductivity (cm/s)	
	Laboratory	Field
Top Surface of the Pile		
Point 1 (P1)		
P 1	$3,03 \times 10^{-3}$	$3,75 \times 10^{-3}$
P 1.1	$1,74 \times 10^{-3}$	$3,12 \times 10^{-4}$
P 1.2	$1,10 \times 10^{-3}$	
Average	$1,95 \times 10^{-3}$	$2,03 \times 10^{-3}$
Point 2 (P2)		
P 2	$6,35 \times 10^{-4}$	$1,04 \times 10^{-3}$
P 2.1	$6,20 \times 10^{-3}$	$5,17 \times 10^{-4}$
P 2.2	$7,51 \times 10^{-3}$	$2,06 \times 10^{-4}$
Average	$4,78 \times 10^{-3}$	$5,88 \times 10^{-4}$
Point 3 (P3)		
P 3	$4,03 \times 10^{-4}$	$3,12 \times 10^{-4}$
P 3.1	$2,33 \times 10^{-4}$	
P 3.2	$1,83 \times 10^{-3}$	$3,30 \times 10^{-4}$
Average	$8,23 \times 10^{-4}$	$3,21 \times 10^{-4}$
Slope Surface of the Pile		
B 1	$6,94 \times 10^{-3}$	$9,50 \times 10^{-4}$
B 2	$2,38 \times 10^{-3}$	
B 3	$9,70 \times 10^{-4}$	
Average	$3,43 \times 10^{-3}$	$9,50 \times 10^{-4}$

Individual soil-water characteristic curve was determined, from large pressure plate apparatus technique, for each sampling point. The results reveal that it is not possible to

characterize different groups of materials inside the pile by means of this strategy. This finding contradicts the evidence presented so far and can be explained by the fact that samples collected by the ring sampler don't represent adequately the heterogeneities found in the pile. This problem could have been overcome if experiments in laboratory with non-deformed blocks were made. The difficulties generally found in collecting non-deformed waste-rock samples as well as in the appropriate characterization of waste-rock pile property functions have led the scientific community to develop new technologies aimed at determining the constitutive relationships of unsaturated materials (Fredlund, 1991). Figure 4 shows the hydraulic property functions used in the simulation.

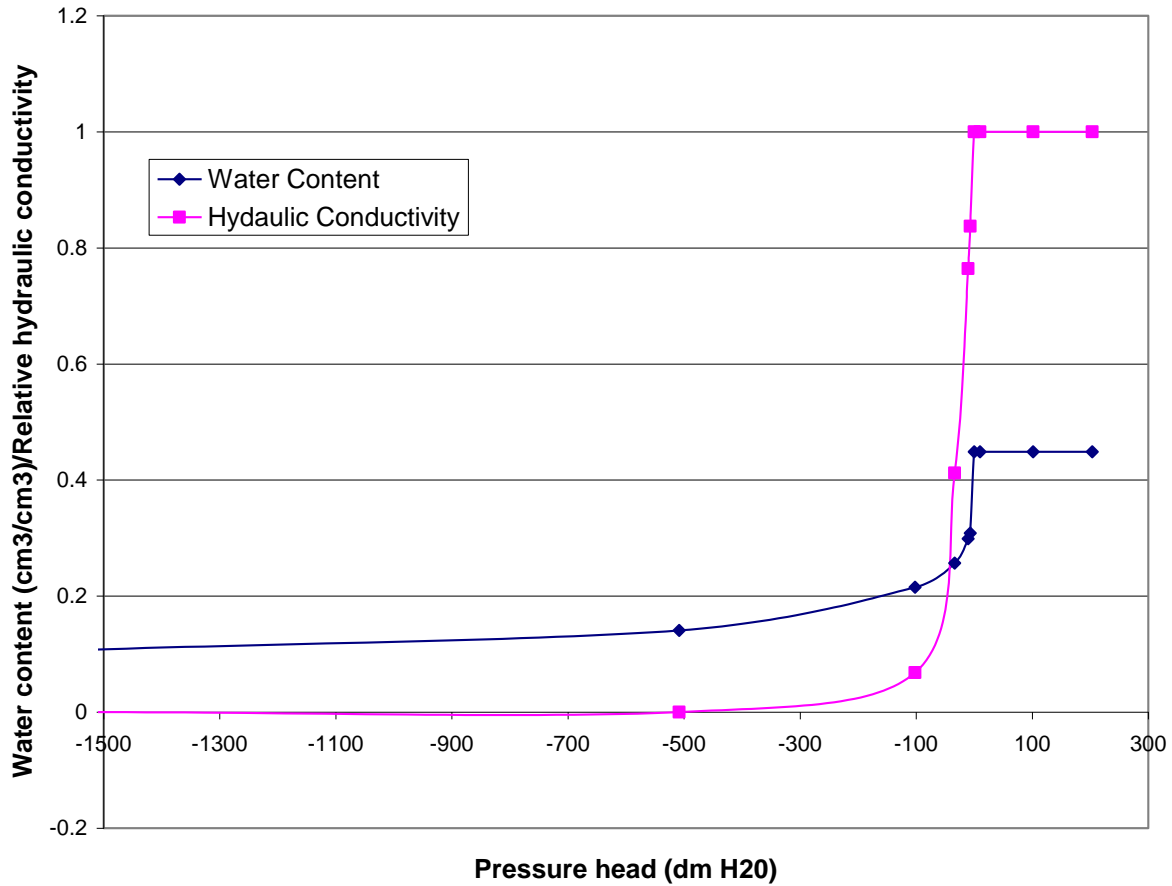


Figure 4 – Hydraulic property function used in the simulation.

Simulation

The estimated outflow of the pile ($223.3 \text{ dm}^3/\text{d.dm}$) is in good agreement with the measured data ($222 \text{ dm}^3/\text{d.dm}$). This result demonstrates the ability of the model in reproducing the water budget appropriately.

The modeled data indicate that the velocity field has huge variations, with values varying from 0.5 cm/d to 130 cm/d . However, most of the pile presents small values of velocity, of about 10 cm/d . The highest velocities were found in the constriction areas at the bottom of the pile. The comparison between modeled values with measured ones is impossible to be done due to the

lack of field observations. The preliminary results of the velocity field distribution inside the WRP-4 is shown in the Fig. 5.

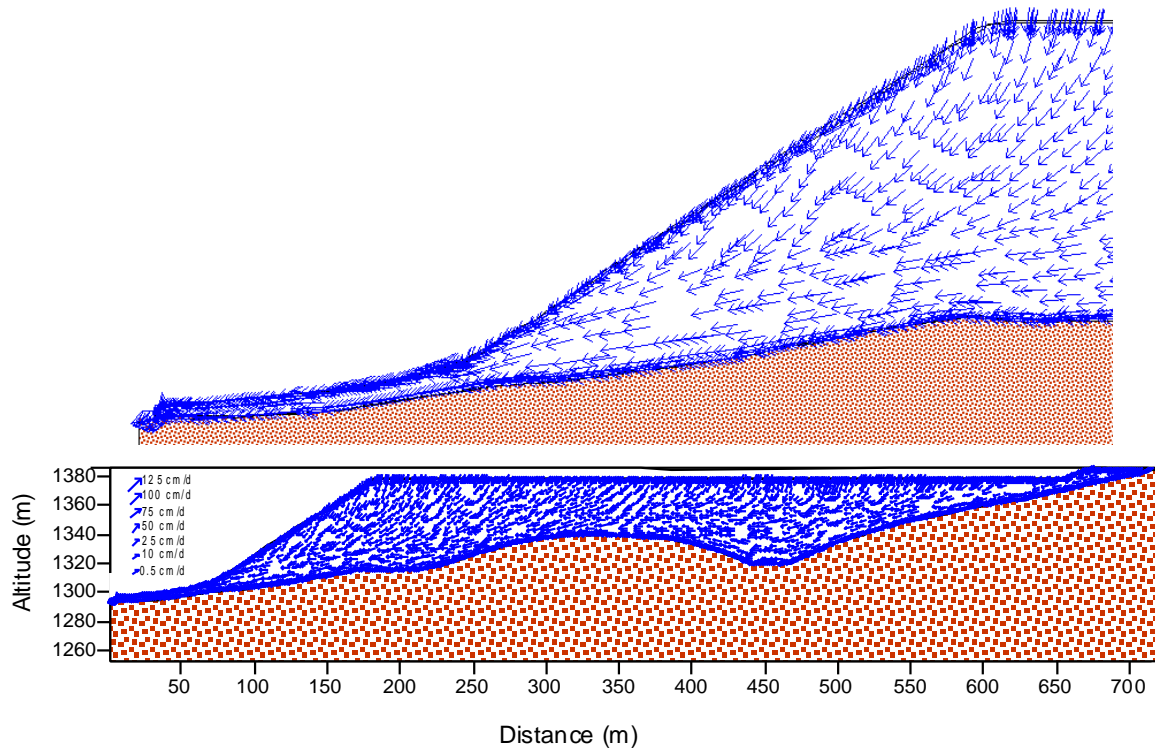


Figure 5 – Distribution of the velocity field inside of the WRP-4.

The estimated results of the pressure head shows that almost all the pile is under unsaturated conditions (Fig. 6). The maximum value of the saturated layer given by the model is 35 m. This value is almost four times higher than the measured water level inside the pile as previously reported in this paper. There is a discrepancy here, the value noted earlier in the paper is much lower. This difference can be explained by the fact that an impermeable boundary condition was used in this simulation.

Despite this difference, it can be accepted that the model is simulating well the water behavior inside the pile.

Conclusions

Measurements of hydraulic conductivity in the field and in the laboratory were different from each other but to an extent of no more than 30%, if average values are taken into consideration. The conceptualisation of the pile as being composed by only two types of layers (with different values of hydraulic conductivity) did not prevent the model from predicting accurately the water balance inside the pile. The overestimation of the saturated layer thickness at the base of the pile produced by the model may be attributed to the boundary conditions that were used in the simulation. However, it is likely that this won't be of primary impact in the prediction of

pollutant concentrations in the drainage. The pile conceptualisation did not allow for the proper prediction of potential preferential flow paths inside the pile, however the unsaturated nature of the system must be considered, it will favour the oxidation of pyrite by oxygen that diffuses into the pore spaces of the rocks. In this way, the primary role of the infiltrating water into the pile would be to maintain a sufficient level of humidity and to flush the pollutants downwards.

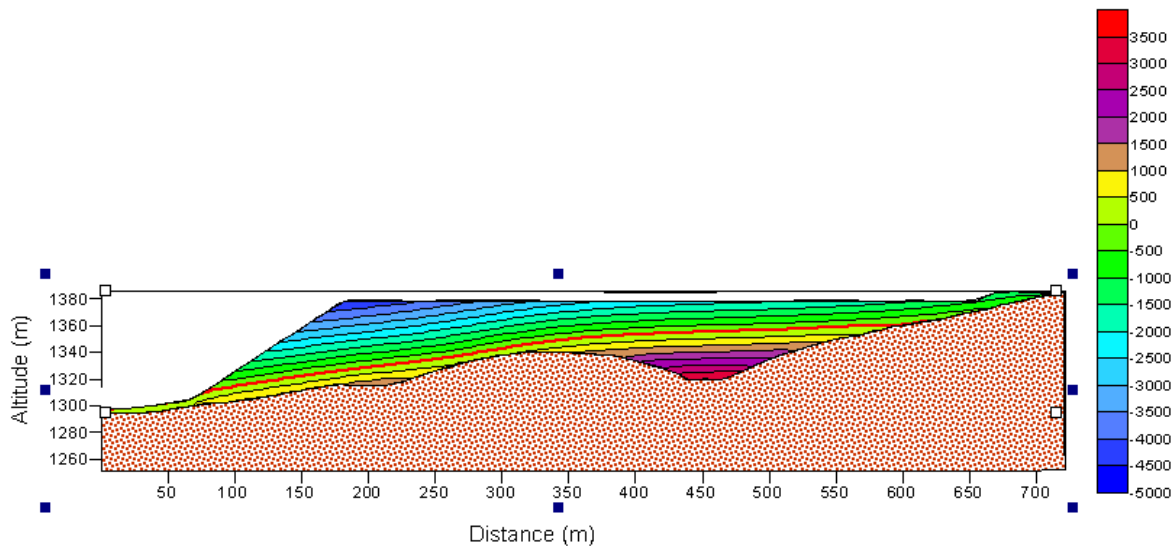


Figure 6 – Distribution of pressure head inside the WRP-4.

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