Field Performance and Numerical Analysis of Cover Systems

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ABSTRACT

Twenty three years ago, at the district of Paracatu, in the State of Minas Gerais, Brazil, Rio Paracatu Mineração (RPM) started the production of gold in an open cast mine, in a reserve that was entirely considered to be ore. Gold is present as free leachable gold and is also associated with pyrite, arsenopyrite and chalcopyrite. To avoid formation of acid drainage of mines, there is a great concern related to the design of cover systems for final decommissioning and reclamation of different mine areas. In order to acquire useful information for these designs, two store-and-release monitored cover systems were built at a place where RPM operated a pilot plant for approximately 10 years. The monitoring system consists of a complete weather station and water content reflectometers in each soil layer of the cover systems. This paper presents the performance of the cover systems during two and a half years of monitoring, together with comparisons with numerical results obtained with finite element analyses of the cover systems.

KEYWORDS: Cover Systems, Lysimeters, Acid Drainage of Mines.

INTRODUCTION

Annually the mining industry explores hundreds of millions of tons of soil and rock to extract minerals that, after improvement, are used to produce a large amount of fundamental products for the human life (Carrier III et al., 1983).

Frequently, most of the explored material is residue or tailings. In some cases, as in copper or gold mining, tailings may represent more than 99% of the ore material.

One of the most serious environmental impact associated with mining activities is the oxidation of sulfide minerals in presence of oxygen and water, generating an acid aqueous solution denominated acid drainage of mines (ADM).

RPM operates a non-conventional open cast gold mine that essentially entails the removal of Morro do Ouro (“Hill of Gold”) without producing waste rock. The entire reserve is considered to be ore, and is sent to the processing plant. The mine started in 1987 producing approximately six million tones/year and has undergone major expansions in 1995, 1997 and 1999 to achieve the production rate of 20 million tones /year. Two years ago, an expansion project was concluded to increase the production to 80 million tones/year and to extend the useful life of the mine for more 20 years. With this expansion, the “Hill of Gold” will become an open pit, about 350 m deep that will demand the excavation of, at least, 200 m of soil, generating a considerable volume of waste rock.

Gold is present in the leached ore and is also associated with arsenopyrite (FeAsS), pyrite (FeS_2) and chalcopyrite ($CuFeS_2$).

There are two main ore types, the oxide and the sulfide. Normally there are two mine fronts in operation, producing a blend of 50/50 oxide and sulfide ores. These ores are sent through a crushing and grinding circuit and, to prevent acid formation in the crushed tailings, limestone is added during grinding. The final grinding product consists of a material 80% passing the 74 microns mesh. Gold (and sulfide minerals) are concentrated in three flotation stages. The residues from the final concentration process, a mud with 30% of solids, are pumped to “Specific Tanks”. The final flotation tails are partly diverted to two tailings thickeners for water recovery. Thickener underflows and the remaining tails stream gravitate to the “Main Tailings Impoundment” at a solid content of less than 30%. The “Specific Tanks” contain approximately 30 to 40% sulfide and the tailings impoundment less than 0.4% sulfide.

The plan to close the mine involves a final decommissioning, not only necessary for the mining area, the main tailings dam impoundment and the specific tanks, but also for the open pit and the 200 millions tones of waste rock pile that will be generated.

There is a great concern in relation to the final decommissioning and reclamation of mine areas to avoid formation of ADM. Soil cover systems have to minimize oxygen diffusion and precipitation infiltration in mining area, the main tailings impoundment and the specific tanks.

Cover systems are used mainly to reduce water infiltration and to control the migration of gases (Koerner and Daniel 1997; O'Kane and Barbour 2003; Abichou et al. 2004; etc). They are, usually, divided in two types: prescriptives and evapotranspiratives. The prescriptive covers use low hydraulic conductivity layers to minimize infiltration and to maximize runoff and evapotranspiration. The basic components of prescriptive covers are a soil layer with high organic matter content appropriate for planting and a barrier layer, normally made of a low hydraulic conductivity compacted clayey soil. Vegetation, besides the aesthetic function, guarantees protection for the barrier layer against erosion and cracking, also increasing evapotranspiration. The barrier layer minimizes the passage of liquids.

The first layer of evapotranspiratives covers is also made of a high organic matter content soil appropriate for planting, underlain by a low compacted soil layer that has the function of storing infiltration during rain period and release it back to atmosphere through evapotranspiration during the dry season (store-and-release layer, SR layer). During rainy periods this layer, progressively, saturates without allowing a significant amount of liquids to reach the base. As soon as precipitation ceases or decreases, evapotranspiration prevails and, progressively, reduces the soil moisture of the SR layerl until the next rainy period, when the storage and release process is resumed. Therefore, in this case, the soil layer instead of "preventing" the passage of liquids works as a "water tank" that fills up during rainy periods and empties down during drought periods. These SR layers are made with silty sands and/or clayey silts and shall be sufficiently thick so that the humidity increment does not occur close to its base, where the material to be protected is placed. The thickness depends on the climatic conditions (evaporation), the vegetation type used in the topsoil layer (transpiration), and the hydraulic properties of the SR soil layer (hydraulic conductivity and water retention functions).

Basically, there are two types of evapotranspirative covers: monolithic and capillary barriers. The first has been described previously. Evapotranspirative covers with capillary barriers use a system in which the SR layer overlies a coarser soil layer that increases the water storage capacity of the SR layer due to the non-saturated hydraulic conductivity contrast between them (Figure 1a).

In Figure 1b, it is observed that for same high suction values, the SR and the barrier layers have soil moisture equal to Ac and Af, respectively. Due to differences between the water retention curves of the two soils, Af is much larger than Ac. Consequently, the coarser soil will have a hydraulic conductivity significantly smaller than the one of the fine soil, Figure 1c, and it will work almost as an impermeable boundary for the SR layer soil, therefore increasing its storage capacity.

According to Dwyer (2003) and Carlsson (2002), two main problems exist regarding capillary barriers. The first is the clogging of the coarse material by the fine soil. In that case, the use of a geotextile as a separation element is advisable (Figure 1a). The second problem is related with long and high precipitation periods. In such circumstances, the SR layer may saturate till its bottom. Consequently, the coarse soil will also saturate and its hydraulic conductivity will become much larger than the one of the SR layer, facilitating, instead of preventing, infiltration ("capillary barrier break").

Nyhan et al. (1990) and Khire et al. (1994) affirm that capillary barriers have been more effective than conventional ones, besides being easier to build and cost less than prescriptive covers.

Morris and Stormont (1997) comment on that capillary barriers are not efficient in regions where moderate to high precipitations occur.

Benson and Khire (1995) mentioned that field studies have showed that capillary barriers with two layers are effective in arid and semi-arid regions.

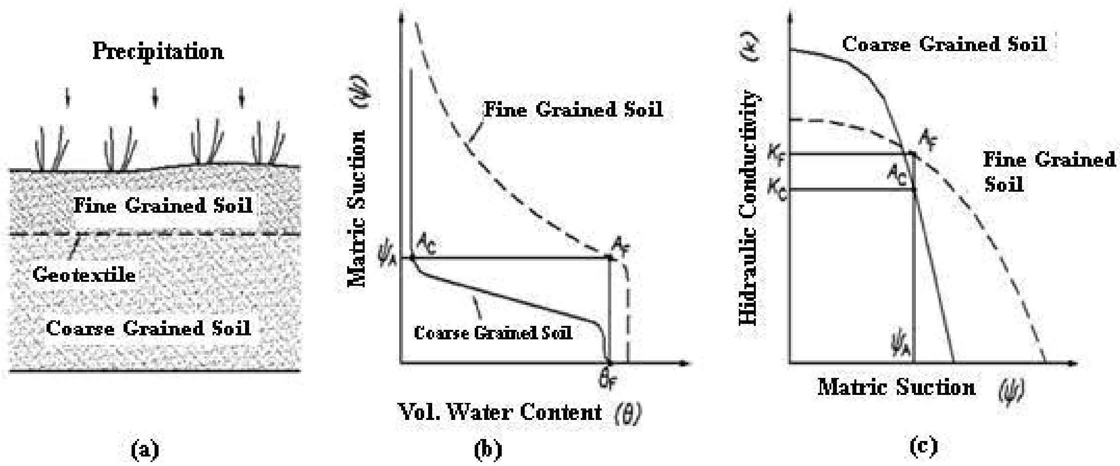

Figure 1: (a) Capillary Barrier, (b) Water retention curves, (c) Hydraulic conductivity curves (adapted from Qian et al., 2002).

A number of researchers have highlighted the important role of numerical modeling in the analysis of layered soil covers (Bussiere et al., 1995; McMullen et al., 1997; Mbonimpa et al., 2003; Swanson et al., 2003).

McCartney and Zornberg (2003) present numerical analysis results for an evapotranspirative cover constructed in a semi-arid climate. They observed that the numerical model provided accurate results at the beginning of the analyses after what the results agreed only in trend but not in magnitude. Percolation measured in the field and numerically calculated were similar. Simulation results were sensitive to the hydraulic properties of the soil but were not influenced by different selection of solar radiation, wind speed or hysteresis of the water retention curve. The authors concluded that numerical modeling is an important tool to analyze the performance of cover systems.

The RPM mine is located in the border of semi-humid and semi-arid regions in Brazil, where annual precipitation and evaporation are almost equivalent. According to studies in the literature shown previously, the efficiency of SR coverage system in areas with such weather conditions is debatable. Therefore, this paper presents the construction, the instrumentation and the performance of two experimental SR cover systems constructed at the RPM mine site. Also, in order to verify McCartney and Zornberg (2003) conclusions, a numerical modeling of the experiment was performed and comparisons between field performance and finite element analyses during two and a half years of monitoring are included.

MATERIALS AND METHODS

The experiment described in this paper was accomplished in an area denominated "Barraginha", used to release tailings of the mine pilot plant for 10 years. The tailings formed a layer with thickness varying from 1.0 to 2.5 m, which had no bearing capacity to carry the traffic of machines to build the cover systems. Therefore, it was necessary to built a foundation layer, approximately 1.0 m thick, overlying the tailings. The two cover systems described below were built on the top of the foundation layer, each one occupying, approximately, half of the area and presenting the following characteristics:

- Cover system 1 was composed of a 0.15 m thick layer of organic soil overlying a 0.50 m thick silty soil layer, which was placed over a 50 cm thick layer of a compacted clayey soil (hydraulic barrier).

- Cover system 2 was composed of the same 0.15 m thick organic soil and the 0.50 m thick silty soil layers placed over a 0.50 m thick layer of gravel (capillary barrier).

On the top of the foundation layer, below the cover systems, two large lysimeters were constructed to collect infiltration water.

Figure 2 presents a drawing of the general arrangement of the area, showing the lysimeters, where the instrumentation of each cover system was placed, and where the systems to measure runoff and the lysimeters percolations were installed.

Figure 3 shows the area under construction, whereas Figure 4 presents an overview of the same place at the beginning of the experiment.

Water content reflectometers (WCR) were used to measure soil moisture in each soil layer. The position of these instruments are shown in Figure 5.

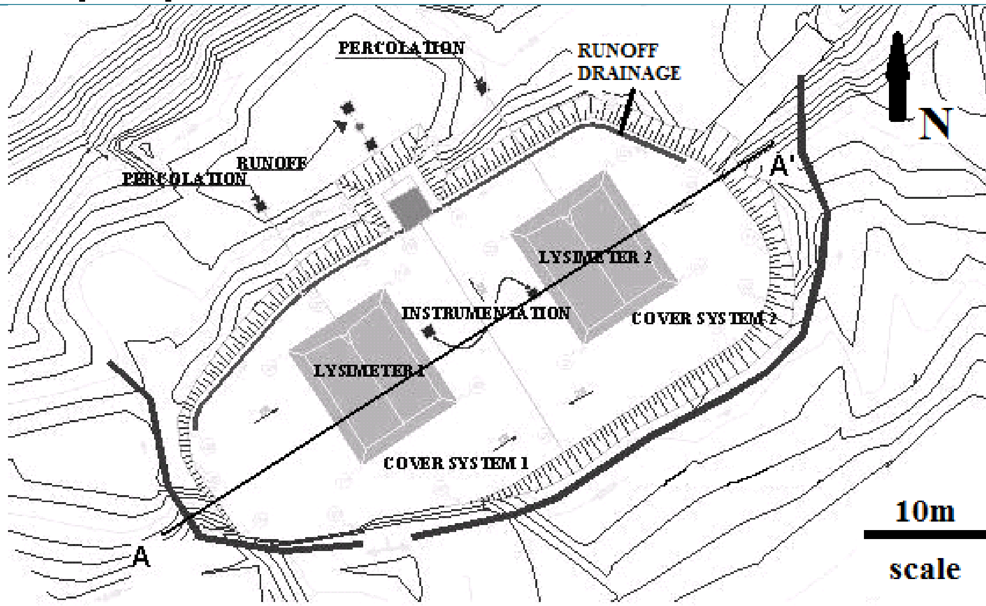

Figure 2: General Arrangement of the Experiment.

Figure 3: The area under construction.

Figure 4: Overview of the area at the beginning of the experiment

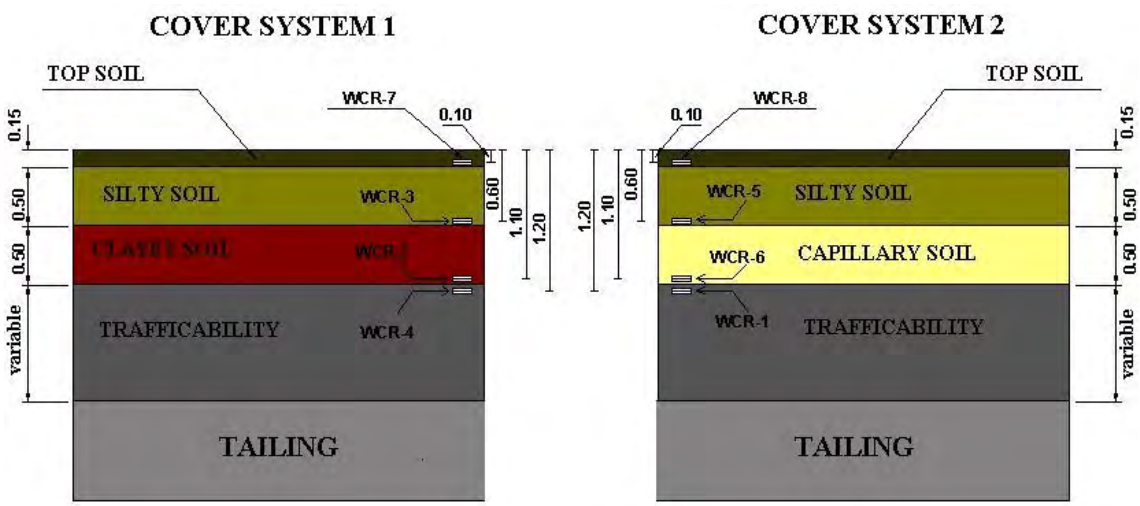

Figure 5: Location of the WCR used in the cover systems.

A complete weather station was available at the RPM site to measure daily maximum and minimum temperatures, precipitations and relative humidity, as well as wind velocity and net radiation.

A 2-D finite element numerical simulation of the experiment was performed using cross section AA' (Figure 2). The numerical model simulates the liquid water flow using Richard's equation, water vapor diffusion using Flick's law, and heat flow using the Fourier equation. At the soil surface, actual evaporation is calculated as a function of potential evaporation, soil suction and air temperature and humidity. The model considers all water balance components - precipitation, evapotranspiration, runoff, etc. - during the specified period of analysis.

The numerical model requires extensive input data, including soil, meteorological and vegetation data. Soil properties, water retention and hydraulic conductivity versus suction curves, for all soils used in cover layers, were obtained in the laboratory. Climatic data were supplied by RPM weather station.

Vegetation data, leaf area index, plant moisture limiting and root depth, were estimated according to the species planted in cover layers.

Figure 6 presents the finite element mesh and the boundary conditions used in the numerical analysis.

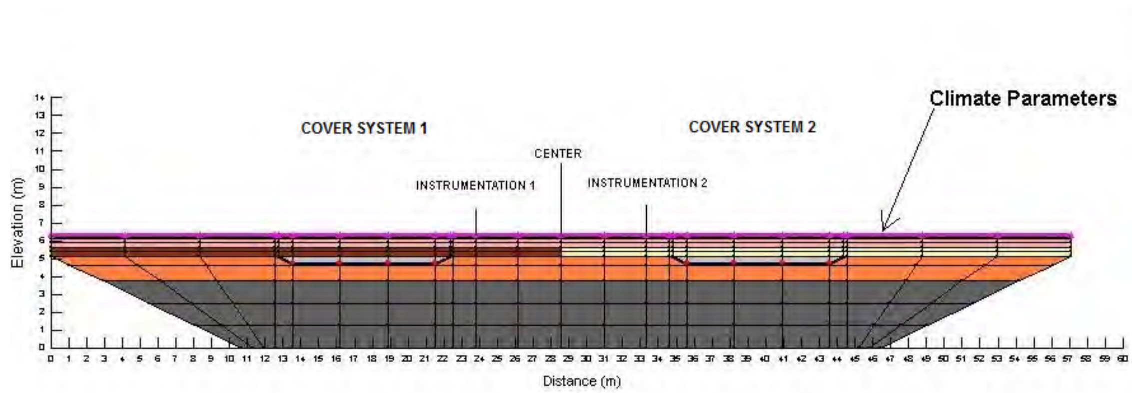

Figure 6: Finite element mesh and boundary conditions used.

RESULTS AND DISCUSSIONS

Figures 7 to 14 show comparisons between the volumetric water content measured in the field and with those obtained numerically, for each layer of the cover systems.

For the superficial and SR layers, Figures 7 to 10, the comparisons show that the numerical model represented relatively well the results measured in the field. The differences observed during the first dry season may be attributed to the vegetation, considered mature in the model, and yet not mature in the field.

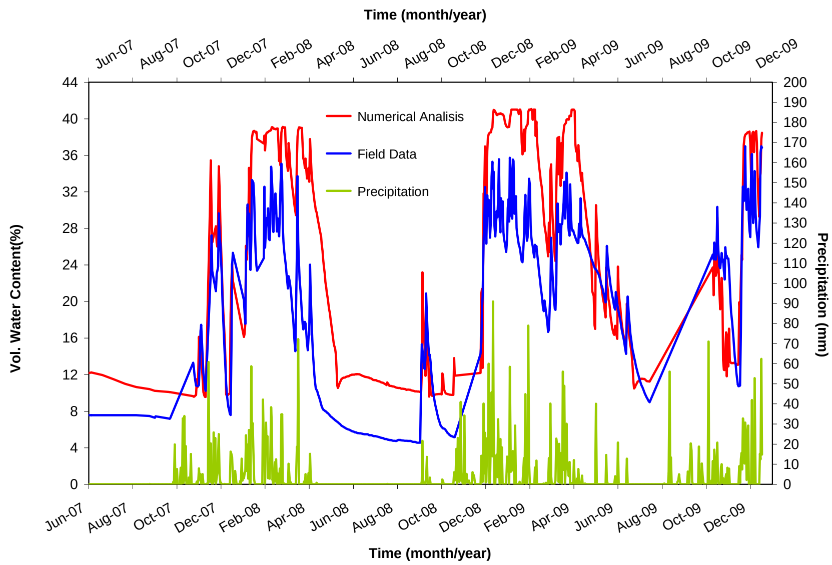

Figure 7: Volumetric water content versus time for the superficial soil layer (Cover 1).

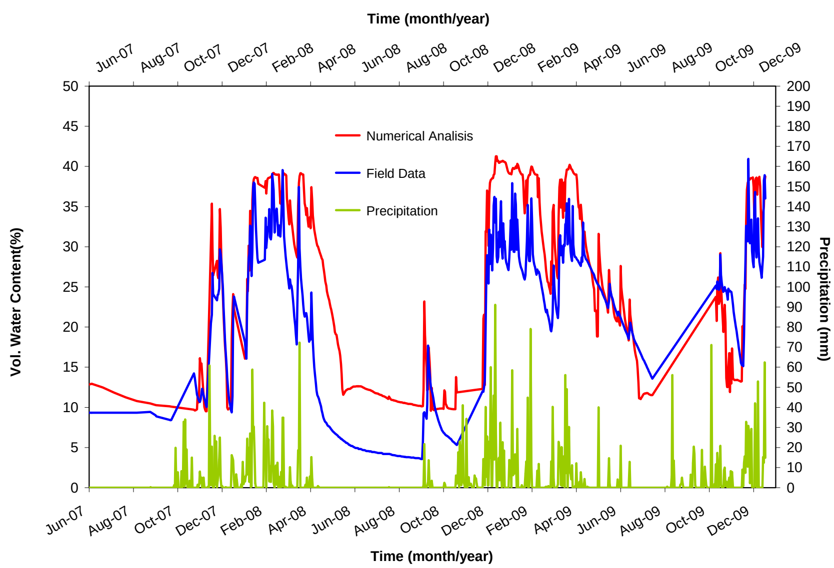

Figure 8: Volumetric water content versus time for the superficial soil layer (Cover 2).

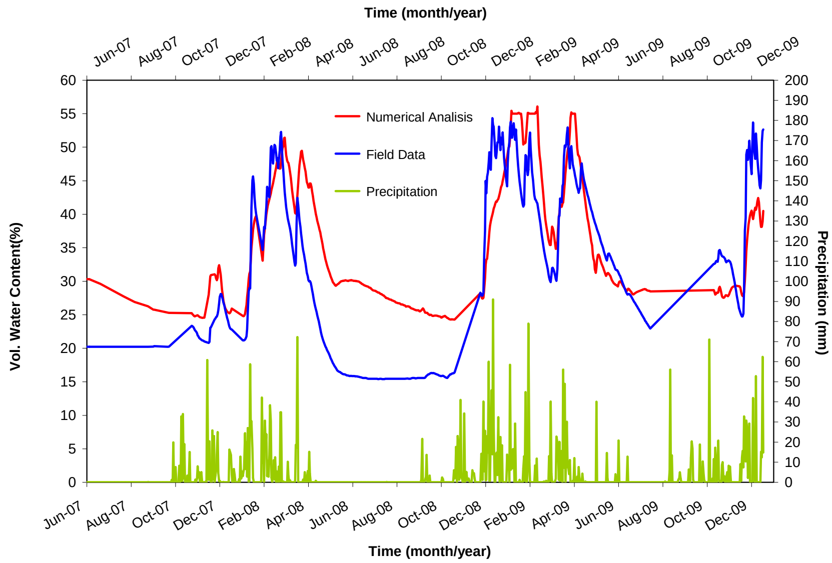

Figure 9: Volumetric water content versus time for the store and release soil layer (Cover 1).

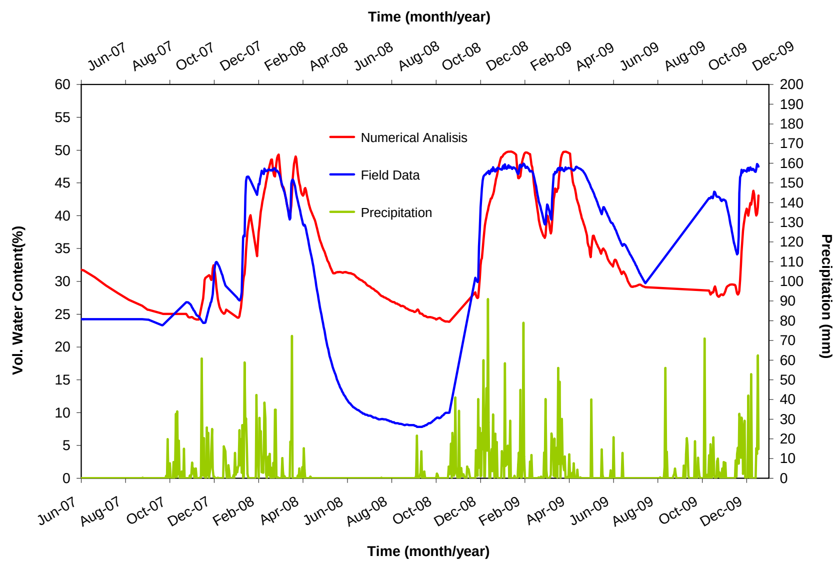

Figure 10: Volumetric water content versus time for the store and release soil layer (Cover 2).

For the hydraulic and capillary barrier soil layers, Figures 11 and 12, the trend showed by of field results was well captured by the numerical model, although some differences may be observed in the magnitude of the results. It can also be pointed out that the model was not able to capture sharp water content variations in short time periods observed in the field during the rainy seasons. A possible reason for this discrepancy is the different time intervals used in the field measurements (four hours) and in the numerical analyses (one day).

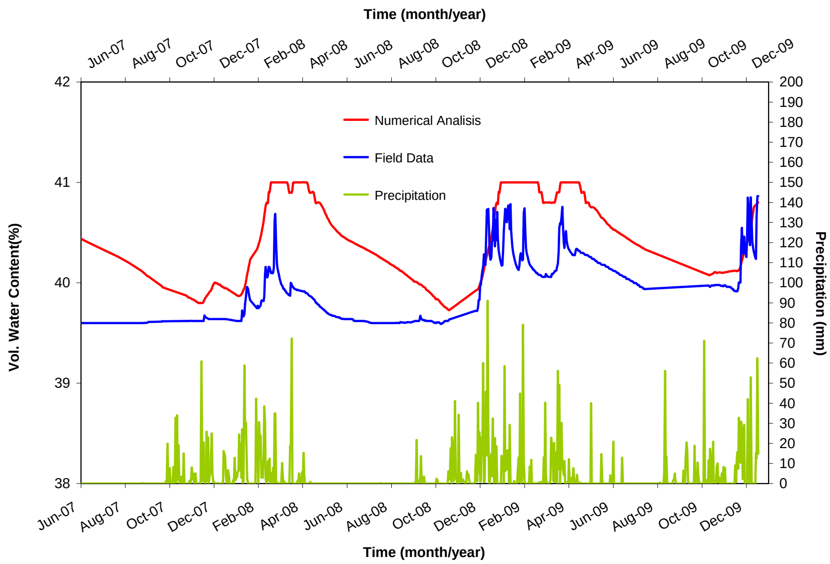

Figure 11: Volumetric water content versus time for the hydraulic barrier soil layer (Cover 1).

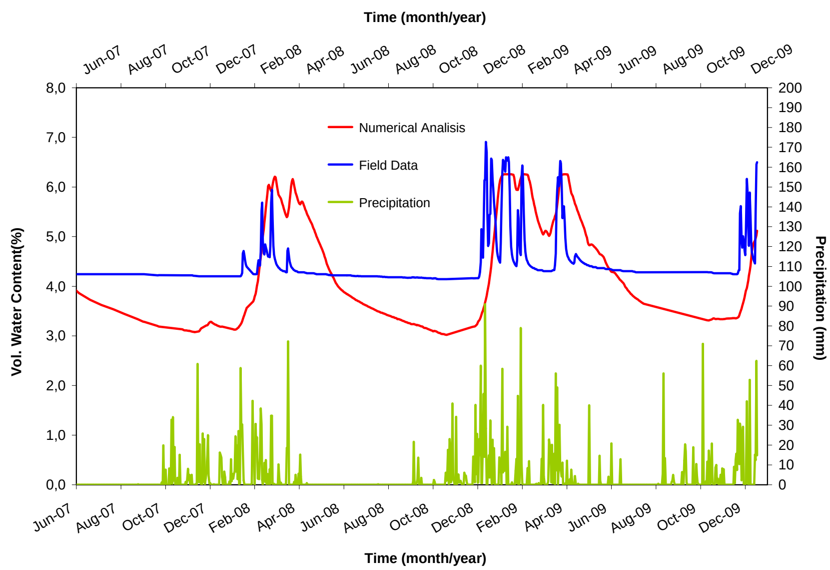

Figure 12: Volumetric water content versus time for the capillarity barrier soil layer (Cover 2).

For the foundation layer, Figures 13 and 14, the scatter between the results was more significant than in the other layers, particularly for Cover 1, where significant differences occurred, both quantitative and qualitative, probably because reflectometer WCR 4 did not work properly.

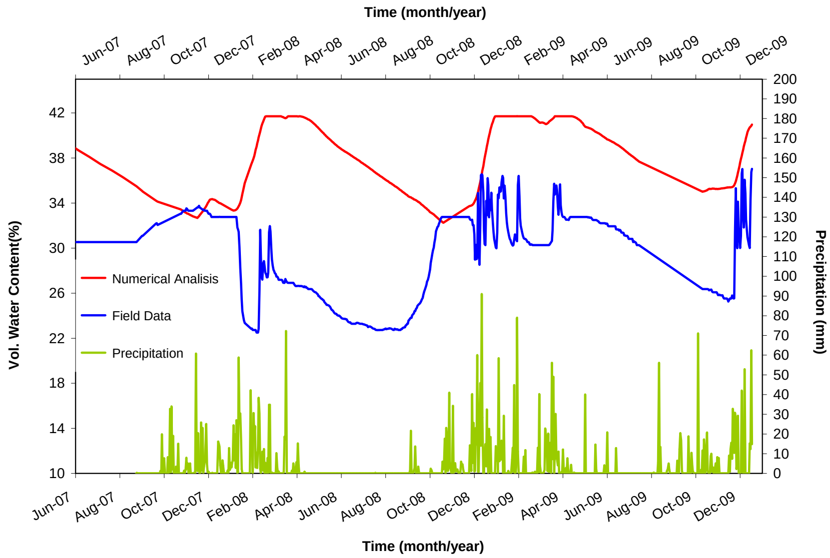

Figure 13: Volumetric water content versus time for the foundation soil layer (Cover 1).

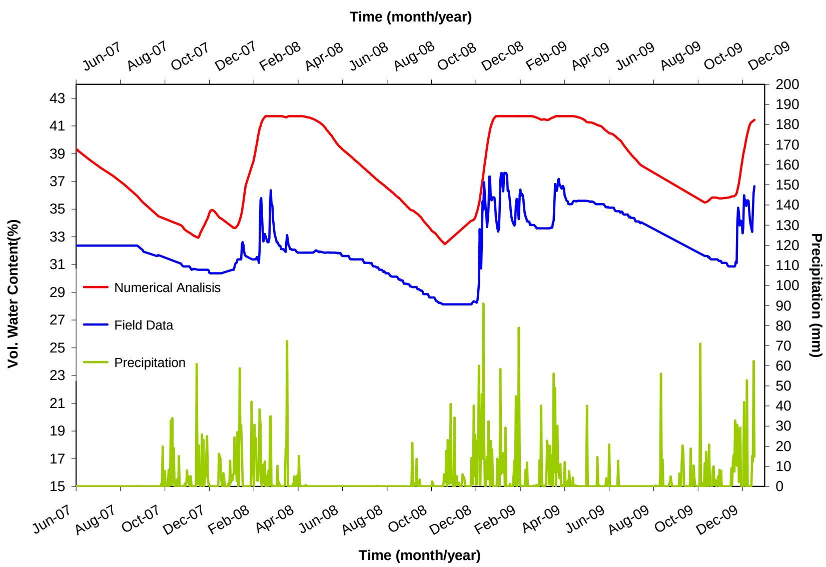

Figure 14: Volumetric water content versus time for the foundation soil layer (Cover 2).

Figures 15 to 18 present water content profiles obtained numerically during the monitoring period. As can be seen, particularly in Figures 17 and 18, humidity in the tailings decreased during the period analyzed. Hence, it is possible to conclude that both cover systems were able to prevent water infiltration in the tailings.

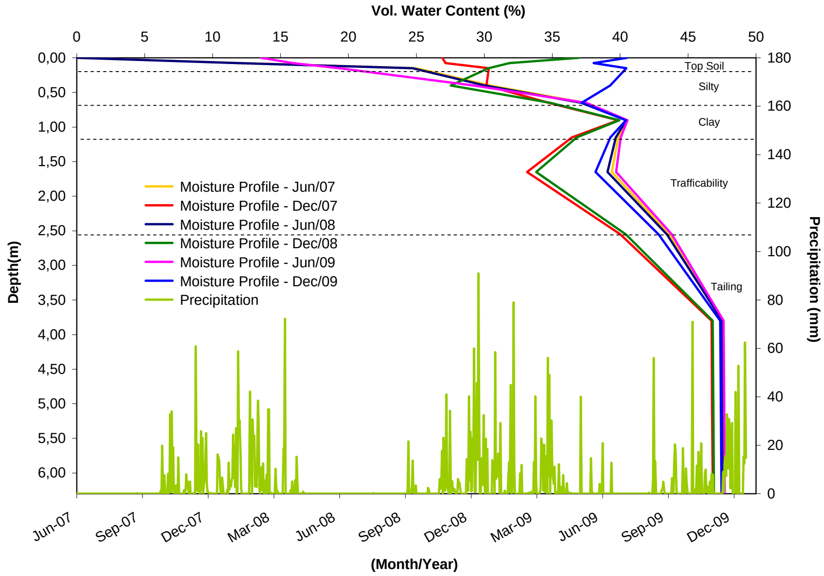

Figure 15: Volumetric water content profiles from June/2007 to December 2009 (Cover system 1).

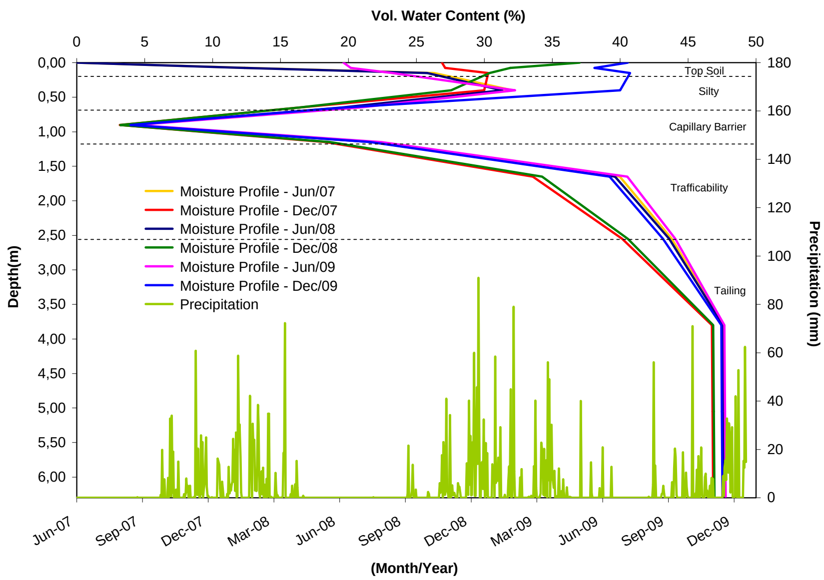

Figure 16: Volumetric water content profiles from June/2007 to December 2009 (Cover system 2).

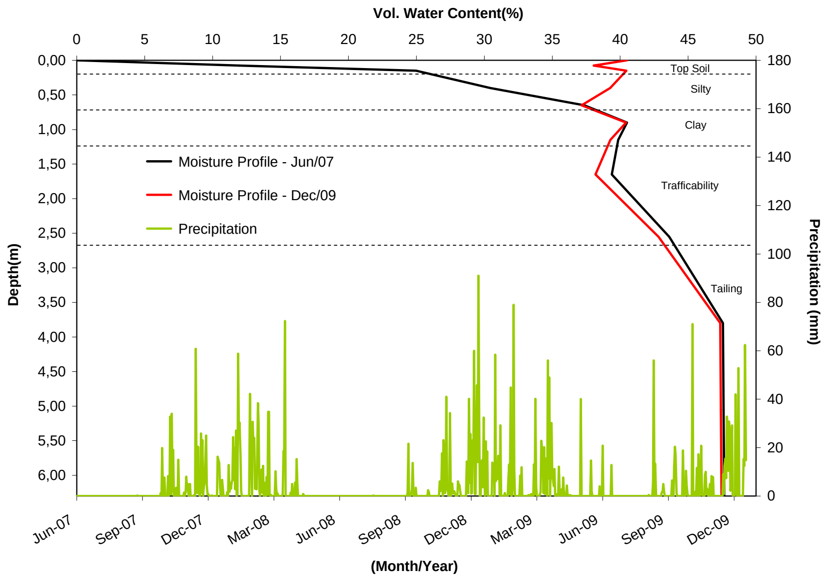

Figure 17: Volumetric water content profiles at the beginning (June/2007) and end (December 2009) of the period analyzed (Cover system 1).

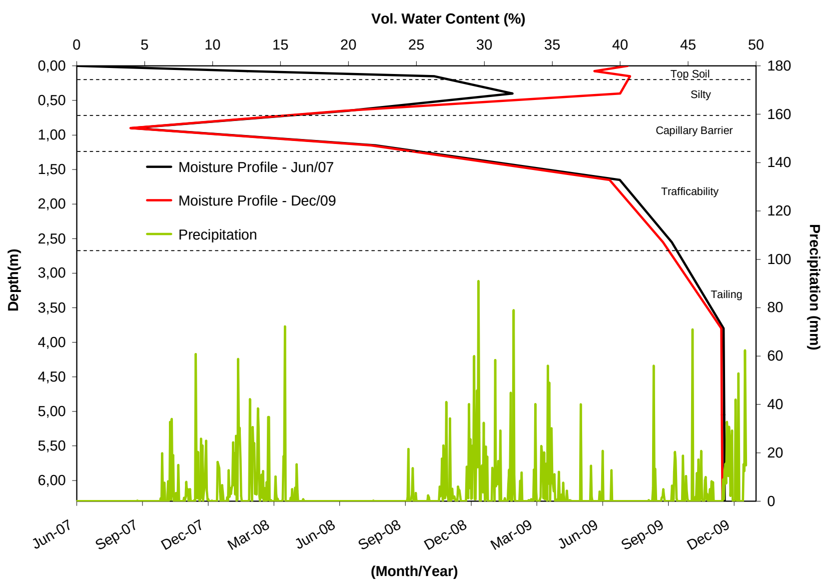

Figure 18: Volumetric water content profiles at the beginning (June/2007) and end (December 2009) of the period analyzed (Cover system 2).

CONCLUSIONS

This paper described the construction of two cover systems, their performances during two and a half years of monitoring, and comparisons between field and numerical finite element results. The following conclusions were drawn from this work.

For the superficial and SR layers the numerical model represented relatively well both the magnitude and the trend of the results measured in the field. Differences observed on the results for the first dry season may be attributed to the vegetation, considered mature in the model, and yet not mature in the field.

The trend of field results was well captured by the numerical model for the hydraulic and capillary barrier soil layers, although some differences are noted in the results magnitude. The model was also not able to capture sharp water content variations in short time periods observed in the field during the rainy seasons, possibly due to different time intervals in the field and used in the numerical analyses.

The scatter between the results was more significant for the foundation layer, particularly for Cover 1, where significant differences occurred, both quantitative and qualitative, probably because reflectometer WCR 4 did not work properly.

Water content profiles showed that the volumetric water content in the tailings decreased during the period analyzed. Hence, it is possible to conclude that both cover systems were able to prevent water infiltration in the tailings. However, since to avoid oxidation of sulfide minerals it is necessary to prevent percolation of both water and oxygen, Cover system 1 seems to be more appropriate, once the clay layer (hydraulic barrier) stays close to saturation most of the time, thus being also able to avoid oxygen (gas) migration.

In general, the numerical model represented relatively well the field results and provides an important tool for the evapotranspirative cover performance assessments.

ACKNOLEDGMENTS

The authors would like to acknowledge Rio Paracatu Mineração (RPM) for the financial support which made possible the construction of the experiment described in the paper, and also to Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for the scholarship provided to the first author.

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