Saturation required for continuum flow through different mine waste materials

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Keywords: continuum flow, hydraulic conductivity function, mine waste materials, saturation, soil water characteristic curve, tailings, unsaturated conditions, waste rock

ABSTRACT

In soil mechanics, "continuum flow" is described by Darcy's Law, which requires that the soil be at least 85% saturated to provide continuous water-filled flow paths. This applies to fine-grained mine tailings. For coarse-grained materials such as loose-dumped, weathered and fresh mine waste rock, the degree of saturation required for continuum flow is much reduced, to about 59% and 27%, respectively, for loose-dumped weathered and fresh waste rock. The density or, more specifically, the porosity of the material may also affect the degree of saturation required for continuum flow. At degrees of saturation below the thresholds for continuum flow in the different materials, preferred pathway flow will dominate. Locally, preferred pathway flow can be relatively high, but the net flow rate over a large area will be minor, and much less than continuum flow rates. There is an almost common value of unsaturated hydraulic conductivity at which the range of mine waste materials considered achieves continuum flow, corresponding to the rate of rainfall infiltration. The paper presents some simple analyses of the wetting by rainfall infiltration of the different mine waste materials, leading to the development of continuum "breakthrough" at the base. Field data are used to support the analyses.

1 INTRODUCTION

Understanding how rainfall infiltrates, is stored within, and is transported through stored mine wastes is essential to predicting the rates and quantities of mineral weathering products released to the environment through seepage. Rates of water flow in waste rock and tailings are not well understood.

For waste rock dumps, the slow infiltration following light rainfall is largely restricted to fine-grained layers and may largely go into storage, while fast infiltration following prolonged heavy rainfall may be dominated by distinct preferred seepage paths. Infiltration into uncovered, loose-dumped, waste rock is commonly assumed to be 30 to 60% of annual rainfall, the remainder assumed to be lost to runoff and evaporation. However, there are a lack of field data to confirm this. Infiltration into covered waste rock can be as low as 1% of incident annual rainfall, as found at Kidston Gold Mine in Queensland, Australia. A trial waste rock dump has been constructed at Cadia Hill Gold Mine in NSW, Australia. It has a flat, traffic-compacted top and sides at the angle of repose of the loose-dumped waste rock. Rainfall infiltration and percolation are monitored by lysimeters at its traffic-compacted top, and at its base beneath the flat top and angle of repose side slopes of the dump, respectively.

Mine tailings are conventionally deposited as a slurry, initially generating saturated seepage. However, as they desiccate during operation and following closure their unsaturated hydraulic conductivity drops appreciably, and it is this that governs rainfall infiltration and seepage.

2 EFFECT OF SURFACE MINE WASTE STORAGES ON FOUNDATION MOISTURE STATE

In an arid or semi-arid environment, which describes the climate in which many of Australia's mines operate, the moisture state of natural ground, vegetated with Australian native plants and trees, is relatively dry. The groundwater table is typically deep (typically 15 to 40 m below the ground surface) and recharge rates are very low (typically < 1 mm/year), since native vegetation is highly efficient at transpiring the majority of the rainfall infiltration. Prior to the construction of a surface mine waste rock dump or tailings storage facility, the surface vegetation is removed (eliminating transpiration) and the topsoil is stripped and stockpiled for future rehabilitation purposes.

The deep natural groundwater table ensures unsaturated conditions towards the natural ground surface, which initially limits the rate of wetting of the foundation from any seepage from stored mine wastes. As the foundation wets, its hydraulic conductivity increases, expanding the wetting front towards the groundwater table, causing mounding, which will be faster and greater beneath freshly deposited tailings than beneath a waste rock dump. Lateral spreading of the wetting front may also occur since horizontal hydraulic conductivity is often several times the vertical value. Groundwater mounding will reduce gradually after an effective rainfall infiltration-limiting cover has been placed on the mine wastes, as the stored water drains down at an ever-decreasing rate.

2.1 Waste rock dumps

The loose-dumping of waste rock on a prepared surface cuts off evaporation, and represents the placement of a "sponge" for the storage of rainfall infiltration. Waste rock is excavated from an open pit at a very low moisture content (typically 1.5 to 5% gravimetric = mass of water/mass of solids, expressed as a %, or 0.03 to 0.09 volumetric water content = volume of water/total volume), increasing with the degree of weathering of the rock. Hence, it initially has a very low unsaturated hydraulic conductivity.

Rainfall infiltration initially goes largely into storage, wetting the surfaces of the waste rock particles, but will eventually emerge as seepage either at the toe or from the base of the dump. If the dump is left open to rainfall infiltration long enough for its degree of saturation to reach the continuum breakthrough rate, then any further rainfall infiltration will cause seepage from the dump at the same rate. The time taken to reach this state will depend on the rainfall, the height of the dump and the nature of the waste rock (dictating the degree of saturation necessary to cause continuum breakthrough). If the waste rock dump is effectively covered to limit rainfall infiltration, the rate of seepage will reduce exponentially with time towards the percolation rate through the cover, as the waste rock desaturates and loses hydraulic conductivity. Store/release cover systems placed on the flat top surface of waste rock dumps have been shown to limit infiltration to 1% of average annual rainfall, and perhaps up to 5% of unseasonally high annual rainfall totals (Williams et al., 2006). The time to reach continuum breakthrough of an uncovered waste rock dump roughly matches the time post-covering for the seepage rate to drop to the cover percolation rate.

For the side slopes of the dump, no cost-effective and sustainable, low percolation cover system has been developed. The side slopes of most dumps will remain prone to infiltration during heavy or continuous rainfall. It is therefore essential that they be constructed of benign waste rock of sufficient thickness to avoid seepage intercepting reactive waste rock and affecting the quality of runoff and seepage.

2.2 Tailings storage facilities

The placement of tailings slurry on a prepared foundation cuts off evaporation, initiates seepage towards the base of the tailings layer and causes the ponding of supernatant water on the surface. About 20% of the tailings water expelled reports to the base of the tailings layer, whose hydraulic conductivity drops as it consolidates under its self-weight, and 80% to the pond (Murphy, 2007). If the tailings are left to consolidate further and desiccate, the rate of seepage and surface ponding will diminish. The ponded water, including rainfall runoff, should be removed from the tailings surface to reduce seepage, and either recycled to the processing plant or stored in evaporation ponds if it is unsuitable for re-use. Post-closure, the consolidated and desiccated tailings will reduce in hydraulic conductivity, reducing or eliminating seepage, and gain water storage capacity. The desiccated tailings may form an effective rainfall-limiting cover, or a purpose-built cover may be required.

3 APPLICATION OF UNSATURATED SOIL MECHANICS

The flow of water through waste rock dumps and desiccated tailings is governed by unsaturated soil mechanics principles. The concept that unsaturated waste rock has a very low unsaturated hydraulic conductivity appears at first to be counter-intuitive, since waste rock is free-draining when saturated. A useful analogy is to consider a bucket and watering can (Scott, 2005). Imagine a pile of dry, coarse-grained waste rock. If you were to pour a bucket-full of water into it, the water would almost immediately flow through, since the pores between the rock particles would rapidly fill with water allowing the water to flow. This is saturated flow. The rock would then rapidly dry. Alternatively, if you were to sprinkle water from a watering can with a fine nozzle over a wide arc over the pile of rock, the water would be stored within the rock pores, filling the larger pores first, without any flow-through. This is unsaturated behaviour.

3.1 Key unsaturated soil mechanics functions

The key functions used to describe the unsaturated behaviour of soil-like materials, including waste rock, are the Soil Water Characteristic Curve (SWCC) and the unsaturated hydraulic conductivity function (Fredlund and Rahardjo, 1993). The SWCC is a plot of soil water (conventionally in terms of volumetric water content; but it could also be in terms of degree of saturation, or the gravimetric or mining moisture content) versus soil suction. It provides the loci of moisture states of a soil from the saturated to the "oven-dry" state, at a particular test density (the higher the density the lower the intercept on the soil water axis).

Soil Water Characteristic Curve data are conventionally measured in the laboratory by drying a sample from the saturated state in a Tempe cell, and a curve is then fitted to the measured data using one of a variety of methods such as that of Fredlund and Xing (1994). Depending on the application for which the SWCC is required, drying, wetting or both drying and wetting curves may be appropriate. Where only one curve is measured, it is usually the drying curve, since it has the common starting point of saturation. An estimate of the laboratory drying SWCC may be obtained from the particle size distribution, dry density and specific gravity of the soil using Fredlund et al. (1997) and the library of data contained within the program SoilVision.

From the SWCC and measured saturated hydraulic conductivity of the soil, the unsaturated hydraulic conductivity function of the soil may be calculated using the method of Fredlund et al. (1994).

4 CHARACTERISATION OF MINE WASTE MATERIALS CONSIDERED

The mine waste materials considered included fresh and weathered waste rock and typical metalliferous tailings, which are described in terms of their particle size distribution, SWCC and hydraulic conductivity function in the following paragraphs.

Particle size distribution curves for typical weathered waste rock (representative of that excavated following blasting at shallow depth above the groundwater table), fresh waste rock (representative of that excavated following blasting from below the groundwater table) and metalliferous tailings are plotted on Figure 1. The corresponding SWCCs calculated using the method of Fredlund et al. (1997) and SoilVision are plotted on Figure 2, and the corresponding unsaturated hydraulic conductivity functions calculated using the method of Fredlund et al. (1994) are plotted on Figures 3 and 4, in terms of suction and volumetric water content (VWC), respectively. In deriving the unsaturated hydraulic conductivity functions, saturated hydraulic conductivities of 10^{-5} m/s, 10^{-3} m/s and 5 x 10^{-7} m/s were adopted for the weathered and fresh waste rock, and metalliferous tailings, respectively.

5 ESTIMATED WETTING OF STORED MINE WASTES DUE TO RAINFALL

Using the calculated SWCCs (Figure 2) and unsaturated hydraulic conductivity functions (Figure 4), simulations of the wetting by rainfall of Cadia mine waste materials (weathered and fresh waste rock, and desiccated tailings) were carried using iterative spreadsheet calculations in which the unsaturated hydraulic conductivities of sub-layers of representative heights of the stored mine waste materials were updated as they wet from the top surface due to rainfall infiltration. The downward progression of rainfall infiltration was continued until all infiltration was held up by the lower hydraulic conductivity of the underlying drier material or continuum breakthrough occurred. No allowance was made for preferred pathway flow, which was assumed to be minor. Spreadsheet calculations were preferred over numerical methods, which incur convergence problems due to the high suction gradients within the materials as they wet up.

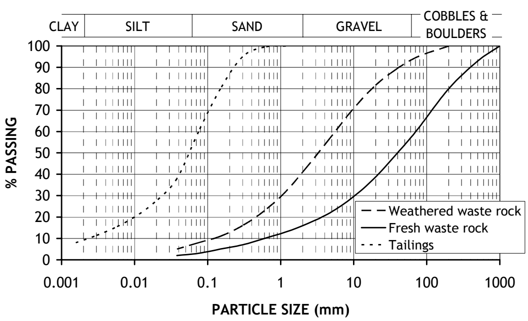

Figure 1: Particle size distribution curves

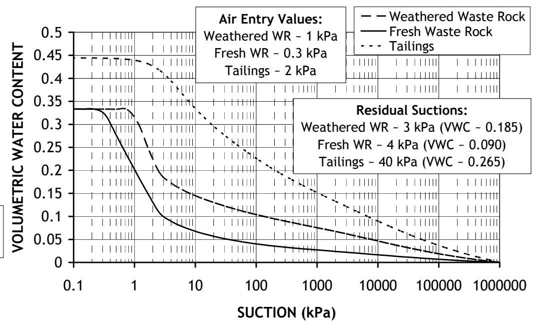

Figure 2: Soil water characteristic curves

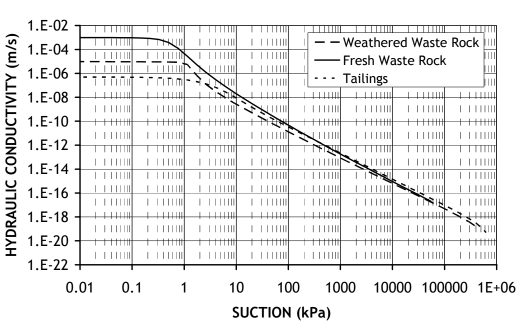

Figure 3: Hydraulic conductivity vs suction

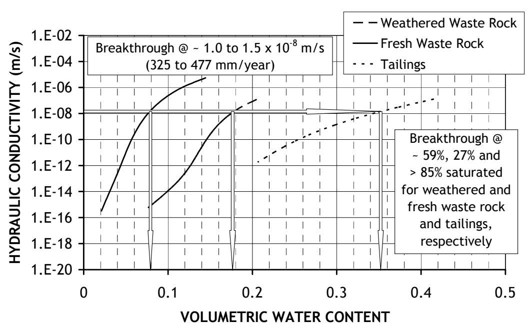

Figure 4: Hydraulic conductivity vs VWC

5.1 Input data

The simulations were applied to loose-dumped, weathered and fresh waste rock, and desiccated tailings, at Cadia Hill Gold Mine. A specific gravity of 2.7 was assumed for all of these materials. For the weathered and fresh waste rock, the simulations were applied to the uncovered top of the instrumented, 15 m high, trial waste rock dump. The trial dump covers an area of 7,000 m^2, and has been monitored since its completion in January 2006. For both the weathered and fresh waste rock cases, an initial gravimetric moisture content of 1.5%, a porosity of 0.33 and a dry density of 1.8 t/m^3 were assumed (as supported by the testing of recovered samples and field density testing). During the 12 months of monitoring, the site has recorded 650 mm of rainfall (well below the long-term average annual rainfall of about 900 mm) spread over 110 days, 73.4% of which infiltrated the top of the dump, the remainder being lost to evaporation and runoff. The majority of the rainfall infiltration has gone into storage within the dump, with only 2% on average percolating beneath the flat top of the dump and 4% on average percolating beneath the angle of repose side slopes. The minor measured percolation has occurred via preferred seepage pathways.

Uncovered desiccated Cadia tailings in a closed storage facility 15 m deep were also considered, the depth selected being representative of the tailings storage facility at Cadia, and matching that of the trial waste rock dump to facilitate comparisons. The desiccated tailings were assumed to have an average porosity of 0.407 and an average dry density of 1.6 t/m^3. A typical moisture profile was adopted for the desiccated tailings, based on a range of measurements. The proportion of rainfall infiltrating the desiccated stored tailings at Cadia is unknown, but was assumed to be 50% since the lower hydraulic conductivity of the tailings would restrict infiltration, increasing surface ponding and evaporation. In addition, allowance was made for the concentration of rainfall runoff over only the lower 14% of the area of the tailings beach.

In all simulations, the annual rainfall recorded in 2006 was assumed in future years, and infiltration was allowed to occur only during days on which rainfall occurred (110 days/year). The simulations were continued for up to 10 years.

5.2 Results of simulations

The results of the simulations are shown on Figures 5 to 8. Figures 5 to 7 show the wetting of 15 m heights of weathered and fresh waste rock and desiccated tailings, respectively, from which it can be seen that the weathered rock wets most slowly, closely followed by the desiccated tailings, with the fresh waste rock wetting fastest. Fully developed continuum breakthrough of each of the three materials corresponds to approximately the same hydraulic conductivity of 1.0 to 1.5 x 10^{-8} m/s (dictated by the infiltration rates of 325 to 477 mm/year), at degrees of saturation of 59%, 27% and almost 100% for the weathered waste rock, fresh waste rock and desiccated tailings, respectively. This is also highlighted on Figure 4.

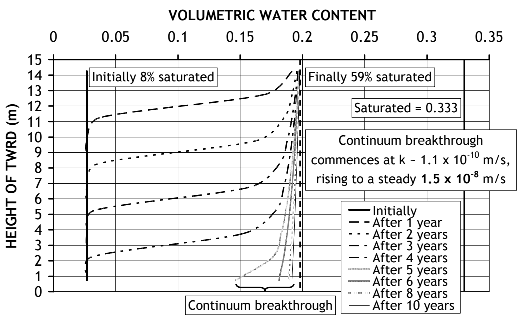

Figure 5: Wetting of weathered waste rock

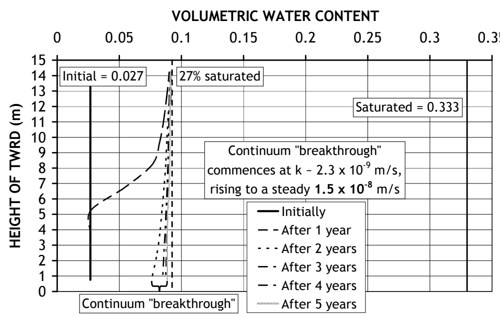

Figure 6: Wetting of fresh waste rock

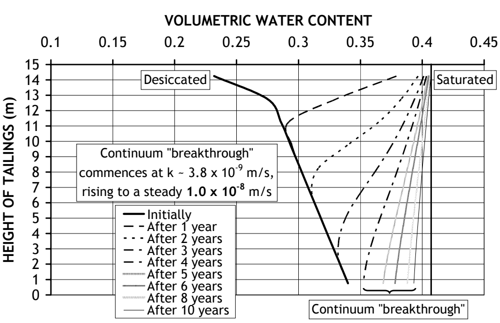

Figure 7: Wetting of desiccated tailings

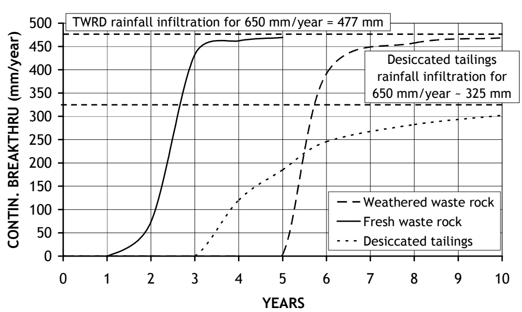

Figure 8: Time to continuum breakthrough

Continuum breakthrough is given by the rate of seepage approaching the rate of rainfall infiltration, since the waste materials can store no more water. Figure 8 shows the estimated number of years required to initiate and fully develop continuum breakthrough in each case, as summarised in Table 1, corresponding to unsaturated hydraulic conductivities very much lower than the saturated values.

Table 1: Estimated time to initiate and fully develop continuum breakthrough

Waste material	Years to initiation of continuum breakthrough	Years to full continuum breakthrough
Fresh waste rock	1	3
Weathered waste rock	5	7
Desiccated tailings	3	10

5.3 Implications for the operation and closure of mine waste storage facilities

Since the rate of preferred pathway seepage from a waste rock dump is minor, the degree of saturation necessary to achieve continuum breakthrough of potentially contaminated seepage should ideally be avoided by covering the top of the waste rock dump with an effective rainfall infiltration-limiting cover, such as a store/release cover, long before continuum breakthrough is likely. The side slopes, which cannot be effectively covered to limit rainfall infiltration must be constructed of benign waste rock of sufficient thickness to avoid seepage intercepting reactive waste rock and affecting runoff and seepage water quality.

For a tailings storage facility, fresh tailings should ideally be deposited in relatively thin layers in a number of cells in rotation, in which they are allowed to desiccate prior to the placement of the next layer. This will limit the amount of potentially contaminated saturated seepage to the foundation, maximise the use of the available storage volume by producing a more dense deposit, and provide storage capacity to accept the seepage from subsequent layers of fresh tailings.

6 CONCLUSIONS

Fully developed continuum breakthrough of the three mine waste materials considered corresponds to approximately the same hydraulic conductivity of 1.0 to 1.5 x 10^{-8} m/s (dictated by the infiltration rates of 325 to 477 mm/year), at degrees of saturation of 59%, 27% and almost 100% for the weathered waste rock, fresh waste rock and desiccated tailings, respectively. Continuum breakthrough of potentially contaminated seepage from a waste rock dump should ideally be avoided by covering the top of the dump with an effective rainfall infiltration-limiting cover long before continuum breakthrough is likely. Tailings should ideally be deposited in relatively thin layers in a number of cells in rotation and allowed to desiccate to limit the amount of potentially-contaminated, saturated seepage to the foundation.

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ACKNOWLEDGEMENTS

This paper includes research data from Cadia Hill Gold Mine. The assistance of the mine site personnel involved, and the research funding provided by the company and the Australian Research Council, are gratefully acknowledged.