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Mine Closure as a Driver for Waste Rock Dump Construction

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1 INTRODUCTION

Waste rock dump construction is driven largely by the costs associated with hauling the rock. In recent times, there have been large increases in certain costs associated with conventional haulage; namely, the cost of diesel and the cost and restricted availability of new tyres. These cost pressures have impacted on the balance between horizontal and vertical haulage, affecting the areal extent and height of the dump. Dumps tend to be expanded, both upwards (by additional lifts) and laterally, in stages. There has been little incentive to progressively cover the waste rock dump during construction, since the dump is kept active to accommodate expected and possible expansion of the mine and Net Present Value accounting promotes delayed mine closure.

Increasingly, other drivers are coming to the fore, including mine closure requirements. These include the need to encapsulate, with benign waste rock, potentially acid forming waste rock; the need to limit potentially contaminated seepage from the dump; and the need to limit erosion loss off the dump. Since benign waste rock may only be produced during the early stages of open pit mining, there is the risk that it will be buried beneath deeper-won potentially acid forming waste rock, leaving no benign material with which to encapsulate the potentially acid forming waste rock. Potentially acid forming waste rock needs to be placed beneath the flat top surface of the dump, and the relative proportions of benign and potentially acid forming waste rock will dictate the dump width to height ratio, and the final angle of the outer batters of the dump, that makes this possible.

By keeping the dump active throughout the mine life, rainfall and oxygen are free to infiltrate the dump, leading to the wetting up of the dump and the oxidation of potentially acid forming waste rock. Even after an effective rainfall percolation-limiting cover has been placed on the dump, the water stored within the dump during its operation will continue to seep at a diminishing rate for many years, carrying with it any oxidation products. The conventional practice of placing a fine-grained growth medium on the steep side slopes of the dump often leads to unacceptably high rates of erosion loss. The paper presents refined approaches to waste rock dump construction driven by mine closure requirements.

2 WASTE ROCK DUMP CONSTRUCTION AND CLOSURE

Waste rock dumps are conventionally constructed by end-dumping on the surface in a series of lifts with a vertical height of about 15 m. End-dumping creates an oxidation reactor, in which the base rubble zone delivers oxygen to the coarse-grained angle of repose layers, which in turn deliver oxygen to the adjacent fine-grained layers that present a high reactive surface area. There will be some ingress of oxygen into the sides of the dump and a minor amount of diffusion of oxygen through the traffic-compacted flat top surface of the dump.

Each lift is typically extended over the entire footprint of the dump, and the entire footprint left exposed to rainfall for the life of the dump. Typically, on closure, the top surface of the dump is covered with a fine-grained, low percolation cover, while the side slopes of the dump are dozed and covered with a growth medium.

2.1 Physical Characterisation of Waste Rock

The 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 tailings (for completeness) are plotted on Figure 1, which highlights the distinct differences between the particle size distributions of the three waste materials.

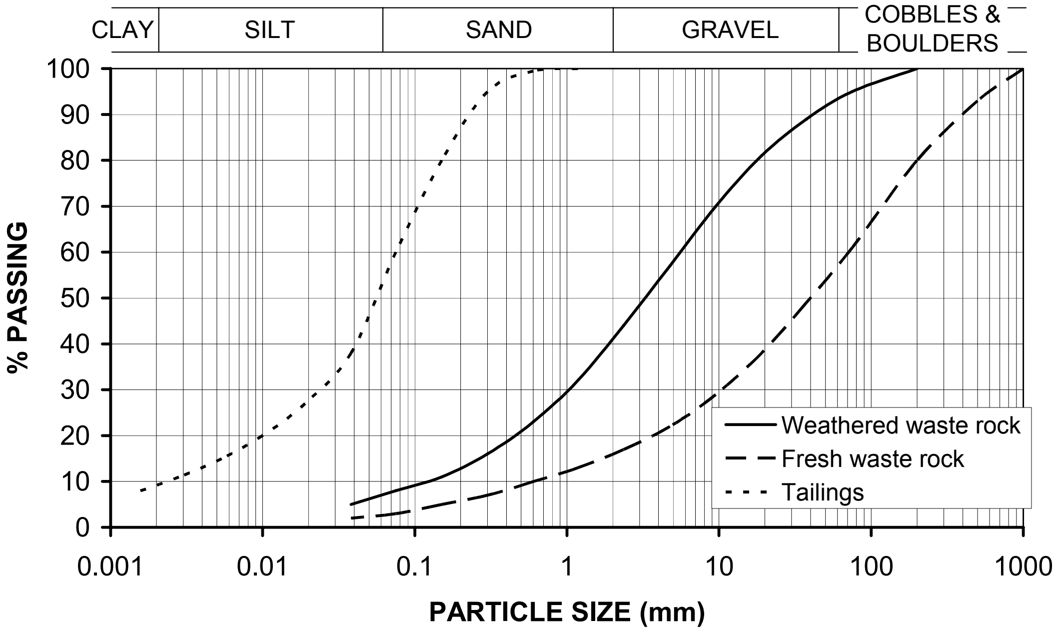

Figure 1 Particle size distributions for typical mine wastes

2.2 Moisture State of Waste Rock Dumps

Rainfall infiltration into loosely-dumped, oxidising, mineralised waste rock transports any oxidation products in the form of acid drainage, laden with dissolved metals, if available. Rainfall infiltrates into, stores within, and passes through an uncovered waste rock dump via preferred pathways, which may dominate initially when the rock is dry, and continuum flow, which becomes dominant as the dump approaches its "breakthrough saturation". The breakthrough saturation is a function of the pore size distribution, which is reflected by the particle size distribution and density (usually placed loose by end-dumping) of the waste rock.

2.2.1 During operation

In an arid or semi-arid environment, which describes the climate in which many of Australia's mines operate, waste rock emerges from an open pit with a low moisture content. The gravimetric moisture content (mass of water/mass of solids, expressed as a percentage) is typically 2 to 5%, which equates to a volumetric water content (volume of water/total volume, expressed as a decimal) of 0.035 to 0.09. The precise moisture content depends on the degree of weathering of the waste rock and hence its particle size distribution and moisture retention characteristics.

From the outset, a waste rock dump closes off evaporation (the amount of pan evaporation being several times that of rainfall in arid and semi-arid climates), while allowing rainfall infiltration. A proportion of the rainfall infiltration will go into storage within the voids in the dump, with any excess infiltrating further into the dump, ultimately emerging as seepage at the toe and into the foundation. Due to its very low hydraulic conductivity, the initially dry waste rock will store infiltration from light rainfall events, and a high waste rock dump of relatively dry material may be capable of storing considerable infiltration without significant breakthrough. The wetting front will progress through the dump as the ability of the waste rock pores to store water is exceeded, this occurring well below the fully saturated state, since the waste rock will have achieved a sufficiently high hydraulic conductivity to pass further rainfall infiltration.

Initially, percolation into the foundation is limited by the very low hydraulic conductivity of the unsaturated zone within the foundation. A wetting front advances downwards, aided by any preferred seepage paths, raising the hydraulic conductivity of the unsaturated zone and causing mounding of the groundwater table at depth, with any contaminants in the seepage able to reach the groundwater.

The amount of rainfall infiltration into the dump can be restricted by sloping the traffic-compacted top surface to avoid ponding. The loose-dumped outer slopes of the waste rock dump should be constructed of benign waste rock of sufficient thickness to produce clean runoff and seepage.

2.2.2 Post-closure

Low percolation covers, such as the store/release cover system developed for arid and semi-arid climates (Williams et al., 1997), placed on the flat top surface of waste rock dumps have been shown to limit percolation to 1% of average annual rainfall, and perhaps up to 5% of unseasonally high annual rainfall totals (Williams et al., 2006). While such covers reduce further percolation into the dump, the water stored within the dump during its operation and prior to it being covered will continue to seep for many years (Williams and Rohde, 2006), perhaps for as long as the dump remained uncovered. Seepage from the toe of the dump and percolation (and the transport of any contaminants) into the foundation will diminish over time as the waste rock drains and loses hydraulic conductivity. Combined toe seepage and percolation into the foundation should eventually approach the rate of percolation through the cover. Any groundwater mounding beneath the dump will subside over time, eventually returning to its original elevation.

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, and it is therefore essential that they be constructed of benign waste rock of sufficient thickness to produce clean runoff and seepage.

3 APPLICATION OF UNSATURATED SOIL MECHANICS

The flow of water through waste rock dumps is governed by unsaturated soil mechanics principles, as described in the following sections. The concept that unsaturated waste rock has a very low 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 dump 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 dump 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; increasing the density, for example by compaction, will induce drainage).

Soil Water Characteristic Curve data are conventionally measured in the laboratory using a Tempe cell and the curves are 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, re-wetting or both drying and re-wetting curves may be appropriate. Where only one curve is measured, it is usually the drying curve.

On drying from near-saturated conditions at a given density (or porosity), waste rock begins to take air into its voids at the Air-Entry Value (AEV), beyond which it is no longer able to remain saturated. On further drying beyond the AEV, the slope of the SWCC indicates the water storage capacity of the waste rock and the ease with which it may be dewatered. A Residual Suction (RS) and corresponding moisture content is reached, reflecting the driest state the waste rock is likely to achieve. To this point, matric (or capillary) suction and liquid water flow dominate.

Field SWCC data may also be collected, and the curve fitted using the same method. The laboratory and field data may produce quite different SWCCs, the differences being greatest where there is significant structure or cementation in situ, which is destroyed on sampling and laboratory testing. The SWCC for a soil with significant structure or cementation is shifted to the right, having a much higher AEV and steeper post-AEV slope. However, the RS may be similar to the laboratory value.

An estimate of the laboratory drying SWCC may be obtained from the particle size distribution, dry density and specific gravity of the soil using the 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).

3.2 Estimated Wetting-Up of Stored Mine Wastes due to Rainfall

Using the particle size distribution curves shown on Figure 1, the corresponding SWCCs calculated from these using the method of Fredlund et al. (1997) and SoilVision, the corresponding unsaturated hydraulic conductivity functions calculated using the method of Fredlund et al. (1994) are plotted on Figure 2, in terms of suction and volumetric water content, respectively.

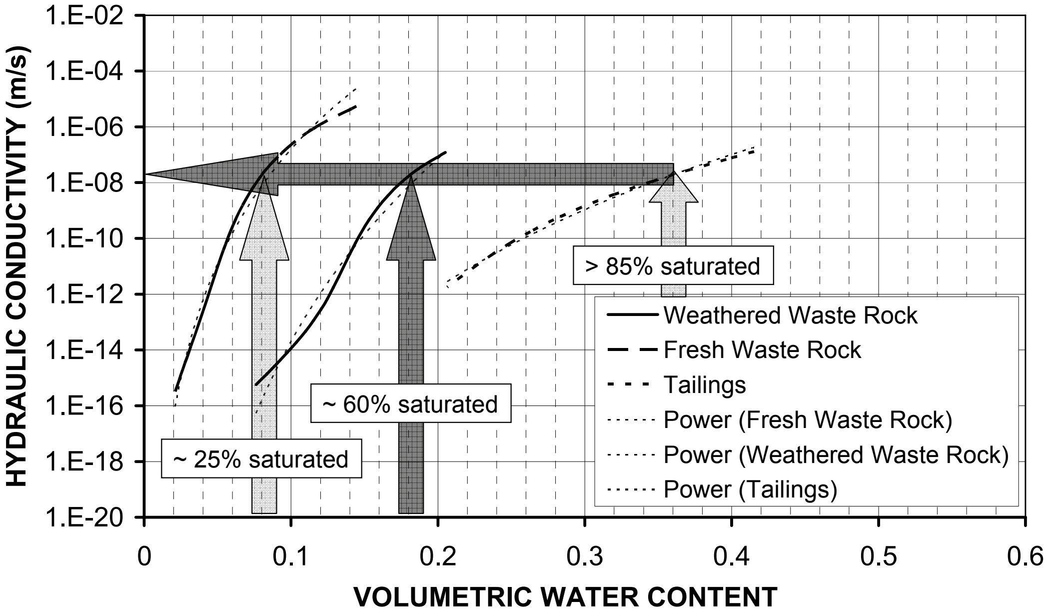

Figure 2 **Typical unsaturated hydraulic conductivity functions for mine wastes in terms of volumetric water content, including "continuum breakthrough" values**

Using the unsaturated hydraulic conductivity functions (Figure 2), simulations of the wetting-up of mine waste materials (including weathered waste rock, fresh waste rock and desiccated tailings) by rainfall may be undertaken. It has been found (Williams, 2006) that fresh waste rock, weathered waste rock and desiccated tailings achieve continuum breakthrough at degrees of saturation of about 25%, 60% and > 85%, respectively, at comparable unsaturated hydraulic conductivities, as shown on Figure 2.

Herein, the simulations are restricted to a consideration of weathered waste rock, since experience has shown that even initially fresh waste rock rapidly weathers and breaks down in a dump. Simulations were carried out for uncovered waste rock dumps at Kidston and Cadia Hill gold mines. The simulations were based on iterative spreadsheet calculations in which the unsaturated hydraulic conductivities of sub-layers of weathered waste rock were updated as they wet-up. Spreadsheet calculations were preferred over numerical methods, which would incur convergence problems due to the high suction gradients within the waste rock as it wet-up. To facilitate the simulations, average annual rainfall totals for the two sites were used, 50% of the rainfall was assumed to be available to infiltrate (the remainder assumed to be lost to runoff and evaporation), and infiltration was allowed to occur only during days on which rainfall occurred.

The Kidston waste rock dump averages about 40 m high, and the long-term average annual rainfall of 700 mm falling over 55 days/year was adopted. The volumetric water content profiles with depth calculated for various cumulative years of rainfall are shown on Figure 3, from which the annual continuum breakthrough amounts (out of the dump) plotted with time on Figure 4 were obtained. Over the up to 15 years that the waste rock dumps were left uncovered, the calculated annual continuum breakthrough amounts are seen to approach the rainfall infiltration amounts, with little capacity for further water storage within the dump.

The Cadia trial waste rock dump is 15 m high, and both the long-term average annual rainfall of 900 mm falling over 123 days/year and the average annual rainfall for the last 5 years of 600 mm falling over 82 days/year were analysed. The volumetric water content profiles with depth calculated for various cumulative years of 900 mm/year rainfall are shown on Figure 5. From this and corresponding profiles obtained for various cumulative years of 600 mm/year rainfall, the annual continuum breakthrough amounts (out of the dump) plotted with time on Figure 6 were obtained. It is seen that the uncovered trial waste rock dump is predicted to reach continuum breakthrough in 3 to 4.5 years, approaching the rainfall infiltration amounts after 5.5 to 6.5 years, with little capacity for further water storage within the dump.

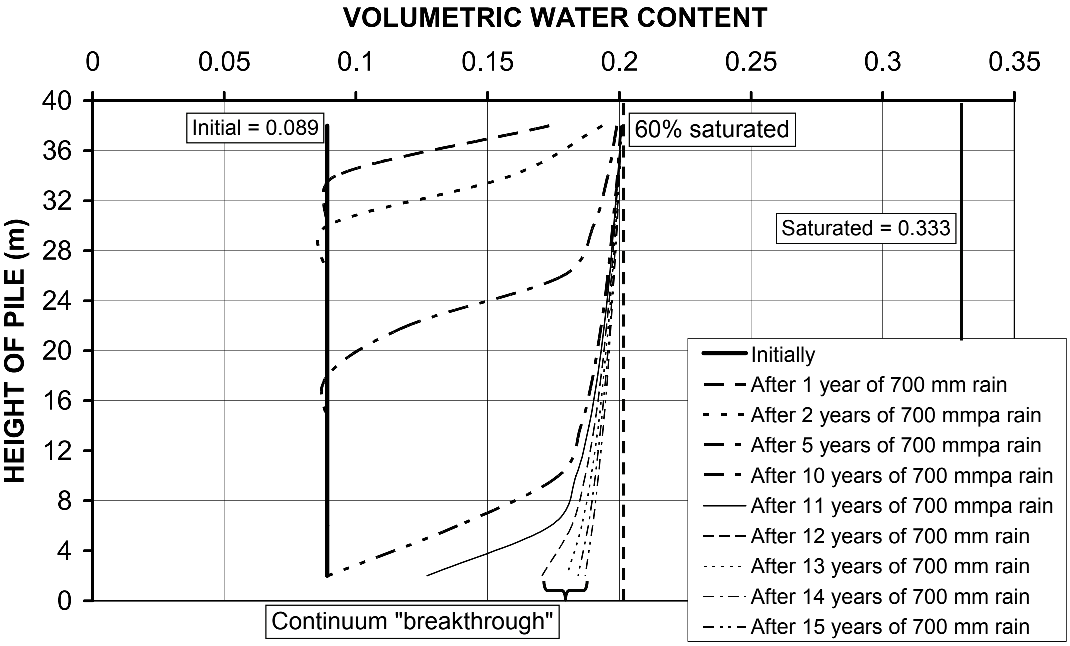

Figure 3 **Estimated wetting-up of Kidston weathered waste rock dumps for average annual rainfall of 700 mm**

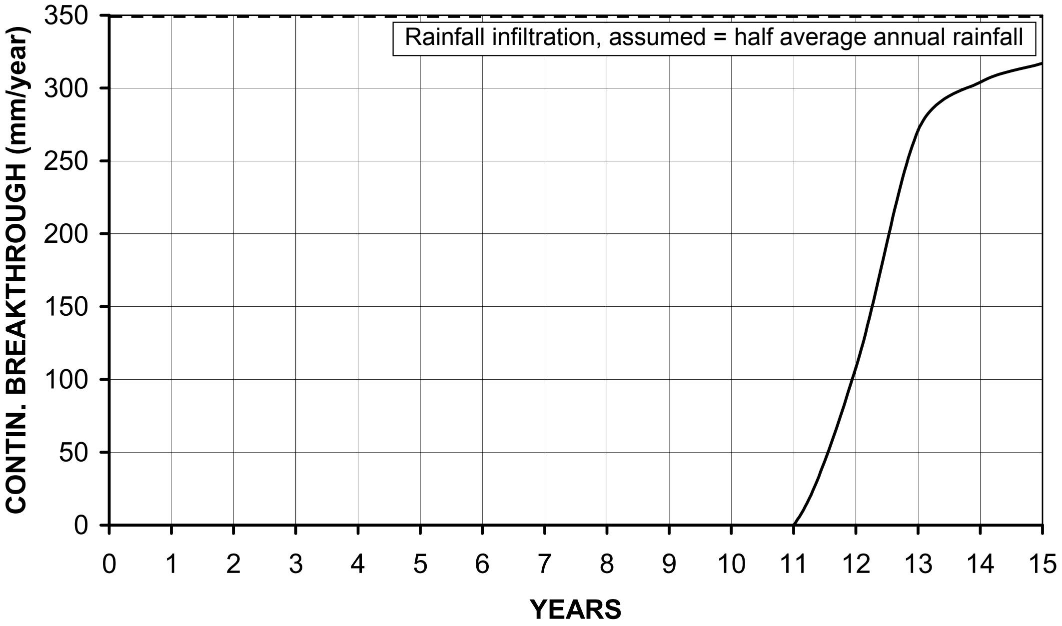

Figure 4 Estimated continuum breakthrough for Kidston weathered waste rock dumps

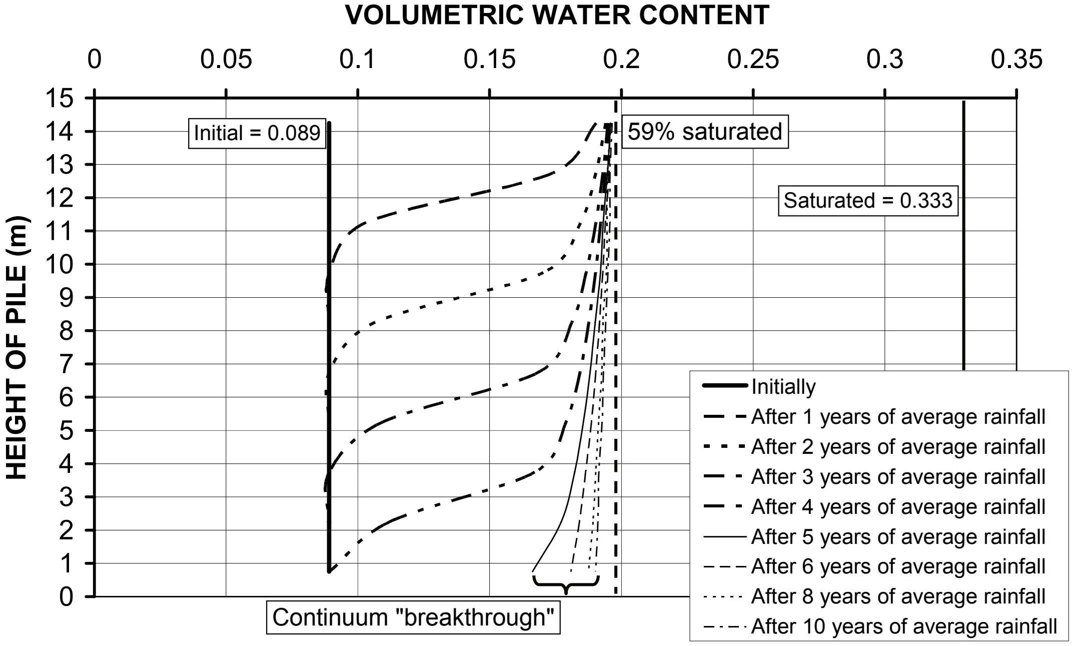

Figure 5 Estimated wetting-up of Cadia trial weathered waste rock dump for average annual rainfall of 900 mm

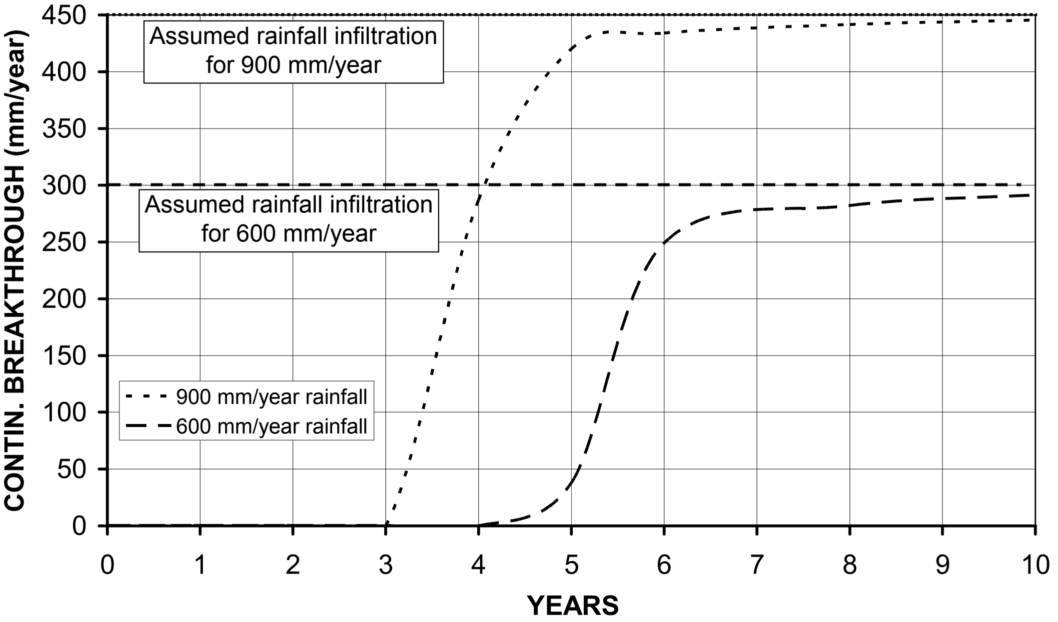

Figure 6 **Estimated continuum breakthrough for Cadia trial waste rock dump**

Figure 7 shows the predicted hydraulic conductivity at breakthrough as a function of annual rainfall for weathered waste rock and various proportions of rainfall infiltrating.

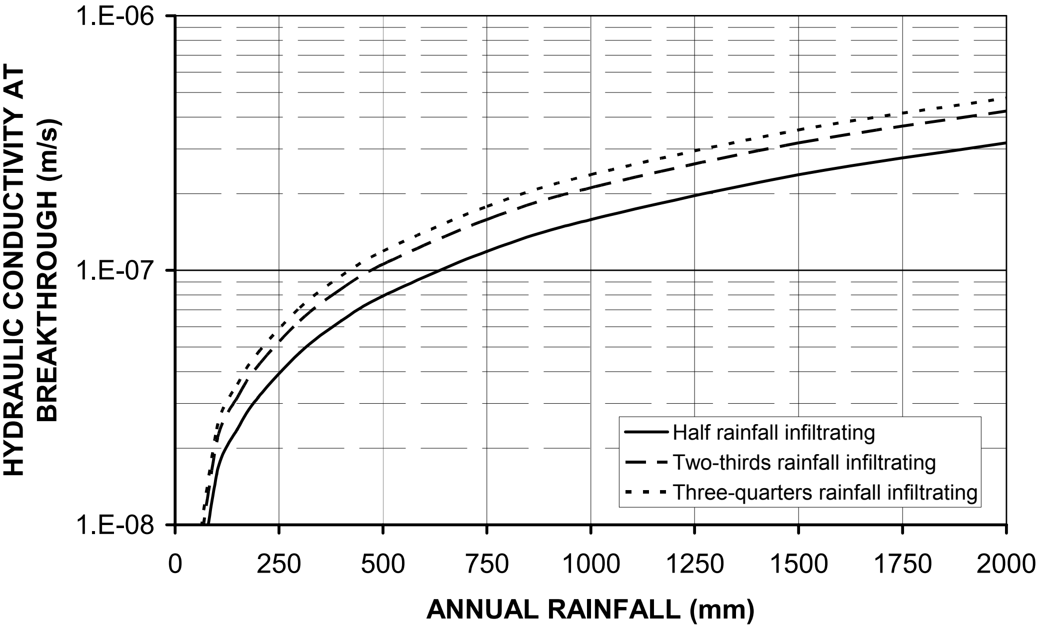

Figure 7 **Predicted hydraulic conductivity at breakthrough as a function of annual rainfall for weathered waste rock and various proportions of rainfall infiltrating**

3.3 Estimation of Ongoing Waste Rock Dump Seepage Post-Closure at Kidston

Closure of the mineralised waste rock dumps at Kidston involved the construction of low percolation, vegetated, store/release covers over the flat top surfaces of the dumps, which have been shown to limit percolation into the dump to generally < 1% of annual rainfall (Williams et al., 2006). The store/release waste rock dump covers were completed in late 2001. Since then, seepage from the toe of the waste rock dumps has been monitored and found to be decreasing exponentially. From this data, and the estimated continuum breakthrough amount from Figure 4 after 15 years of it being uncovered, the seepage flow rate and volume have been estimated as shown on Figure 8. It can be seen from Figure 8 that it will take an estimated 17 years (to the end of 2018), before the seepage flow rate emanating from the covered dumps matches that percolating through the cover. The equilibrium seepage volume at that stage will mainly comprise that which infiltrates through the sides of the dumps, and should be relatively clean.

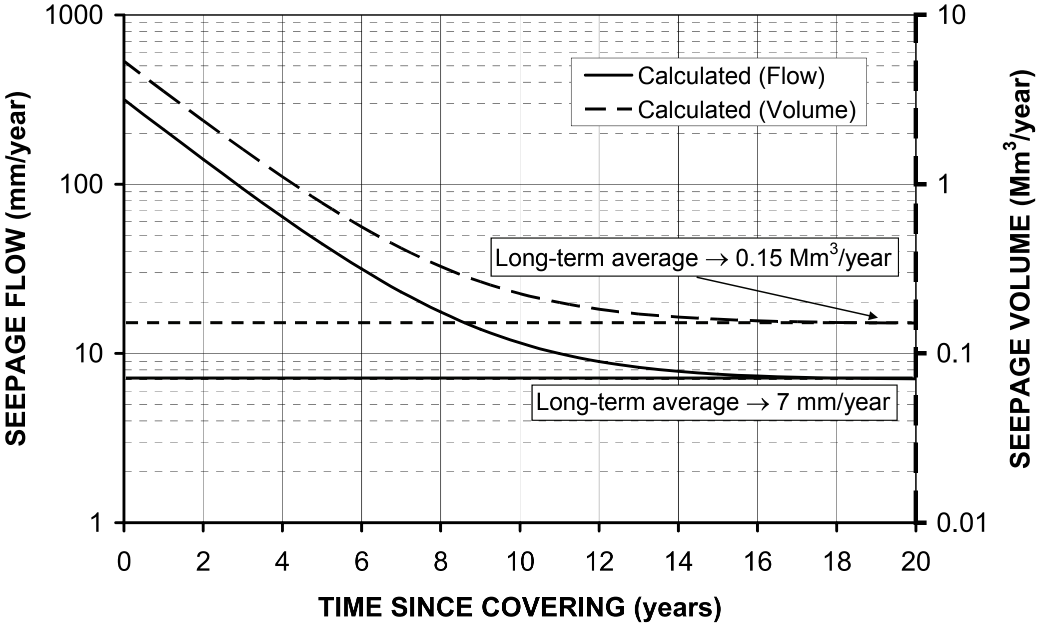

Figure 8 **Predicted decline in Kidston waste rock dump toe seepage**

3.4 Measured Percolation at Cadia

The 15 m high, 7100 m², 200 kt trial waste rock dump at Cadia Hill Gold Mine was completed in late-January 2006, and the rainfall and base lysimeter flows have been continuously monitored since via electronically-recorded tipping buckets. Automated measurement of the moisture content of the waste rock was not attempted, since its coarse particle size and relatively low saturation even at breakthrough prevented this.

Of the nine lysimeters located beneath the traffic-compacted top surface of the dump, only three have recorded any flows to date. The flows have ranged up to 12% of cumulative rainfall and have averaged 1.6%. Of the 15 lysimeters located beneath the angle of repose side slopes, 10 have recorded flows to date. These flows have ranged up to 13% of cumulative rainfall and have averaged 4.1%.

Figure 9 shows the detailed average responses of the top and slope lysimeters to 77.8 mm of rainfall over two days in mid-February 2006. Immediate preferred pathway base seepage beneath the side slope averaged 0.790 mm or 1% of rainfall (ranging up to 4.390 mm or 5.6%), with negligible immediate preferred base seepage beneath the flat top surface of the dump. Delayed base seepage over 30 days averaged 3.687 mm or 5% of rainfall (ranging up to 11.630 mm or 15%) beneath the side slope, and averaged 2.673 mm or 3% of rainfall (ranging up to 21.63 mm or 28%) beneath the top of the dump. Overall, the total average base seepage attributable to the two-day rainfall event was 6% beneath angle of repose side slope and 3% beneath the traffic-compacted, flat top surface of the dump, with the majority of the rainfall infiltration into the dump going into storage within the dump. Ultimately, as the dump wets up, a point will be reached at which no further storage is possible and any further rainfall infiltration will report as seepage at the base. At this point, the proportion of rainfall reporting as infiltration will be revealed.

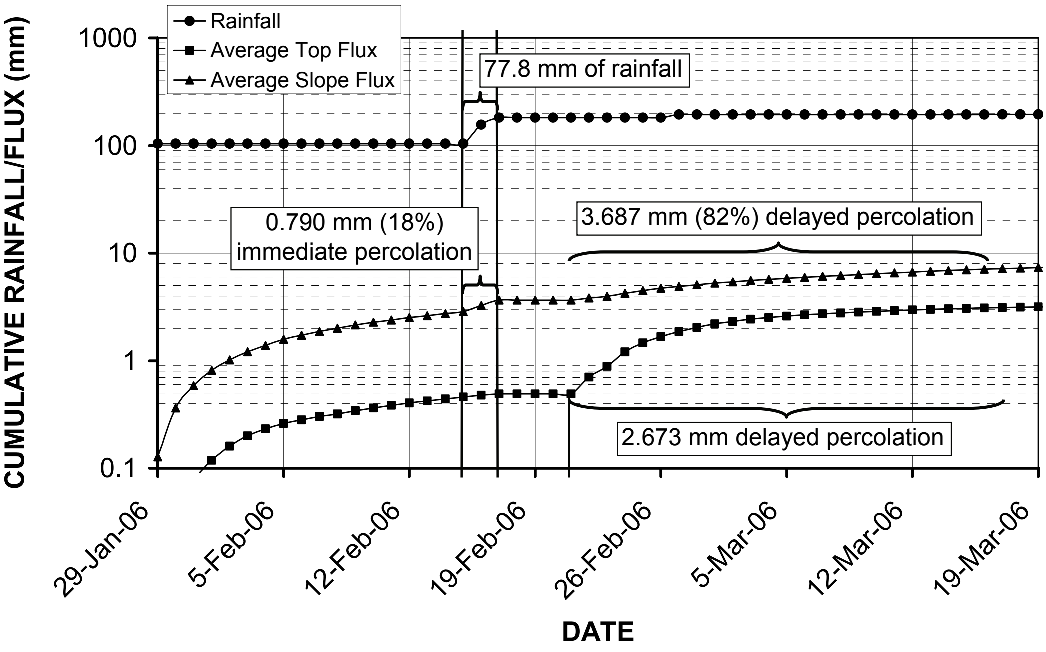

Figure 9 **Cumulative rainfall and infiltration through Cadia trial waste rock dump for 77.8 mm rainfall over two days**

4 IMPLICATIONS FOR WASTE ROCK DUMP CONSTRUCTION

In the planning of waste rock storages, the waste rock must first be characterised physically to assess its likely hydraulic conductivity, and geochemically to assess its potential to generate contaminants such as acidic drainage and salinity. Waste rock falls into two main categories: (i) benign, including weathered (oxidised) rock excavated from above the groundwater table and fresh unmineralised rock excavated from below the groundwater table outside the hallo of the orebody, and (ii) fresh mineralised rock excavated from below the groundwater table within the hallo of the orebody or in other mineralised units. The proportions of the two categories and the scheduling of their excavation will dictate the design and construction of the waste rock storage to minimise the breakthrough of potentially contaminated water at the toe or into the foundation.

The majority of the benign waste rock will typically come from shallow depth in the early stages of the open pit, unless the pit is developed by a series of deep cut-backs. As the open pit develops, the proportion of mineralised waste rock is likely to rise. In order to encapsulate the mineralised waste rock with benign waste rock, the benign waste rock should be selectively used to form a base layer and a wide side encapsulation, with the mineralised waste rock stored beneath the flat top surface of the dump, which is covered to minimise percolation. Mineralised waste rock should not be stored beneath side slopes and intermediate benches, since rainfall infiltration into side slopes will be substantial and cannot sustainably be limited by a fine-grained seal.

The proportion of mineralised waste rock compared with benign waste rock, and the scheduling of the two waste rock streams, will dictate the balance between dump height, area and final side slope required to fully encapsulate the mineralised wastes rock beneath the flat top surface of the dump. Haulage costs will also influence the dump width and height, since the cost of vertical haulage is about four times that of horizontal haulage, and dozing costs will influence the final side slope angle adopted and the selection of post-mining land use.

Ideally, reactive waste rock should be placed in cells constructed to full height and encapsulated with benign waste rock, with the flat top surface of each cell covered as it is completed. This will best limit the amount of infiltration and water storage within the dump, and the subsequent seepage from the dump. It will also minimise the need to stockpile benign waste rock and overburden soils for use in encapsulating and covering the mineralised waste rock.

5 CONCLUSIONS

The conventional storage of waste rock in dumps that are left uncovered for the life of the mine causes a wetting up of the waste rock and an eventual breakthrough to the foundation during operation. Any seepage from the toe of the dump or percolation into the foundation will continue for many years, even after an effective low percolation cover, such as a store/release cover, has been constructed. Reactive waste rock should therefore be placed in cells constructed to full height and encapsulated with benign waste rock, with the flat top surface of each cell covered as it is completed to limit wetting-up.

The planned continued monitoring of the base lysimeters underlying the trial waste rock dump at Cadia Hill Gold Mine will ultimately reveal the proportion of rainfall reporting as infiltration.

ACKNOWLEDGEMENTS

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