Are You Doing All You Could Be to Optimise your Closure Alternatives?

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ABSTRACT

Characterisation and assessment of waste rock has been the subject of considerable research, with the publication of a sizeable body of international guidance documents. Although detailed information exists for geochemical characterisation of waste rock, there is limited detail on how to integrate these studies into engineering planning decisions around waste management options. A quantitative assessment is required to balance environmental management risks and operational cost constraints to facilitate planning decisions.

Current industry practice, and the majority of guidance documentation, focuses solely on geochemical classification, without the subsequent connection to engineering planning. Hence, a disconnect exists between study outputs and operational requirements for placement method risk and cost assessment.

A quantitative assessment methodology is required to determine risk/cost of various waste management approaches. This assessment must consider the complex interplay of factors influencing water quality at operations in long into closure. Only once these contributing factors to water quality are quantified can one appropriately understand, and quantify, risks associated with closure; in short, to properly Plan for Closure by achieving close alignment with mine planning and closure planning.

This paper provides an overview of an assessment process based around a quantitative risk tool to now allow the mining industry to accurately assess the risk/cost trade-off of waste management to water quality. The assessment process captures multifaceted inputs, and employs an analytical model to provide quantitative analysis and outputs. Quantitative analysis and outputs allows risk to be assessed based on waste placement technique and facility engineering design; not solely material properties. Our approach allows assessment of progressive management measures against a deferral of all risks to final closure solutions, such as cover systems and/or mine effluent collection and treatment

1.0 INTRODUCTION

This paper asks the question: "Are you doing all you could be to optimise your closure alternatives?" The focus of this paper is technical; however, to address the question posed in the title, as well as the proposed follow-up question, context is needed. In short, whether or not one is "preparing well enough", comes down to a question of risk acceptance. That is to say, to what extent will you encounter unrecognised and unfunded liability during closure, or when undertaking detailed closure planning leading up to closure? Typically this liability manifests as water quality issues resulting from geochemical and hydrologic processes occurring within waste storage facilities. Hence, in the context of mine closure planning, it is often challenging to undertake closure while meeting the proposed commitments of the mine's licenses and/or bonds; effluent collection / treatment and sludge management practices illustrates this challenge. The majority of sites surveyed reported that there was an expectation to treat in perpetuity. As such, the mine's choice of treatment is critical not only for economic but also for environmental reasons. That is not to say that these sites are not economic, or weren't economic; rather, that because of unfunded and unrecognised liability during mine planning and operations, a liability that was only fully recognised as part of more focused closure planning efforts. In short, in the context of achieving typical mine closure objectives, these projects are not economically optimised. The examples of additional cost and/or liability as reported in MEND (2013), beyond that which was anticipated during feasibility, mine planning, and operations, and is a common occurrence across the mining industry worldwide. Clearly then, there is an economic impetus to addressing this potentially unfunded and unrecognised liability associated with mine effluent water quality (and flow) such that the mining industry can move towards and economically optimising projects.

2.0 METHODOLOGY

To address encountering unfunded and unrecognised liability at closure, the mining industry is moving towards an appreciation for aligning feasibility studies and mine planning, with closure planning. To optimise the economics of a project, this alignment must occur early, and often, during feasibility studies and mine planning so that there is an opportunity to incorporate community / stakeholder expectations and closure objectives in the most economic manner. The most appropriate tool to manage and communicate these multi-faceted issues is a transparent risk-based process. Holistic risk based decisions, using a transparent risk process that includes common failure modes known to arise when implementing closure measures, then allows for mine planning and closure planning to align along realistic time frames.

It is often challenging for mine closure planning practitioners to effectively communicate to mine planners that there might be value, or economic benefit in building, for example, a waste rock dump (WRD) "differently". This is because the mine planner is very often answering a "different question" than being asked by a mine closure planning practitioner. Mine planners typically tasked with optimising ore grade, extraction, blending, etc. for the lowest cost possible; and time frames are typically life-of-mine (LOM). In contrast, a mine closure planning practitioner does not function on a LOM time scale; rather, it is a mine-life cycle time frame, where the realities of closure planning are often brought forth by communities and stakeholders that are highly knowledgeable and possessing an understanding for longer term closure liability (i.e. longer that LOM).

The key then is to "change the question" such that mine planners and closure planners are working within the same time frame, which is fundamental to effective, transparent, and holistic risk management. Changing the question allows a mine planner to, for example, not be limited to: "building the lowest cost LOM WRD …***OR***… minimising contaminated mine water effluent". Rather, the mine planner is provided the opportunity to: "optimise construction of the LOM WRD…***AND***…minimise risk (environmental and economic), which can result from generation of contaminated mine water effluent. The "OR" question is not necessarily "wrong" as it drives us to be compliant and efficient; however, the "AND" question drives us to be effective and sustainable.

Appropriately addressing this "New Question", from a technical perspective, is not a trivial challenge. However, the following presents a quantitative assessment approach to addressing this new question. The assessment approach has been developed by the authors of this paper such that the benefits of aligning mine planning and closure planning when designing a WRD can be understood, quantitatively.

2.1 Mine Waste Rock Management Assessment Tool

The overarching principle, or foundation, of the author's mine waste rock management assessment tool is that the physical setting and characteristics of mine waste rock within a WRD are as important, if not more important, as the geochemical characteristics in influencing effluent water quality, water flow, and the evolution of both.

Characterisation and assessment of waste rock forms the initial stage of waste management strategy planning. Prior to decision making, waste management strategies should evaluate both costs of waste management and risks associated with exposure, stockpiling and placement of waste materials, such as spontaneous combustion, toxic gas production, and AMD. These risks are complex, are all interrelated, and are associated with air and water entry into the waste material where subsequent oxidation reactions occur (Lottermoser, 2010).

It has become common practice in the industry as part of waste characterisation to classify material in a deterministic manner on the basis of primarily geochemical risk factors and to define material types, for example, as potentially acid forming (PAF). Material that is determined to pose significant risks for AMD, such as PAF is then prescribed a specific management method such as "encapsulation" as part of a placement strategy to reduce potential AMD risks. However, this assessment method is prescriptive and polarised as materials are categorised into a few catch all categories. For example, material categorised as PAF results in polarised decisions, such that all PAF must be managed in a set manner even though a range of risk across the category is possible.

AMD risks are known to be complex and interrelated; they are strongly related to the structure of the WRD and how this influences oxygen transport and water flow / storage into and within the WRD, where subsequent oxidation reactions can occur. The influence of airflow, water flow and storage, and the site specific diurnal or seasonal variations in these are key risk drivers.

Geochemistry forms only one of the many risk factors. However, the typical industry approach to AMD assessments is for the study to be based for the most part on laboratory testing related to geochemical properties only. A simple summary of this observation is to state that although the characterisation of materials is important, the method and timing of placement, and the site environment in which they are placed are perhaps more important variables; and are often disregarded in the typical industry approach for assessing AMD risk.

To evaluate risk based on multifaceted variables requires application of semi-quantitative analysis. The authors of this paper herein have developed an assessment process based around a risk matrix that captures these multifaceted inputs and employs an analytical approach to provide semi-quantitative analyses and outputs. This method of assessment allows risk to be assessed on the basis of placement technique and not just on material geochemical properties in isolation. A full description of this method is outside the scope of this paper and is described in detail in Pearce *et al* (2015a). In summary, the assessment process is based around a quantitative risk assessment tool that utilises a series of complex algorithms and connections of processes to assess how waste materials will react to placement in a given scenario. Outputs from the assessment tool are then collated into a risk matrix that captures these multifaceted inputs. This method of assessment allows risk to be assessed on the basis of placement technique, and incorporation of closure mitigation solutions, and not just on material properties in isolation. The assessment tool developed evaluates advective gas transport, intrinsic oxidation rate(s) (pyrite and carbon) spontaneous combustion, seepage, water storage, carbonate dissolution rate, and acidity generation.

2.2 Waste Rock Dump Construction and Links to AMD Seepage Risk

Construction of WRDs generally includes one, or some combination of the following methods: end-tipping, paddock dumping, push-dumping, or encapsulation. The specific method used on a given site to construct the WRD is generally based on availability of equipment, cost and the scale of construction; hence, construction methods are far from uniform across all sites.

Some aspects contributing the largest AMD risk are typically overlooked. For example, construction using end tipping methods results in unfavourable hydrogeological characteristics to control air (oxygen) and water flux throughout the waste material. Given that oxygen and water flux are major controls in the production and release of AMD to the receiving environment, WRD construction is clearly a very significant variable to factor into AMD risk.
The waste rock placement strategy to address AMD risk focuses on minimising oxidation of sulfide minerals during waste placement. By placing waste rock in a manner to minimise stored oxidation products (or more appropriately, stored acidity), long-term reliance on a cover system and/or mine water effluent collection and treatment as the "sole" means of managing seepage from a WRD is reduced, or eliminated entirely. At the very least, the length of time over which a cover system and/or mine water effluent collection and treatment is required is substantial reduced by minimising airflow capacity within a WRD while it is being constructed. Minimising oxidation of sulfide minerals involves strategic placement of run-of-mine (ROM) waste such that advective gas transport within the WRD (i.e. oxygen transport) is limited because airflow capacity (air permeability) is controlled. The primary airflow mechanism being addressed by utilising this strategy is convection, which results from a temperature differential within, and external, to the WRD. This management strategy also allows operators to selectively, and cost effectively, manage highly reactive materials being placed in a WRD and the potential for elevated temperatures (e.g. spontaneous combustion).

3.0 CASE STUDY

The Martabe gold and silver mine in the Province of North Sumatra is operated by Agincourt Resources. The mine is situated approximately 40 km south of the port of Sibolga. The primary Waste Rock Storage Facility (WRSF) is integrated into, and being developed as, the main downstream containment structure of the tailings storage facility (TSF). The WRD will include all mine waste, including PAF waste rock, from open pits. There are currently two active pits, and over time additional pits are expected to be brought on line as exploration and resource development activities are progressed.

3.1 *Waste Rock Management*

A detailed waste rock management plan has been developed by OKC and Agincourt Resources technical teams (mine geology, exploration, mine planning, TSF) for the Martabe mine. The plan provides technical guidance for specific aspects of waste rock management during the development and operational phases, and an overall framework for the management of waste materials during construction of the TSF.

Agincourt Resources have developed a significant materials characterisation database through geochemical characterisation of the waste rock. Several sources of geochemical data were available to develop the risk-based waste rock classification process flow methodology for operational use in characterising blocks of waste rock.

Waste classification and subsequent modelling into discrete class system in the reserve model and schedule have been designed to take into account the broad characteristics of the deposit and translate this into a means of identifying material based on predicted AMD risk, potential utility for use in construction (i.e. also the physical characteristics of the mine waste material, such as materials more amenable to compaction for example), and potential acidity buffering (presence of carbonates such as calcite).

A detailed mine waste schedule has been developed for the site based on the waste classification system and identifies the sources of materials over LOM to ensure that the build plan can meet the design specification. It is therefore important that the mine schedule and LOM build plan reference each other to ensure the successful management of waste requiring management as it exits the pit. Scheduling is important to be carried out over LOM because design specification indicates that construction of the layers that are key to managing airflow capacity within the WRD is key to managing sulfide oxidation..

3.2 *The Progressive Encapsulation Method and Oxygen Ingress Assessment*

The conceptual model for assessing AMD risk assumes that oxygen availability to PAF waste rock within the WRD is dominated by diffusion rather than advection. This is primarily because of the manner in which the WRD is constructed, as well as the design taking advantage of the site's high rainfall characteristics.. Key to this is creation of advective gas barriers, or "sealing layers", such that encapsulation of the PAF waste rock in cells is meaningful in terms of the availability of oxygen for sulfide oxidation. These "engineered tension saturated layers" across the surface of the embankment during WRD construction limit oxygen ingress and thus AMD production and release.

Figure 1 shows the engineering concept, with PAF material being progressively encapsulated during construction on a lift by lift basis. The lifts are constructed as part of the embankment raise are 10 m in height, and waste is placed in 1m thick compacted layers.

OKC completed a detailed modelling study of advective airflow within the WRSF LOM design using numerical modelling tools coupled within the GeoStudio (Geo-Slope International, 2012) software suite: TEMP/W, AIR/W, and SEEP/W (Pearce 2016). Surface infiltration seepage rates were calculated using VADOSE/W. The objective of the numerical modelling program was to develop guidelines for waste placement.

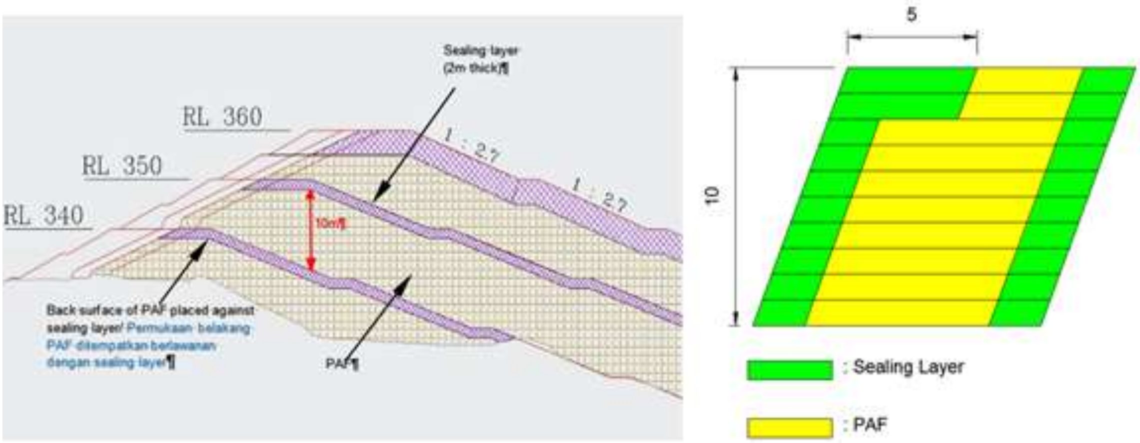

Fig. 1. Progressive encapsulation method design used as basis for modelling assessment

Key conclusions from the airflow modelling work include:

- Advective airflow rates are substantially lower than diffusion rates as a result of the WRSF "wetting up". As long as the material maintains sufficient saturation, advection will not contribute a significant source of oxygen for oxidation.
- Oxygen ingress due to thermal convection cells is anticipated to be low, even with elevated internal WRSF temperature and low degree of saturation conditions (worst case scenario).
- The placement of high grade sulfide sulfur near the outlying slopes of the landform should be minimised.
- Oxygen ingress was shown to be substantially decreased by the presence of the sealing layers. Oxygen ingress varied greatly for the material depending on the texture of the material, its water retention characteristics and the assumed in-place dry density.
- With increased as-placed waste density a decrease in oxygen ingress results. Additional compactive effort produces increased density leading to decreased porosity, increased air entry value and water retention, and a decreased hydraulic conductivity. All leading to an increase in the degree of saturation of the encapsulation system materials and decreased oxygen ingress rates.

Results from the numerical modelling program were used to inform waste material placement guidelines encompassing the range of potential waste and operational interim cover system materials (i.e. the sealing layers) for the interior of the WRSF. Material envelopes were developed based on particle size, and included the geotechnical specifications required for the as-constructed sealing layer to reach the specific targets for oxygen ingress.

3.4 *WRSF Concept Validation*

PT Agincourt initiated a program to validate the WRSF engineering design concept in 2015, with the objective of confirming that sulfide oxidation within the WRSF embankment is being reduced due to the implementation of the waste rock management concept. Validation work to date has consisted of OKC designing and installing monitoring systems within the sealing layer profile at two locations, and monitoring temperature gradients, oxygen concentration, pore-water pressure, volumetric water content (VWC), and matric potential.

Preliminary monitoring data indicates that performance of the sealing layers are akin to the conceptual model and as per modelling predictions. VWC and suction data are indicative of material that is maintaining a high degree of saturation (above ~80%). Oxygen concentrations within and below the sealing layer are reduced to near zero (Figure 2).

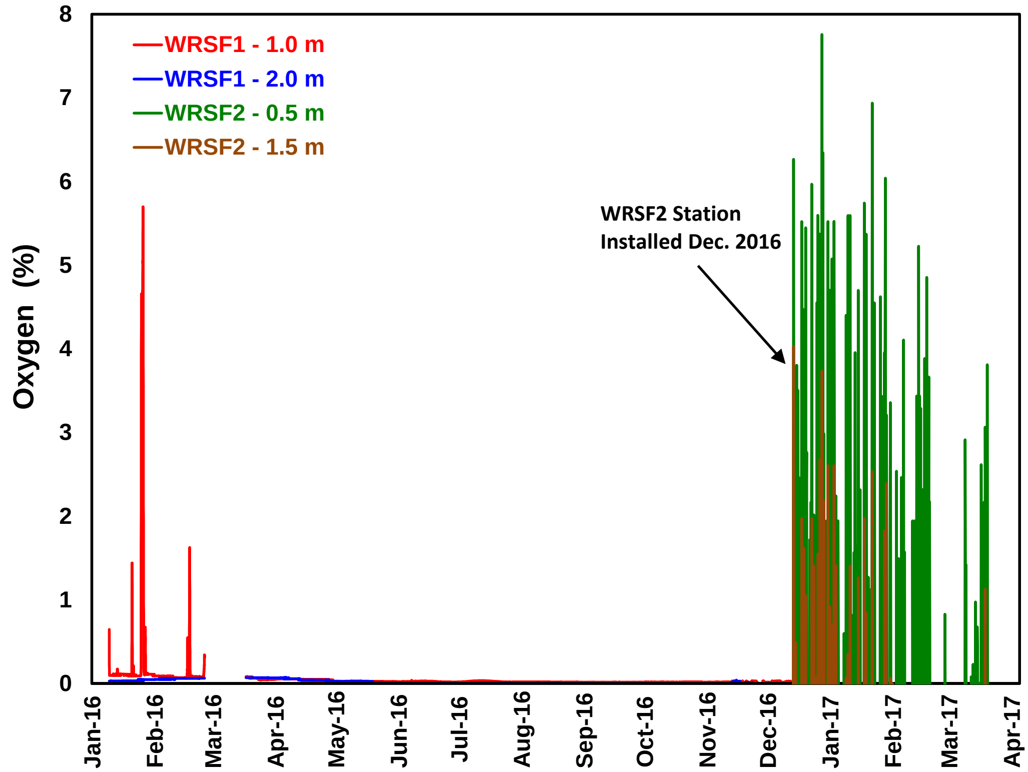

Fig. 2. Oxygen concentration within WRSF sealing layer.

Material characteristics and monitoring data collected during the 2016 monitoring period, were utilised to develop estimates of a range of air permeability (k_{air}) for the field for the various material envelopes at the Martabe site under a range of dry density values (Fig. 3), which is an important facet in understanding the potential air permeability. *In situ* dry density significantly affects the achieved field k_{air}, as illustrated in Figure 5. The estimates in k_{air} shows that material can have up to an order of magnitude decrease with increases in compaction effort.

When the degree of saturation is maintained above 75%, air permeability is lower than 1×10^{-10} m^2, which limits the dominant oxygen ingress mechanism to diffusion, irrespective of the envelope the material falls in. There is inherent flexibility in the construction of the WRSF sealing layers given that if sufficient finer-textured material is not available, oxygen ingress targets can still be achieved through application of increased compaction effort.

4.0 CONCLUSION

This paper presents a technical framework, for LOM development of a WRD whereby the waste placement methodology is viewed as being as important, if not more important, to closure performance, as compared to a final (closure) cover system and mine effluent collection and treatment. The approach clearly illustrates that creating a physical environment within the WRD that addresses the risks presented by the reactive waste material, represents a fundamental shift in the typical approach to managing reactive mine waste. This framework was successfully utilised for the case study site to mitigate AMD risk. It is clear that an assessment of WRD construction requires consideration when final closure solutions, such as cover systems or mine effluent collection and treatment are being selected and relied upon as the main closure mitigation solution for AMD management.

It is notable that to date the strategy has proven to be compatible with the case study mine plan, is logistically feasible, and cost effective. The strategy has been validated to date by detailed *in situ* monitoring studies, with close alignment between modelled and measured performance.

With the technical framework presented here, the industry can now quantify the relative difference in waste placement techniques. Our technical framework represents a substantial advancement in mine waste rock management. The advancement our framework produces is due to the risk / cost trade-off assessment of how WRDs are constructed, how that can be completed at the mine planning stage, and the improvement to mine closure risk and cost estimation. In summary, this paper presents an economic discussion, as well as a quantitative technical framework, which together allows mine operators to appropriately quantify the benefits of closely aligning mine planning and closure planning early on within the mine-life-cycle, and during LOM.

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