What Does "Perpetual" Management and Treatment Mean? Toward a Framework for Determining an Appropriate Period-of-Performance for Management of Reactive, Sulfide-Bearing Mine Wastes

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Abstract Mine wastes, typically millions to billions of metric tonnes and occupying hundreds to thousands of hectares, will remain geochemically reactive for centuries to millennia. Establishing a coherent basis for determining how far into the future proposed mine-site closure must be effective has too often been neglected. Consideration of closure stages, closure risks, and engineering practice suggest that a planning period for management of mine wastes should be nominally 200 years. It should include a semi-quantitative assessment of whether or not major changes in performance are likely to occur between approximately 200 and 1,000 years.

Keywords Perpetual management; design-basis; extreme events; engineering plans *vs.* discounted costs; 200 to 500 and 1,000 years

Introduction

At the time of closure, hard-rock mine wastes, typically including waste rock/overburden and tailing, typically range in mass from a few millions of metric tonnes for small underground mines or heap-leach systems with modest lifetimes to billions of metric tonnes for large, long-term open-cut mines. The waste management units occupy hundreds to thousands of hectares of surface, with some structures at large, end-dumped rock piles extending over several hundreds of metres of vertical relief. If infiltration were 20 % of average annual precipitation of 1,000 mm/a over a waste-rock system covering 500 ha, the steady-state effluent would be 1×10^6 m^3/a, a very substantial volume to be treated if the water is low-pH, high-SO_4 solution with a range of dissolved metals above discharge criteria. Even if a cover system were to reduce that net infiltration by 90 % and one were to allow for ranging flows associated with variable flow paths, for large waste-rock storage systems the water-treatment demand is very significant.

For mine wastes in which the pyrite content is greater than a few tenths of a weight percent, reaction rates for pyrite oxidation are so slow that pyrite will remain active for periods of hundreds to thousands of years, and in many cases much longer.

- Example 1: There is a record of sulfide mining in the Iberian Pyrite Belt that extends at least 4,500 years (Leblanc *et al.* 2000). Massive-sulfide copper deposits of the Eastern Mediterranean were major sources of copper in the Homeric Bronze Age, and they continue to be reactive today
- Example 2: In erosional scars exposed in Quartz-Sericite-Pyrite altered volcanic and intrusive rocks in the Red River Valley, northern New Mexico, the radiometric dating of jarosite and alunite formed by oxidation of pyrite in these scars indicates that pyrite has been reacting *in situ* for periods of 30,000 to 1.5 million years, yet such altered rocks still retain much of their original pyrite. Calculated depletion

times for waste rock there range from ca. 1,500 a to more than 100,000 a, based on plausible alternative models for the hydrodynamics of the waste-rock piles (Logsdon 2011)

Engineered Waste-Management Systems: Design Basis and Extreme Events

Background

For waste-management units at mine sites, closure and reclamation of waste rock or tailing will be designed, built, and maintained to achieve specific reclamation goals. Performance of the engineering structures and related reclamation actions, including seepage, slope stability, erosion control, and re-vegetation, must be sustainable into the future. This section addresses the time frames that are expected for reclamation activities and proposes a design time frame for long-term period of performance of the reclamation.

Engineering structures, including mine structures, are designed to perform with respect to some specific design criteria related to the natural environment, often organized around response to external forces with statistically-defined probabilities of occurring per unit time (equivalently, as "return periods for an event of a given magnitude"). For example, it is usual for hydraulic structures for a specific catchment to be evaluated in terms of runoff resulting from a specified precipitation event (*e.g.* precipitation over a 24-hour period) with a specific return period, *e.g.* 100 years (equivalent to a probability of 0.01/a for such a flow). Similarly, it is common for seismic stability of embankments or rock-pile slopes to be assessed in terms of expected deformation for site-specific seismic events with defined recurrence intervals. In the terminology of geotechnical engineering, one speaks of "design-basis events" and also considers the risks from "extreme events", incorporating both into the detailed design criteria for an entire project that ultimately will be defined and, of course, executed.

To be useful for establishing design criteria, the return periods need to be considered (a) in terms of the duration of relevant activities at the mine and (b) in terms of the consequences if an event were to occur. For example, if a mine had a projected remaining operating life of 20 years, then the binomial probability of a 100-year event occurring in the remaining lifetime of the mine would be 18.2 %. To assess the need for considering large and extreme events, one must therefore consider the relevant time frames for the closure and reclamation activities associated with the waste-management facilities that are required on a site-specific basis. The implications are not often calculated. Suppose that it was decided that the mine reclamation activities needed to be fully functional for 200 years, with a less than 10 % probability of a failure over that period. From a simple binomial model, the design-basis events that need to be accommodated then amount to 2,500-year recurrence intervals, and it is clear that design-basis events such as one-in-a-hundred-year storms will be expected with probability = 1.

Timeframes for Reclamation and Post-Closure Maintenance

There are three reclamation periods that are relevant to establishing a design framework:

1. The period of construction and active reclamation. During this period, there would be active use of heavy equipment to construct the stable forms of the piles and to place any covers. This also is the period of active planting and cultivation essential to the phased re-vegetation of the rock pile surfaces. Based on consideration of the surface areas, volumes and terrains, and using industry-standard assumptions for equipment and manpower, it is expected that the active construction and reclamation period for significant waste-rock piles would require up to 20 years, depending on detailed planning factors, such as how many rock piles can be reclaimed simultaneously. Because the mining company would have a substantial

work force and a large and varied fleet of equipment on hand, maintenance requirements, even substantial rebuilding efforts if they were required, could be managed efficiently.

2. The final reclamation plans typically will require successful establishment of woody species to ensure shallow slope stability and to provide the effective evapotranspiration needed for the cover design to achieve a long-term goal of minimizing net infiltration. Based on experience with reclamation and re-vegetation on mined-rock piles, it is expected that the development of the final, sustainable, vegetative cover would require a period of another 10 to 30 years after the end of the active construction period.

   Following completion of the original re-sloping and reclamation activities, one would expect that equipment and personnel would gradually be reduced to an ongoing maintenance level. Such a team would be capable of handling the level of work associated with ongoing maintenance of the berms and benches on rock piles, however for a major rebuilding effort, if required, the mining company would have to contract outside services, including engineers and major earth moving equipment.
3. Beyond the period of reclamation of up to 50 years, the mining company should anticipate that there will be a period of long-term maintenance and monitoring that will document that the expectations for stable slopes with controlled water-quality performance have been met.

Consideration of Risk in Light of Maintenance Capabilities

The period of greatest vulnerability for the re-sloping and reclamation will be the early days of construction, before re-vegetation would be effective at stabilizing the shallow portion of the slopes. Fortunately, this is the period when the mining company will have the greatest capacity to respond, because the large-scale equipment and large work force will remain on site.

As the workforce and equipment inventory are drawn down, a more formal plan is required. During the longer-term reclamation and post-closure maintenance period, we consider it reasonable to evaluate conditions in terms of the consequences that would ensue from events, particularly hydraulic events, of certain magnitudes. If the events are ones that produce consequences that can be repaired as a matter of course by the maintenance approach, then this represents one set of conditions. If, on the other hand, the consequences of a specific event required a substantial or complete rebuild of the originally-designed closure facilities, then a major intervention would be required, and that would be another class of risk entirely.

We propose the following framework:

- If an event produces geotechnical and hydrological consequences that (a) remain entirely on the Mine property and (b) can be repaired by the available maintenance team in a period of ≤6 months or less, with minimal engineering supervision, then the consequence will be considered "amenable to maintenance".

  For portions of reclaimed rock-pile slopes to have conditions "amenable to maintenance", we propose that the system and subsystems (*e.g.* surface-water conveyances on benches) be designed to control events with a recurrence interval of 100 years. This requires that the long-term maintenance capacity of the Mine's closure program must be equipped and trained to manage impacts to the design-basis slopes and covers from events with recurrence intervals up to 100 years. For example inter-bench surface-water conveyances would be designed to pass the 100-year event, because the expected consequence of failures (minor erosion from overtopping of a lift) would fall within the range of simple repairs that would be expected of maintenance.

- If an event produces geotechnical or hydrological consequences that (a) extend off the Mine property and (b) cannot be repaired within 6 months using the available equipment and manpower, then the consequences would require rebuilding.

The Mine presumably intends that, after all the work that will go into managing the rock piles to be "safe and stable," there would only be a very small probability of consequences off site. For the purposes of discussion, we propose that the design-basis events that would yield off-site impacts or major rebuilding would have a probability of occurrence of less than 10 % during the proposed 200-year period of performance. Based on a binomial model, this means that the design basis for critical structures that would limit consequences to off-site-only impacts must be the 2,500-year recurrence event.

For comparison to a time-frame analysis focused primarily on financial assurance rather than trictly on engineering, readers will wish to consult Kempton (2003).

Period of Performance

There is no industry standard for such a long-term performance of closed mine facilities, nor are there established regulatory criteria for rock piles. The only geotechnical systems for which there has been extensive analysis of long-term periods of performance is for the mining and milling residues controlled under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 (P.L. 95–604). The regulatory standard requires that control of tailings "shall be effective for up to 1,000 years to the extent reasonably achievable and, in any case, for at least 200 years" (EPA, 1983). The UMTRCA time frames were established to consider periods over which climatological and geomorphic processes could reasonably be predicted, given current knowledge of earth science and engineering. In a review of the technical basis for the regulations, the National Research Council, the contracting-review arm of the U.S. National Academy of Sciences, concluded that the 200-year period was consistent with our knowledge of the longevity of engineered systems, but that estimates looking forward 1,000 years must be thought of as qualitative and inherently uncertain.

The Academy has recently returned to this topic in an updated review of the performance of engineered barriers for waste management (NRC 2007). The general conclusion of the NRC is that up to 20 years of field observations indicate that engineered waste-containment systems designed, constructed and maintained appropriately meet or exceed their intended performance. However, NRC notes that the demonstrated period of performance for such systems remains only a few decades, and that longer–term monitoring will be needed to show that performance over hundreds of years can be achieved reliably across the range of waste-management alternatives currently in service. A key finding of the recent study is that on-going maintenance is required (Mitchell 2008).

Industry-standard practice by mining companies and their technical advisors considers that engineered covers, such as a stable, very low erosion slope with a low-net infiltration, sustainable re-vegetated cap can be established. Given the exploration, development and operation history of the mine and an expected construction and reclamation activity on the order of 50 years, there will be nearly 100 years of geologic and hydrogeologic data available for most modern mines. It seems entirely reasonable to project that time period forward and to establish a goal of 200 years performance for the engineered closure system at modern mines, in keeping with the rational of the National Academy.

Conclusions

Consideration of these periods, the scientific basis for understanding closure risk, and established engineering practice leads us to suggest that a reasonable, total planning period for management of mine wastes should be in the range of 200 years, and it probably should include a semi-quantitative assessment of whether or not major changes in performance are likely to occur between approximately 500 and 1,000 years. Plans should include (1) identification of risks to surface and groundwater in terms of adverse impacts to beneficial uses, (2) presentation of a case that mine-waste structures would be stable with respect to erosion by flooding or deep-seated shear failures, and (3) presentation of a case that reactive wastes as disposed for those periods will remain physically stable.

The mine waste will remain a hazard beyond routine monitoring periods, and mine sites may cease operations under one owner through abandonment, bankruptcy, mergers and acquisitions. Therefore waste management plans need to address how responsibilities will be executed in the future. If there is an expectation of a transfer of authority (*e.g.* to the State or a landowner), there should be an explanation of how and by whom this will be (a) funded and (b) physically executed. Furthermore, if original operators are no longer available, there must be clarity as to how and by whom closure obligations will be executed. The closure explanation should show that the proposed successors both understand the nature of the burdens and are capable of executing the management responsibilities over the design-basis time that is established for the specific project.

Although this discussion paper is framed scientifically in terms of sulfide oxidation, the geochemical consequences of concern for mine-waste management include all potential classes and outcomes of reactivity. This includes not only acid-rock drainage and metals leachability, but also neutral drainage with elevated metals or salinity, as well as special classes of geochemical reactivity such as release of nitrogen species from explosive wastes in mined rock, release of selenium from black shale, arsenic mobilization due to reductive dissolution of As-bearing ferric phases, airfall of soluble, smelter-produced solids to soils, and other matters. The nature of the geochemical hazards at a mine site needs to be evaluated in terms of the mineralogy of the rocks, tailing or other wastes (*e.g.* hydrometallurgical or water-treatment sludges), site climate and hydrology, and the nature of sensitive receiving environments (*e.g.* extremely clean site waters or national or traditional heritage sites adjacent to mining operations).

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The specific analysis and recommendations here remain my responsibility.

References

Environmental Protection Agency 1(1983) Standards for Remedial Actions at Inactive Uranium Processing Sites. Federal Register 48/3, 590–606

Kempton, H (2003) Addressing the Dilemmas of Long-Term Mining Impacts Using a Framework of Sustainability and Adaptive Management. 6th ICARD Conference, Cairns, QLD, 12–18 July 2003. Ptroceedings 1048–1052.

Leblanc, M, Morales, JA, Borrego, J, and Elbaz-Pouchilet, F (2000). 4,500 Year-Old Mining Pollution in Southwest Spain: Long-Term Implications for Modern Mining Pollution. Economic Geology 95, 655–661

Logsdon, MJ (2011) Questa Weathering and Stability Study: Geological, Hydrogeological, and Geochemical Framework. Tailings and Mine Waste '11, November 5–9, Vancouver BC. estore.informine.com

Mitchell, JK (2008) Performance of Engineered Waste Containment Barriers. GeoCongress 2008: Geotechnics of Waste Management and Remediation (M.V. Khire, A.N. Alshawabke, and K.R. Reddy, Eds.). American Society of Civil Engineers, Geotechnical Special Publication No. 177, 1–15.

National Research Council 2007. Assessment of the performance of engineered waste containment barriers. National Academy Press, Washington, D.C., 119 p.