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Reclaiming waste rock piles at Bingham Canyon Mine

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Abstract

More than 115 years of mining at the Bingham Canyon Mine has produced over 3 billion tonnes of ore bearing copper, gold, silver and molybdenum and over 6 billion tonnes of mine overburden that cover over 20 km^2 of land adjacent to the major metropolitan area of Salt Lake City, Utah, USA. The waste rock piles were constructed initially by train and railcar haulage in the early 1900s. Waste rock haulage fully transitioned to diesel off-road mining haul trucks by the 1980s. The waste rock piles are very tall and in places approach 520 m of total elevation gain, and until recently, some angle of repose slopes had approached a continuous slope distance of approximately 550 m. Reclaiming these historic waste rock piles presents unique challenges to the operation due to the physical constraints presented by the toe and crest of the piles at Bingham Canyon Mine. This paper discusses the design constraints for grading the waste rock pile slopes to the standard industry design criteria of 3H:1V and the adaptation of site-specific grading of inter-bench slopes, ranging from 2.75H:1V to 2.37H:1V. This paper also discusses the processes undertaken to evaluate viable methodologies for blending and applying the cap and cover to support revegetation, manage erosion, and ultimately minimise acid rock drainage. Lessons learned from the field trials and implementation are included.

Keywords: *reclamation, mine waste piles, mine waste rock dumps, reclaimed slopes*

1 Site description

Bingham Canyon Mine is a large open cut copper mine operated by Rio Tinto Kennecott located near Salt Lake City, Utah, USA. Open cut mining operations commenced in 1904 with an excavation now measuring nearly 4.5 km across and 1,500 m deep. The Bingham Canyon deposit is a large porphyry copper, molybdenum, silver, and gold deposit. Traditional open cut mining methods are employed – salvage of cover materials; drilling and blasting of ore and waste rock; excavation using electric and hydraulic shovels to load large-capacity mining trucks, which haul the material to the crusher; low-grade ore stockpiles; and waste rock piles surrounding the pit.

The mine is located in a high-desert climate, with waste rock piles situated at elevations from 1,600 m at the toe of the East Dumps and can reach elevations near 2,300 m along the crest of the West Dumps. Precipitation ranges from 38 cm to over 70 cm, depending upon elevation.

The waste rock piles are grouped into four primary areas: Bingham Canyon Dumps, East Dumps, West Dumps, and South Dumps. See Figure 1 for the general layout of the waste rock dumps.

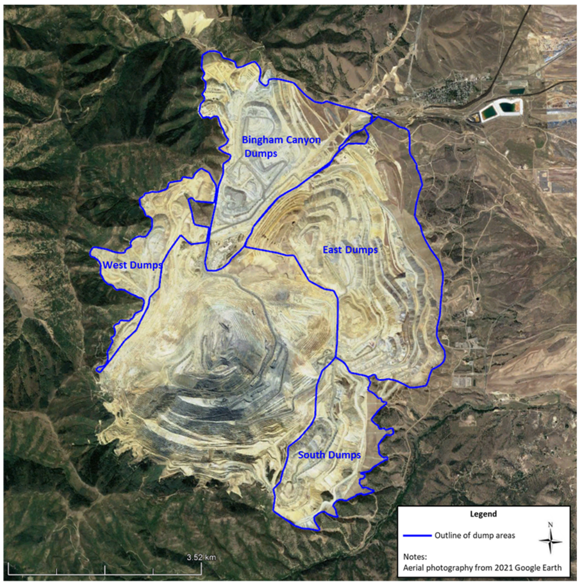

Figure 1 Primary waste rock areas

2 The birth of waste rock reclamation at Bingham Canyon Mine

The first waste rock reclamation efforts at Bingham Canyon Mine were focused on the lower toe of the East Dumps during the installation of the waste rock contact water collection system (East Side Collection System). Waste rock was graded to a variety of slope angles typically not exceeding slopes 3H (Horizontal):1V (Vertical). The cover was a 50:50 blend of native growth media with an elevated carbon content and mixed with sludge removed from the then unlined reservoir below the mouth of Bingham Canyon. The sludge was the sediment remains left over from active waste rock leaching and was high in iron content with a pH below 5. The materials mixed created a circum-neutral pH material that was placed atop the historic waste rock at a depth of 30 to 45 cm.

Between 1995 and 2006, several small waste rock piles in the vicinity of the West Dumps and no longer existing Top Dumps were opportunistically graded and vegetated based upon the mine plan at the time, which indicated no future disturbance in these areas. Segments of waste rock were dosed with limestone to achieve a more neutral pH, but in general, the growth media was coarse and barren of minerals as these areas were further from the orebody and closer to the native forested mountainside. Due to the high elevation, which provided cooler temperatures and considerably more precipitation, grasses, shrubs and trees tended to have a better survival rate than those planted at lower elevations. One set of test plots containing shrubs and seedlings was watered on a bi-weekly basis and experienced success until the plots were ultimately lost to new mining activity.

Reclamation began in earnest at Bingham Canyon Mine in 2006 with a stakeholder obligation to reclaim the first 244 m (total vertical relief) of the newly placed Bingham Canyon waste rock pile within two years of its completion. The 60-hectare area was completed over a five-year period. The inter-bench slope was designed and constructed at 2.5H:1V, which equates to an overall slope of 2.75H:1V. The waste rock is generally placed in 61 m lifts and stepped 87 m to allow for 15 m benches to remain once the slope was relaxed from angle of repose to its final configuration. The grading was performed by mine operations equipment operators, a large percentage of which were experienced dozer operators and assigned specifically to reclamation activities. The experience of the operators helped with quality control, which, at that time, was limited to the judgement of the operator and the instrumentation inside the cab of the equipment. The operators were encouraged to grade the slope to include gentle undulations in an effort to make the slopes appear more natural and less 'man-made'. The cover was designed to be native growth media salvaged from the footprint of the Bingham Canyon Dump, which tended to be quartzite host rock, which included all soil horizons and some fracture bedrock, and ranged in size from silt-size material to large rocks up to 30 cm in diameter.

Material was not segregated in any fashion to separate soil types or sizes. The cover material was placed along the crest prior to final placement and was placed on the slope at a specified depth ranging from 45 to 91 cm. Furrows were constructed on contour with the slope using the ripper tools on the back of the dozer to half ripper depth. A Caterpillar D-10 dozer was typically used to place the cover materials and rip furrows, but occasionally a D-6 was used when it was available. The wide-track D-6 was preferable to the D-8 or D-10 due to the stability on side slope operation. Seed was initially applied using a seed spreader affixed to the back of the D-10 dozer. This proved to be ineffective (the results of which were visible for years due to the poor vegetation success), so application transitioned to broadcast using a shoulder-mounted seed spreader. Tree species native to Utah but grown in Montana using regional seed stock were hand planted at a density of 350 trees per hectare. The seedlings generally did not survive more than a season or two, with loss attributed to a lack of water or browsing by deer.

Many valuable lessons were learned by the reclamation lead and mine operations teams over this initial period of waste rock reclamation. Through the evolution of the Bingham Canyon Mine reclamation program, several lessons were captured and contributed to the now common practices at Bingham Canyon Mine. A few of these concepts are listed below and provide context for the remainder of the paper:

- Changes to mine plans may conflict with concurrent reclamation.
- Initial mine designs focus on operational efficiencies; concurrent reclamation needs to be considered in the mine design stages and during changes to the mine plans.
- Plants may require supplemental water, especially in arid climates.
- Precipitation can accumulate on benches and runoff will always flow down gradient to concentrate at the low spot, potentially breaching the berm and causing erosion.
- Vegetated cover depth should mimic plant rooting depth.
- Coarse cover material is more resistant to erosion than fine cover material.
- Soil salvaged from the waste rock pile footprint prior to development saves money for future salvage and sourcing of cover materials.
- The application of soil amendments with high nitrogen content promotes undesirable species.
- Elements of quality control have a place in reclamation.

3 Concurrent reclamation

Reclamation of the waste rock piles at Bingham Canyon Mine involves regrading and recontouring to relax the slope gradient, application of a soil- and rock-blended cover to armour and provide a vegetation growth base as well as limit erosion, and seeding to promote revegetation.

The primary objectives of reclamation of the waste rock piles align with the regulatory and constructive obligations to:

- Promote physical stability of the waste rock piles to support the defined post-mining land use.
- Establish systems to contain natural seepage and control erosion.
- Re-establish a self-sustaining native vegetation comparable to pre-mining vegetation (or reference area).
- Reduce long-term acid rock drainage generation by minimising infiltration of meteoric water.

Reclamation is performed concurrently with pit and waste rock pile development, where practical. The older South Dumps have been undergoing concurrent reclamation since 2014, as no further waste rock placement was planned and to lessen the stark appearance to the Salt Lake Valley community.

3.1 Regrading

Reclaiming the South Dumps presents several challenges. The older waste rock piles were steep, with 37-degree repose slope angles, and tall, with continuous slopes exceeding 500 m from toe to crest prior to regrading. The regrading and recontouring is restricted by the waste rock contact water collection infrastructure (South Side Collection System) constructed at the toe of the waste rock piles. To avoid the potential for contact water escaping the collection system, mine waste rock is not placed or regraded on or beyond the regulatory permitted contact water collection structures.

Several evaluations were conducted to assess the reasonable options to reduce either the slope length or the slope gradient in order to improve the long-term erosional stability and reclamation sustainability.

3.1.1 Inter-bench slope design trade-off assessment

An inter-bench slope length trade-off assessment was completed to compare slope design criteria to analyse design options to reduce either the slope length or inter-bench slope gradient to improve the long-term erosional stability and reclamation sustainability (Golder Associates 2017). The base case slope design criteria are 2.5H:1V inter-bench slope gradient with 15 m wide horizontal benches located at 61 m vertical intervals resulting in an inter-bench slope length of 165 m. The long and steep slope lengths pose higher potential for slope erosion, scour, and more frequent and higher long-term maintenance costs. The trade-off assessment utilised a multi-criteria analysis approach incorporating technical, operational, safety, reliability and financial criteria. A key consideration in the trade-off assessment was the constructability and practicality of regrading existing waste rock piles, and the operational costs to construct new waste rock piles to the alternative design criteria.

The most cost-effective means to constructing the final configuration of the waste rock piles is to place the material in a manner where minimal reshaping is needed. Current mine operational practices entail construction of waste piles in 61 m vertical lifts. An alternative configuration that was assessed considered construction of the waste piles in 30 m vertical lifts, which could provide slightly flatter overall slopes to reduce slope gradient. However, the adjusted design was determined to have negative implications on the short- and medium-term mine plan waste haulage, adding considerable incremental costs to the operations. Cross-sections for the alternative configurations are shown in Figure 2.

Slope regrading is most cost efficient when it is performed using direct cut to fill with dozers pushing material cut from the crest down the slopes to fill areas at the toe. Where there are toe constraints, as experienced at the South Dumps where the toe below the waste pile is fixed to avoid encroaching on the water collection infrastructure, the slope design criteria were modified to avoid excess cut and rehandle. The slope design criteria accepted for the South Dumps is steeper than other waste rock pile areas at Bingham Canyon Mine due to the toe design constraints. An inter-bench slope design of 2.37H:1V is applied, equating to a 2.5H:1V overall slope gradient. Experience has shown the potential increased risk of scour and erosion on these steeper slopes can be effectively managed with proper construction techniques of the regraded slopes, surface water management systems, and re-establishment of a sustainable vegetative cover.

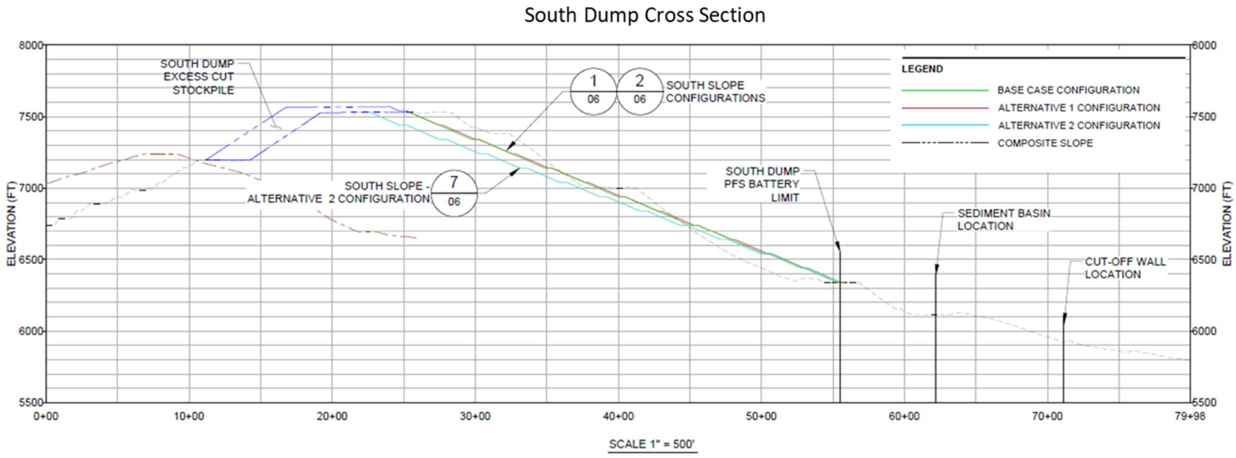

Figure 2 Inter-bench slope trade-off evaluation of alternative designs to reduce slope length considered design constraints, cost of construction and long-term safety, stability, and cost to maintain

3.1.2 Regrading south dumps

The key to successful waste rock construction and grading begins with a detailed survey. Upon completion of the soil salvage efforts, the slope is scanned with a drone using photogrammetry to create a three-dimensional surface. The waste rock dumps are designed to blend with the existing topography and consider grading requirements to achieve final design while aiming to balance cut-and-fill. Often, this means placing more waste rock in the centre of the drainage to account for the longer dozer push distances associated with the centre of the drainage. Figure 3 provides an example of the initial 'as-dumped' slope at 37 degrees and the relaxed slope at 22 degrees during the regrading phase.

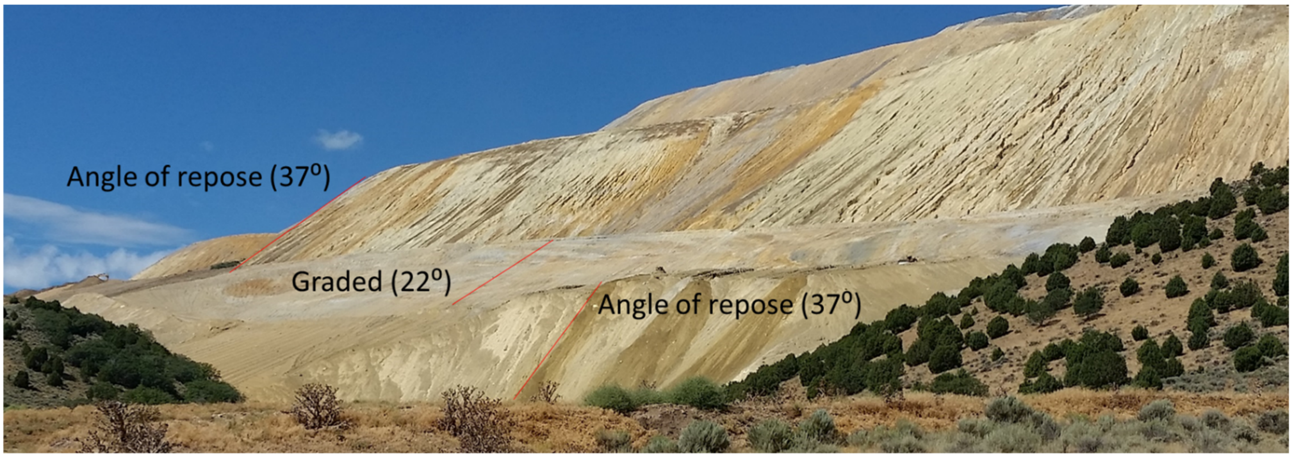

Figure 3 Regrading the lower slopes of the South Dumps

Quality control continues to be an important component. Not only do operations need to build to plan but also the reclamation team needs to perform routine checks of the crest to ensure the dump construction meets the design for reclamation grading.

Upon grading, the dozer operators, equipped with GPS blade-mounted instrumentation, are provided with a digital design of the graded waste rock shape. Typically, the D-10 dozers are utilised to perform the bulk pushing, while a D-8 dozer follows along to fine-tune the final surface to design. Generally, the grading starts at one side of the drainage or hillside slope and the dozer operators push the waste rock to match the stripped hillside, as illustrated in Figure 4. The operator then progresses across the slope incrementally.

Figure 4 Regrading the lower slopes of the South Dumps

Surveys conducted during regrading often determined the graded slope would be short of material by about 5% of the total calculated volume, requiring additional waste rock to be placed to achieve the final design grade. Relative to the large volume of material being moved, the 5% variance is considered as a positive outcome and generally easy to address.

3.1.3 Regrading lessons learned

Lessons learned from regarding the steep slopes include:

- Survey as the waste rock is placed to confirm it is constructed to design:
  - Waste rock placement with large haul trucks may present a construction constraint if the waste rock pile design is too intricate; survey control for placement of the waste rock and verification of as-dump slopes are key controls to achieving final design grade and minimising rework and rehandle.
- If tying a graded waste rock pile into a native face:
  - Survey the topography before and after the soil is stripped to allow adjustment in the waste rock placement plan prior to placement to account for changes in topography as a result of the soil salvage efforts.

3.2 Surface water management

A significant component to waste rock reclamation, particularly on the steeper slopes, is management of the surface water and sediment. If waste rock pile slopes are not graded and relaxed, or reclamation efforts are done incorrectly, intense rain events can mobilise waste rock sediment and debris, resulting in damage to water control structures and possibly exceeding the containment structures. Bingham Canyon Mine experienced several intense rain events that affected the steep South Dumps between 2007 and 2013, which initiated the need to improve the existing surface water management system.

3.2.1 Stormwater management design objectives

Surface water conveyance systems at Bingham Canyon Mine have been designed to be robust and easily maintainable. The systems are designed to accommodate intense rain events.

Storm event magnitude design criteria have evolved over the past 20 years at Bingham Canyon Mine. Regulatory requirements prescribed surface water management systems to be designed for a 10-year/24-hour storm event for all existing structures (i.e. historic waste rock piles) but did not necessarily consider sediment mobilisation or the potential impact to downgradient surface waters. Between 2009 and 2012, Bingham Canyon Mine employed a minimum storm event design criteria of a 25-year/24-hour event and began to design to the 100-year/24-hour storm event, where possible, given area-specific constraints. However, concern over climate change by industry and regulators has prompted Bingham Canyon Mine to adopt a change in design criteria to consider the 100-year/24-hour event as a minimum design storm event with more intense storm events ranging from 500-year to 1,000-year to be evaluated and designs adjusted according to risk. Bingham Canyon Mine adapted to the change in design criteria and is completing concurrent reclamation for the future potential increase in storm intensity.

The South Dumps are located in steep, narrow canyon drainages and have the greatest potential to discharge offsite due to the terrain and proximity to the mine permit boundary. The area-specific constraints and susceptibility to erosion and sediment transport (in the unreclaimed configuration) of the South Dumps made the area a priority for concurrent reclamation to mitigate concerns during intense storm events. Figure 5 provides an example of sediment overwhelming a detention basin.

Figure 5 The South Dumps Yosemite drainage detention basin buried after an intense rain event in 2009

In general, the surface water management strategy involves a ‘barber pole’ configuration, with runoff from the inter-bench slopes reporting to outslope channels, located on the benches, which then convey flow to downdrains. The downdrains are steep, linear armoured channels designed to convey flows from the outslope channels down to the toe area of the waste rock piles, where the flows are then transferred to perimeter channels. Energy dissipators, in the form of hydraulic jump stilling basins, are constructed at the base of the downdrains to manage the hydraulic jump, dissipate energy in a controlled manner, and prevent erosion at the toe of the facility (Figure 6).

Figure 6 Articulated concrete blocks downdrain, energy dissipator on bench, and catch bench

The designs evaluated for the downdrains at the Bingham Canyon Mine considered revetment type, including riprap or other armouring materials, and the longitudinal profile, incorporating benches (i.e. 'stepped downchute') or one continuous, uniform slope profile.

Riprap is a well-established revetment and widely used channel-lining material. However, applications of its use on steep slope downdrain applications on landfills and mining facilities have been problematic, often resulting in high maintenance and repairs. Riprap has inherent design uncertainties for high-flow velocity regimes, exhibits variations in roughness, and is susceptible to erosion of bedding materials and instability during both high- and low-flow events when used in downdrain applications.

Articulated concrete blocks (ACB) were selected for revetment of the downdrains due to their being erosion resistant, reliable, and needing less long-term maintenance (when installed properly).

Stepped downchute profile for the downdrains was selected for the South Dumps due to the need for vehicular access across the benches for long-term operational and maintenance access. To mitigate concerns with the transition of flow at each bench (at the 61 m vertical intervals), energy dissipation structures are incorporated into the design.

3.2.2 Stormwater conveyance structure construction

Construction of the stormwater conveyance structures starts with bulk grading of the waste rock slope to reprofile and incorporate the horizontal benches. The waste rock pile top and bench channels are sloped gradually at 2% gradient towards the downdrains to prevent ponding on the surface. The downdrain channels are constructed with base widths between 3.6 and 6 m to accommodate the anticipated contributing area flows and the construction equipment (dozer blade width). Downdrain construction preparation (Figure 7) and ACB installation (Figure 8) are presented below.

Figure 7 Subsurface grading and compaction preparation of stormwater downdrains

Figure 8 Installation of the articulated concrete block (ACB) revetment in the stormwater downdrains

3.2.3 Stormwater management lessons learned

Lessons learned from the design and construction of the stormwater management structures on the steep slopes of the South Dumps:

- The size of the storm event is an important design objective to consider. When selecting the storm event to which the system will be designed, consider what part of that system is most vulnerable to failure (i.e. steep slope open channels), and the consequences of a potential failure, and consider building those features to a larger event.
- Surface water conveyance systems should include redundancy or fail safes when possible. Examples include a series of basins should the first become overwhelmed with sediment and debris. Basin outlets should account for sediment-laden waters so if one orifice fails, there are secondary outlets available to convey water.
- Waste rock piles may experience settlement post-grading, especially in the dozed fill areas. The challenge with grading large waste rock dumps is implementing a practical means of compaction. Many factors can influence the amount of settlement a waste rock pile may experience and in turn the deformation of surface water conveyance features. Some factors that influence subsidence

include dump lift height, precipitation events during and after the grading, and foundation preparation (i.e. was the material stripped to bedrock).

- At Bingham Canyon Mine, downdrains were installed after the cover had been placed, which meant the cover had to be disturbed to install the infrastructure. In the case of downdrains, a construction corridor is created on either side of the downdrain to shuttle materials up and down the slope. Upon completion of the downdrain construction, the corridor is restored to match the adjacent surface contouring. A track hoe with a straight blade modification to the bucket is typically used for this effort. It is critical to restore these furrows on contour. The use of the track hoe, which pivots, will tend to create low spots in the furrow and hence a low spot for concentrated surface water flow.

3.3 Cover application

Establishment of self-sustaining vegetation is a primary performance objective and is required to meet Bingham Canyon Mine permit obligations. Vegetation establishment on the waste rock piles is also important to meet other performance objectives and targets, including reducing net infiltration, meeting discharge standards for runoff, improving visual aesthetics, and promoting surface stability by reducing erosion. The waste rock piles at Bingham Canyon Mine are not suitable for direct vegetation; therefore, a growth media cover is needed to support revegetation of the waste rock.

3.3.1 Cover design

The primary cover material sources at Bingham Canyon Mine comprise salvaged soils that were stockpiled prior to pit and waste rock development and mine salvaged materials targeting non-acid-generating and neutralising materials stockpiled from pit excavations. The mine salvage materials (MSM) are characterised as moderately coarse materials (sandy loams) with moderate to high rock fragment contents composed of gravel- and cobble-sized quartzite. The MSM are expected to have a high degree of erosion resistance. The characterisation of the MSM stockpiles revealed that the materials have the potential to generate lower pH conditions detrimental to plant establishment, which limits their suitability for direct use as a cover material.

The soil salvage materials (SSM) are native soils and paralithic subsoils that occur around the mine. The SSM are moderately fine textured and have moderate to low rock fragments, which make them less erosion resistant than the MSM. SSM rock fragments range from gravels to stones of mixed lithology, including andesite, quartzite, and limestone. SSM are neutral to slightly alkaline in reaction and non-saline to very slightly saline. The pH and salinity conditions in the SSM are favourable and they are well buffered and have minimal capacity to generate acidity.

The respective limitations of the two cover materials (SSM and MSM) are mitigated through the combination of the materials. The SSM are expected to offset the acidic and potentially acid-generating constraints of the MSM, which in turn increases the erosion resistance of the SSM (Rio Tinto Kennecott 2017).

The objectives of the cover material design are to:

- Protect the cover and growth media from water erosion to maintain long-term cover function.
- Reduce net infiltration relative to unreclaimed conditions to reduce water treatment requirements.
- Provide conditions for plant establishment, long-term sustainability, and compliance with regulatory requirements.

Several cover designs were evaluated for the waste rock piles at the Bingham Canyon Mine and included monolithic blended covers with different proportions of SSM and MSM, thicknesses varying from 0.6 m to 1.3 m, layered covers, and a synthetic liner system on selected areas. Ultimately, the selected cover design was of a monolithic-blended SSM-MSM mixed 50:50 percent by volume and applied at 1 m thickness (measured vertically). The decision was driven by a constructability and cost review that determined quality control and expense for the large-scale application would be best served by the monolithic cover installation (Golder Associates 2019).

3.3.2 Cover application methodology evaluation

Cover material mixing trials were conducted on the regraded South Dump slopes. The mixing trials were conducted in two phases: (1) a test to evaluate ripping techniques and equipment to blend the cover materials on a flat, top surface; and (2) tests to evaluate mixing techniques on the steep outslopes.

Dozer 'ripping' is a common technique used to mix materials. The objectives of the top surface ripping tests were to determine the depth and spacing of ripping and to trial standard and modified types of ripper shanks to assess effectiveness in achieving a uniform mixture of the MSM and SSM. The flat surface ripping test plot was first covered with a 0.6 m layer of MSM, which was then covered by sections of SSM with thicknesses of 0.15 m, 0.3 m, and 0.45 m (Figure 9). Prior to ripping, the thicknesses of SSM were measured in shallow excavations to determine if the material placement achieved the targeted construction tolerance.

Figure 9 Cover materials are staged in layers by end dumping cover materials in equal parts at the crest of the slope. Material is blended through the dozing process

Once the SSM layer was placed, the area was ripped at a uniform depth of approximately 0.6 m. Ripping was conducted with the shanks spaced 0.9 m apart and required a second offset pass to ensure the entire surface layer was ripped. Two ripper configurations were assessed in the trial. Half of the test area, comprising sections of all three SSM cover thicknesses, was ripped using standard commercial shanks. The other half of the test area was ripped using a modified ripper with wings welded to the ripper boot and sheath, which aimed to promote more mixing action. Limited mixing was observed in the thicker SSM layers for both the standard ripper shanks and the modified ripper shanks. Adjustments were made during the trial to promote mixing at depth. The modified ripper shanks produced negligible differences in results on the flat test plots and presented safety concerns during ripping on the outslopes (Golder Associates 2018).

The cover application trials on the steep outslopes evaluated two cover and mixing strategies. For the first strategy, a similar approach to the flat test plot was employed, where a base layer of the MSM was first dozer-pushed down the slope at the designed thickness (0.7 m and 1 m), followed by a layer of the SSM. Prior to ripping, the thicknesses of SSM were measured in shallow excavations to verify that design tolerances were achieved. After survey and additional grading of areas that exceeded design tolerances, the slope was ripped on the contour.

The second cover and mixing strategy involved placing the cover materials in windrows along the dump crest, which were mixed as the dozers pushed the materials downslope. Initially, the cover materials were placed in alternating windrows of SSM and MSM in a checkerboard-like pattern. This approach required special attention to the haul truck traffic patterns and resulted in reduced cycle times and delays. An alternative approach placed equal parts of SSM and MSM (by volume) in layers at the crest, which improved truck traffic pattern and material haulage sequencing issues and reduced truck delays (Figure 10). After the material was pushed downslope to the design thickness, the slope was once again ripped on the contour.

Figure 10 Cover materials are staged in layers by end dumping cover materials in equal parts at the crest of the slope. Material is blended through the dozing process

Effective and safe mixing was only achieved through dozing the two material types off the crest.

Following placement and mixing of the cover materials, the slopes are ripped on the contour, typically with a Cat D-8 or D-6 dozer, as displayed in Figure 11. Ripping the slope on the contour produces furrows that help to retard surface water flow and reduce erosion while also retaining water and fines, which support revegetation.

Figure 11 Graded and cross-ripped waste rock in preparation for cover placement

3.3.3 Cover application lessons learned

Several lessons were learned from cover application on the steep slopes of the South Dumps:

- Keep it simple. When working through field trials, remember that every step in a process will add time and cost to the production process. Fewer steps are simpler for an operator to apply and make quality control more manageable.
- Not all operators have the same work experience. Cover placement can be an exacting endeavour that requires more skill than knowing the basics of dozer operation.
- The cover needs coarse rock to limit erosion and fines to support rooting and water retention.
- A rougher cover surface provides a place for water to stay on the slope and support vegetation; smooth, compacted surfaces will decrease infiltration and erode quicker.
- Once a cover has been placed and ripped on contour, any disturbance and attempt to restore the contours must be done with utmost care or risk the potential for breaches in the surface capture of the furrow.
- Tie the cover into the native slope with care to not create a channel for water to concentrate.

3.4 Revegetation

Establishing vegetation on waste rock slopes is critical to keeping the newly graded slope in place. A slope and cover without vegetation will tend to erode quickly and may create dust in high-wind events. The seed application should be timed to be in the appropriate season that provides the best chance of success. This idea is typically referred to as the seeding window. At Bingham Canyon Mine, the ideal seed window is in late fall and prior to the first winter storms. A small dusting of snow, less than a few centimetres, is acceptable. This may sound simple and perhaps obvious, but logistically, it can be a challenge for the following reasons:

- The construction schedule runs long (or short) and seed is applied opportunistically based upon the current construction schedule and does not account for what will provide the best chance for success for vegetation establishment.
- Winter precipitation comes early and, depending upon the type of seed application equipment, makes access challenging due to saturated surface conditions (or snow drifts).
- Reclamation seeding contractors are very busy during the seeding window and availability may be a consideration.

The application of native species is very important to establish vegetation that will be successful in the site-specific climate and to match the vegetation in the adjacent landscape. It is especially important to prevent invasive species from establishing. Attention was given to eliminating weedy or invasive species from the cover material prior to salvage or removal from the soil stockpile and to clean equipment before it entered the property. One piece of equipment can carry thousands of seeds from another job site, which can prove troublesome in managing weeds and invasive species.

3.4.1 Revegetation design objectives

Design objectives selected for Bingham Canyon Mine were as follows:

- A sustainable seed mix of species native to the region and adapted to semi-arid conditions:
  - Periodically, cereal rye or QuickGuard® is used as a cover crop to supplement the seed mix. These products have quick germination and are generally sterile, allowing near-term erosion control while the other species germinate and mature.
- Soil stabilisation and erosion control.

- Non-invasive plant species.
- Consideration of type of species based upon aspect and elevation.

Collaboration and concurrence to gain input and support from the regulatory body, Utah Department of Natural Resources – Division of Oil, Gas, and Mining (UDNR-DOGM), was also a key driver in the design process.

3.4.2 Revegetation in application

Due to the steep nature of the waste rock slopes, the revegetation process employs a combination of broadcast seeding and hydroseeding. One primary consideration of these seed application methods is they do not disturb the furrows created by the dozer ripping. The furrows not only minimise surface water movement but also hold water in the bottom of the furrow with fines that have settled to the bottom. Areas below the waste rock slopes, slopes less than 3H:1V, are seeded using a drill seeder. Bingham Canyon was seeded by hand broadcast but proved to be very labour intensive, so this method is typically not used.

The hydroseed application is the preferred method. The hydroseeder can generally spray the mixture about 45 m and can be affected by wind conditions; hence, favourable wind conditions can increase the spray distance (Figure 12). The middle third of the slope is applied using a handheld hose. The slurry is composed of water seed mix, fertiliser, mulch and tackifier. Since water is a large component of the seed application process, the distance to a water source can greatly slow the application process. To expedite the process, a water truck may be used to bring the water to the hydroseed truck laydown at the crest of the slope.

Figure 12 The hydroseed truck moving along the bench and toe of the slope

3.4.3 Revegetation lessons learned

Lessons learned from revegetation of the steep slopes include:

- Spring seeding windows are very challenging. The ground is either too wet or summer comes too soon. In the authors' experience, vegetation of areas where seed was applied in the spring struggle to establish and often take three or more years to gain the appearance of an area that received a fall seed planting.
- Perform vegetation surveys to document what is successfully establishing from a specific seed mix and what is not. Specialty reclamation seeds can be very expensive and those plant species not succeeding should be eliminated.

- Arid climates (i.e. minimal precipitation or long periods of limited precipitation) make plant establishment very challenging. Find ways to irrigate seedlings so they have the opportunity to establish mature roots.

4 Conclusion

The waste rock pile reclamation program has continued to evolve and employ more rigour at Bingham Canyon Mine as every year passes. Concepts that were in their infancy 15 years ago are now commonplace and embedded by Bingham Canyon Mine reclamation engineers routinely. The reclamation process has evolved into a team effort with support from mine operations, who routinely coordinate with the reclamation team to identify opportunities to support cost-effective mine reclamation. Bingham Canyon Mine employs a dedicated principal advisor who functions as a bridge between mine operations and closure planning. The practices developed and the lessons learned from each reclamation project, such as those described herein, are evidence of the successful concurrent reclamation practices.

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