Planning Closure of Arizona Closed Sites using Field Erodibility Studies and Erosion Modeling

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ABSTRACT

BHP is planning for closure at several legacy copper mines in Arizona (USA). A review of the original designs and the performance of the existing post-closure landforms identified long-term erosional stability of the cover systems as key to successful closure. In observing the 10 or more years of post-closure monitoring and maintenance of these cover systems, BHP conducted new field erodibility studies and modelling to re-assess the cost of new landform and/or cover systems with the benefit of reduced long-term maintenance.

The 100m^2 individual test areas included undisturbed native soil material (Gila), a reconstituted Gila cover, Gila with different sized quarried rock placed as rock armor on the surface, and placement of screened (coarse) Gila over the screened Gila fines. These test areas were subjected to simulated rainfall and overland flows. Measurements of infiltration capacity, interrill and rill erodibility, and sediment size and density were made.

Gila was found to be quite erodible in its undisturbed state and when reconstituted. Application of smaller-sized quarried rock as surface armor reduced erosion potential. However, erosion rates were higher when the larger quarried rock was used. Use of screened coarse Gila reduced erosion potential.

The erodibility and sediment parameters were used within the WEPP erosion model to design batter shapes not prone to the high rates that lead to rill or gully erosion. These designs informed the design of large-scale erosion plots that will run over the medium-term (~4 years) and provide validation data from which the WEPP model's accuracy can be confirmed or improved, increasing the confidence in its long-term predictions and as a result the stability of the closure cover systems.

INTRODUCTION

Post-closure site management at mine sites typically includes measuring reclamation success, monitoring surface water and groundwater quality and maintaining active or passive water management systems. The effects of water erosion on engineered covers on regraded surfaces often pose a long-term and costly maintenance challenge for the owner. As a result, development of closure designs that reduce or eliminate these maintenance costs is highly desirable.

Although reclamation practices are established and widely adopted throughout the mining industry in the United States of America, use of process-based erosion models has not been commonly used to inform reclamation designs. Use of empirically based models has been more common.

Greater use of process-based erosion models offers the opportunity for more robust and detailed erosion assessments that in turn can be used to consider cost implications of various designs over long timescales. When coupled with innovative field methods to gather the necessary material-specific erodibility parameters, it will improve the reliability of closure decisions.

STUDY BACKGROUND AND OBJECTIVES

BHP Copper Inc. (BHP) conducted a review of as-built closure designs and observed performance of a selection of post-closure waste landforms in the Globe-Miami area of Arizona. Existing as-built landforms include tailings embankments (gradients of 33%, slope lengths up to 300 m), heap leach facilities (gradients of 33%, slope lengths up to 180 m), and waste rock facilities (gradients of 33-36%, slope lengths up to 90 m). Erosion patterns from more than 10 years of post-closure monitoring data at adjacent sites were considered in conjunction with measures of the frequency and magnitude of maintenance activities. Erosion of the cover system was identified as a key determinant of closure success. The review further considered the strengths and weaknesses of the lateral and fall line channel closure design commonly employed in the US compared to continuous slopes (without lateral fall lines) that are increasingly common in Australia due to consistent failure of the engineered structures (Howard et al. 2011). The impact of vegetation, rock armor, and combinations thereof were also considered.

In order to more robustly consider erosion within closure design timelines, BHP commissioned a rapid, field-based erodibility study at an inactive mine in Miami (AZ) in March/April 2018. The study's objective was to collect the necessary model parameters to improve the accuracy of predicted erosion rates for different erosion resistant regraded slopes. This information is to be used within an iterative process incorporating erosion modelling and civil design to optimise the closure design.

The different stages of the study are shown in Figure 1. During Stage 1A, erosion-resistant cover options were identified based on the earlier review, test plots were constructed, and rapid, on-site rainfall and overland flow simulations were completed. The field data collected were then used to derive material-specific WEPP erodibility parameters (Stage 1B). An iterative process of 3D civil design and erosion modelling will be used to assess the trade-off between economics and long-term erosional performance, and to define optimal closure shapes (Stage 2). The civil design work will define a range of 3D surfaces for reclaimed topography based on the initial WEPP analysis. Erosion modelling will be a combination of 2D (e.g., WEPP) and 3D (e.g., SIBERIA) models using the different landform designs. In parallel with Stage 2, a benchmarking study of closed sites in the region (Stage 3) will be used to provide data from which the designs developed in Stage 2 and the underlying model inputs can be validated over time. This paper focuses on the results of Stage 1A and 1B only. Stages 2 and 3 are yet to be completed.

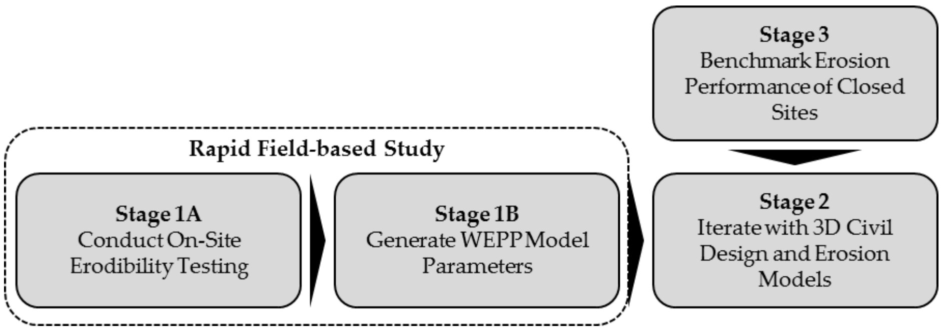


Figure 1 Erosion study stages.

EXPERIMENTAL OVERVIEW

Surfaces studied

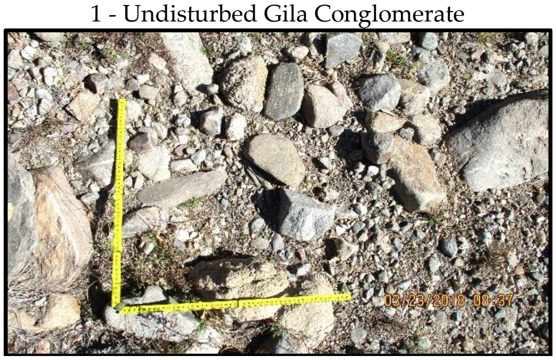
Eight field plots with a 33% gradient were established (Table 1; Figure 2). The selected plot surfaces represent potential design cover layers identified during the review process. They included disturbed (run of borrow) Gila, the native surface soil (Gila) material, and quarried rock products sourced nearby. Two plots (6 and 7) were also created to test whether screening the run of borrow Gila to increase the rock content at the surface improved erosion performance.

Table 1 Surfaces tested during the field-based erodibility study.

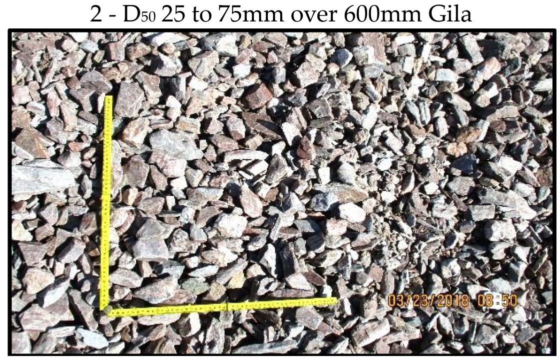
Plot Number	Description	Comment
1	Undisturbed Gila Conglomerate	Represents natural erodibility of the primary soil borrow material
2	300 mm imported rock armor (D_{50} = 25-75mm) overlying 600 mm run of borrow Gila	Small-size rock armor over disturbed borrow material
3	300 mm imported rock armor (D_{50} = 75-150 mm) overlying 600 mm run of borrow Gila	Medium-size rock armor over disturbed borrow source
4	300 mm imported rock cover (D_{50} = 150 mm) overlying 600 mm run of borrow Gila	Large-size rock armor over disturbed borrow source
6	300 mm screened run of borrow Gila (D > 12 mm) overlying 600 mm of the screened Gila fines (D < 12 mm)	Screened product from local borrow source
7	300 mm screened run of borrow Gila (D > 12 mm) overlying 600 mm of screened Gila fines (D < 12 mm) mixed with run of borrow Gila	Screened hybrid product from local borrow source
8	900 mm run of borrow Gila	Represents un-armored erodibility of borrow source
9	450 mm imported rock armor (D_{50} = 200 mm) overlying 600 mm run of borrow Gila	Oversize rock armor over disturbed borrow source

Note: Plot 5 was created with the same cover as Plot 8 except with a 36% gradient. It was not tested during the field study.

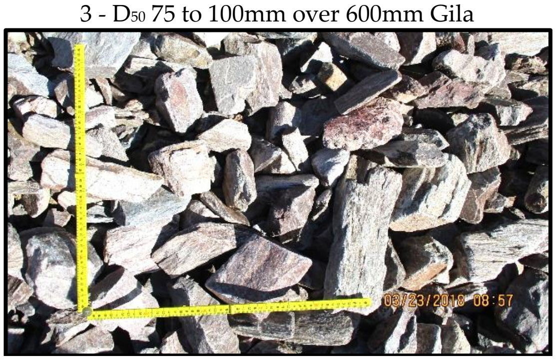
1 - Undisturbed Gila Conglomerate



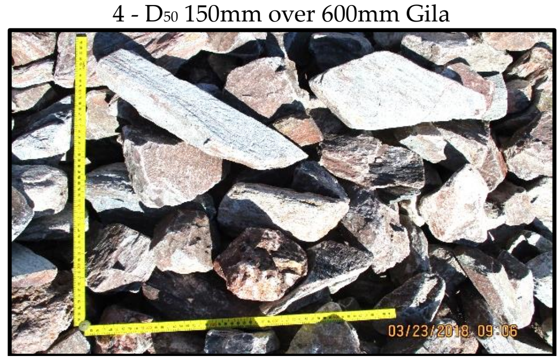
2 - D_{50} 25 to 75mm over 600mm Gila



3 - D_{50} 75 to 100mm over 600mm Gila



4 - D_{50} 150mm over 600mm Gila



6 - Screened Gila over 600mm Gila

7 - Screened Gila over screened Gila fines

8 - Run of borrow Gila

9 - D_{50} 200 mm over 600mm Gila

Figure 2 Test surfaces. Each side of square measure in each photo is 500 mm long.

Erosion modelling

Empirical erosion models such as the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1993) offer a simple means of assessing erosion on an annual basis. However, they cannot consider temporal variations in runoff or erosion potential, explicitly consider erosion resulting from rills, or provide predictions of changing erosion rates along a slope length, giving only a total erosion rate from the slope. In comparison, a process-based model such as WEPP (Water Erosion Prediction Project) (Flanagan and Livingston 1995) operates on a daily time step, provides erosion predictions on an event basis (rather than annual rates only), predicts erosion changes along a slope length, and can account for erosion in rills. Howard et al. (2013) provides a comparison of the RUSLE and WEPP models and how they can be used in mine site closure designs. The WEPP model was used to predict runoff and erosion based on the findings of the field tests. All WEPP simulations used a 100-year climate file developed using parameters from the US Department of Agriculture for Miami, AZ.

Field test methods

The WEPP model defines soil erodibility via specific parameters including interrill erodibility, rill erodibility, critical shear for rill initiation, and effective hydraulic conductivity. Measurement of these parameters can be achieved experimentally by application of simulated:

1. Rain and measurement of runoff and sediment in runoff to obtain estimates of interrill erodibility and effective hydraulic conductivity; and

2. Overland flows to rain-wet surfaces to obtain estimates of rill erodibility and critical shear for rill initiation.

Multiple wetting and drying cycles (4-5) were applied to each plot to assist with consolidation of the surface and the progress the surface armouring process. The rainfall simulator used is described in detail by Loch et al. (2001). In addition to erodibility, the eroded sediment particle size and density distributions can also be described within WEPP using settling column data. Loch (2001) details the methods used to derive the equivalent sand particle size distribution data for each surface. This combines both sediment particle and density distributions and can be directly input to WEPP. Simulated rain was applied with an intensity of 90−100 mm/hr to triplicate plots 1.5 m wide and 5 m long and timed sediment samples taken. Samples used for characterising the eroded sediment were taken from the rain wet plots once the rainfall had ceased. Overland flows were then applied to the same rain wet surfaces and sediment samples taken along with measurements of the rill flow. During the overland flow study, no rain was applied. Select images of the field study are shown in Figure 3.

RESULTS AND DISCUSSION

WEPP parameters derived from the field data are shown in Table 2. Effective hydraulic conductivity values of the undisturbed and run of borrow Gila (Plots 1 and 2) are similar to those measured for the plots that had screened run of borrow Gila at the surface (Plots 6 and 7). This is due to the similar particle size distributions of these materials. When rock covers are placed over the Gila (Plots 2, 3, 4, and 9) the effective hydraulic conductivity decreases with increasing rock size. Larger rocks act to increase runoff potential of the surface because they increase the proportion of the surface that is impermeable and reduce the number of rock/soil interface where water can preferentially infiltrate. This is consistent with findings of Parsons & Abrahams (2009) who report runoff increases when rock size increases beyond 50-70 mm and rock cover levels are greater than approximately 30%.

Figure 3 Rainfall simulations and overland flows being applied to test surfaces.

Table 2 WEPP parameters derived from test surfaces

Plot	Description	Effective Hydraulic Conductivity (mm/hr)	Interrill Erodibility (kg.s/m⁴)	Rill Erodibility (s/m)	Critical Shear (Pa)
1	Undisturbed Gila	18	693,192	0.00049	38
8	Run of borrow Gila	15	1,758,370	0.01194	32
2	D_{50} 25-75 mm rock over Gila	18	249,872	0.00092	33
3	D_{50} 75-100 mm rock over Gila	12	600,721	0.00112	33
4	D_{50} 150mm rock over Gila	11	599,333	0.00110	36
9	D_{50} 200 mm rock over Gila	7	620,420	0.00106	32
6	Screened Gila rock over screened Gila fines	20	387,940	0.00061	32
7	Screened Gila rock over screened Gila fines mixed into Gila	15	632,698	0.00113	36

Interrill erodibility of the run of borrow Gila is very high compared to the other plots due to the high proportion of fines at the surface (Figure 2). Although there is some variation in interrill erodibility for the other plots, this will not translate to significantly different erosion predictions. Rill erodibility is lowest for the undisturbed Gila. It is common that undisturbed surfaces are less prone to rill detachment than more recently constituted surfaces because they have consolidated and armoured over thousands of years compared to the consolidation and armouring that can be achieved by application of a limited number of wetting and drying cycles. Even so, the rill detachment values for the remaining plots except Plot 8 were only approximately twice that of the undisturbed Gila. The rill erodibility of the run of borrow Gila was an order of magnitude higher than the undisturbed Gila. Critical shear for all of the plots is relatively consistent. This reflects that erosion on the very rocky surface plots (Plots 3, 4, 9) was occurring at the interface with the underlying Gila.

The data suggests that as the size of rock placed on the surface increases, it does not act to increasingly protect the surface exposed to erosive runoff from detachment. This is because the surface that is eroding (below the surface at the interface between the rock and the Gila) does contain erodible fines. Added to this, the additional turbulence of the water flowing within the rocky surface layer can act to increase or at least maintain relatively high erosion rates. Further plots are planned in which the rock is incorporated into the run of borrow Gila and runoff is forced to flow on top of the rocky surface rather than through it. In such systems detachment rates have been observed to decrease as rock size increases (Parsons & Abrahams 2009).

The equivalent sand particle size distributions (data not shown) for every plot is similar, due to the homogeneity of the Gila material used to create the plots. It also indicates that the run of borrow Gila is producing similar sediments to the undisturbed Gila.

Table 3 WEPP erosion predictions for a 150 m long linear slope with 33% gradient.

Plot	Description	Runoff (mm/yr)	Mean Average Annual Erosion (t/ha/y)	Peak Average Annual Erosion (t/ha/y)
1	Undisturbed Gila	8	1	3
8	Run of borrow Gila	11	19	51
2	D_{50} 25-75 mm rock over Gila	8	2	6.1
3	D_{50} 75-100 mm rock over Gila	15	4	13
4	D_{50} 150mm rock over Gila	17	3	11
9	D_{50} 200 mm rock over Gila	32	6	22
6	Screened Gila rock over screened Gila fines	7	1	4
7	Screened Gila rock over screened Gila fines mixed into Gila	11	2.2	8

Note: Mean average annual erosion is the long-term annual erosion averaged over the entire slope length. Peak average annual erosion is the maximum long-term annual erosion predicted at a discrete point on the slope.

To demonstrate the relative erosion potential of the different surfaces, WEPP was fitted with the parameters shown in Table 2 and used to predict erosion for a 150 m long linear slope with a 33% gradient. The results are shown in Table 3. The authors have observed that mean average annual erosion rates greater than 5 t/ha/y and peak average annual erosion rates greater than 10 t/ha/y are often associated with batter slopes than are prone to gully erosion. This is consistent with values associated with gully erosion reported by Klingebiel (1961). Predicted runoff increases as effective hydraulic conductivity decreases. Erosion potential of the undisturbed Gila (Plot 1) is similar to that predicted for the D_{50} 25-75 mm, D_{50} 75-100 mm, D_{50} 150 mm, and screened Gila plots (Plots 2, 3, 4, 6, and 7); given their predicted rates, these materials are unlikely to gully on the modelled slope. The plot with the largest rock (Plot 9) is predicted to erode at a higher rate than the plots with smaller rock due to its increased runoff potential and similar rill erodibility and critical shear values. Although it is unlikely to gully, it is possible that the surface may slump under the rock layer as the Gila is eroded beneath it. The run of borrow plot (Plot 8) eroded at the highest rate, and is predicted to be prone to gully erosion. This is consistent with observations of the plot after the application of overland flows as rill networks have already begun to develop (Figure 3).

CONCLUSION

Erosion rates of run of borrow Gila is very high compared to that of adjacent natural land. Application of rocky covers is predicted to reduce the long-term erosion potential of the run of borrow Gila materials, and can achieve rates similar to that predicted for the adjacent undisturbed land. Screening of the Gila provides little benefit beyond that provided by application of the rocky cover. Use of rock that is too large is predicted to result in increasing rates of erosion as the proportion of the surface that is impermeable is increasing and the number of rock/soil interface where water can preferentially infiltrate is reducing. There appears to be a rock size (100 mm is a reasonable value) above which the increased runoff will result in erosion rates that could cause unacceptably high erosion rates. Further test plots are planned to investigate the impact of incorporating the Gila into the rock on material erodibility and long-term erosion rates.

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