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3D Finite Element Seepage and Slope Stability Modeling of a Geomorphic Landform Reclamation

Iuri Lira Santos

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3D Finite Element Seepage and Slope Stability Modeling of a Geomorphic Landform Reclamation

Iuri Lira Santos

Thesis submitted to the
Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Civil and Environmental Engineering

John D. Quaranta, Ph.D., P.E., Chair
Hema Siriwardane, Ph.D., P.E.
Leslie Hopkinson, Ph.D.

Department of Civil and Environmental Engineering

Morgantown, West Virginia

2017

Keywords: 3D Seepage Modeling, Finite Element Method, Unsaturated Soil Mechanics, Cost Estimation.

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ABSTRACT

3D Finite Element Seepage and Slope Stability Modeling of a Geomorphic Landform Reclamation

Iuri Lira Santos

The Royal Scot coal refuse pile in Greenbrier County, WV is being studied in order to reduce the Acid Mine Drainage (AMD) produced by this site. Two approaches to solve this problem were proposed: 1) a hydraulic barrier cover reclamation with a surface vegetative layer and 2) a land cover slope reclamation with a vegetative growth layer placement at the surface.

This thesis evaluated seepage and slope stability of the two proposed designs with a finite element modeling software in a transient analysis under unsaturated soil mechanics. Results from the model analysis were evaluated and further utilized to compare and contrast the cost benefit of both reclamation approaches. The Soil-Water Characteristic Curve (SWCC) was calculated using the Fredlund and Xing (1994) equation and the parameters estimated by the Zapata (1999) and Torres (2011) estimations.

The hydraulic barriers was modeled with 3 different soils: 1) *in situ* (as it is on site), 2) 60% coarse refuse and 40% fine refuse and 3) 80% coarse refuse and 20% fine refuse. Infiltration reduction averages of 26% for the 60/40 barrier and 35% for the 80/20 barrier were calculated. Although the 60/40 ratio had more fines in its composition, the aggregation of fines shifted the GSD curve to a larger particle size, consequently increasing the effective diameter and resulting in a higher hydraulic conductivity. Slope stability modeling showed that both proposals resist sliding failure with a Factor of Safety greater than 2.0.

A cost estimation for the hydraulic barrier was developed and faced with the cost for the land cover reclamation. The estimated amount for the barrier cover was \$2,959,493, while for the land cover reclamation was \$2,288,385.

The AMD treatment cost at the site is expected to be reduced by 35%, proportional to the reduction in infiltration by the 80/20 hydraulic barrier design. Cost assessment for the AMD treatment at this site was performed, predicting a reduction of \$59,167 per year on chemicals from the land cover reclamation to the hydraulic barrier, which will represent a 10 year cost break-even from one design to the other after the beginning of the construction.

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1. INTRODUCTION

1.1 Research motivation and problem statement

Coal extraction has been an economic engine at the Appalachian region of the United States. Following the Second World War, the demand for energy Appalachian region had developed. According to Berger et al. (2001), in 1997 the profitability and importance of the coal mine industry employed 60,000 people in the Appalachian region, representing around 2% of the workforce and 3.3% of the total earnings.

In West Virginia, almost 19,000 people were working for coal mining companies in the year of 1997, the high number of employees in the Appalachian region, representing 6.1% of the workforce of the state and producing \$1.25 billion in the year. This amount was 9.8% of the state total earnings. Table 1 presents data for regional states in Appalachia. (Berger et al., 2001).

Table 1 - Coal Statistics in Appalachian Region in 1997. (Berger et.al. 2001)

	Alabama	Kentucky	Maryland	Ohio	Pennsylvania	Tennessee	Virginia	West Virginia	Region
Total Coal Production (Millions of tons)	24.5	120.9	4.2	28.6	76.2	3.3	35.8	173.7	467.2
Coal Mining Employment (n° people)	5,297	13,061	549.0	3,958	10,409	739.0	7,149	18,937	60,009
Coal Mining Total Employment	0.95%	13.70%	1.70%	1.80%	0.60%	1.10%	16.40%	6.10%	
Coal Mining Earnings (Million)	\$396.9	\$719.6	\$26.4	\$218.4	\$1,025.7	\$34.1	\$360.0	\$1,246.7	\$4,027.8
Coal Mining Total Earnings	1.80%	19.10%	2.10%	2.80%	1.50%	1.30%	19.70%	9.80%	
Total Coal Output (Million)	\$966.9	\$2,979.5	\$113.7	\$635.6	\$2,033.1	\$103.5	\$1,012.3	\$4,530.0	\$12,373.6

During the mining process, a mixture of coal and rock is extracted. Post mining material management is performed to separate the market coal from rocks/shale materials that are refused by the coal purchasers. The coal goes to the energy plants, and coarse and fine refuses are produced (Subba Rao and Gouricharan, 2016). Southern West Virginia mining practices place the coarse

refuse piles next to the mine or transfer it to refuse impoundment. A description of the coal mining industry cycle is shown in Figure 1.

Figure 1 - Coal industry cycle

The major problem with the coal pile refuses is the potential for acid mine drainage (AMD) production. The AMD water drains into streams and water bodies around the mine site, causing environmental impacts (Skousen and Ziemkiewicz, 1996).

1.2 Studied Site Background

The Royal Scot coal refuse site is a bond forfeiture mine located in southern West Virginia. The refuse site was abandoned in 1999 with continued AMD production (Ward, 2001). The pile consists of pyritic shale refuse which is generating AMD. According to the Federal Water Pollution Control Act (1972), it became the State's responsibility to treat the AMD production where there is no owner/claimant for the site and the costs to treat AMD be very high. Skousen (2010) stated that in a five year operation period, the cost of treatment could vary from \$2,187 up to \$4,911,286 depending on the flow, concentration and treatment method chosen. In order to reduce this cost to the public, the West Virginia Department of Environmental Protection (WVDEP) was advancing with a conventional land reclamation approach. The Civil and Environmental department of the West Virginia University is collaborating with WVDEP to design a reclamation project for the Royal Scot mining site. The proposed reclamation for this coarse coal refuse (CCR) pile was a

geomorphic landform design of the slopes and a cap system composed of a CCR and short paper fiber (SPF) blend, mixed in a proportion of 60% CCR, 40% SPF in volume.

1.3 Purpose

The purpose of this research is to investigate and develop a 3D finite element seepage and slope stability modeling of the reclamation of the Royal Scot coal refuse site. This will be made comparing two proposed reclamations using coarse coal refuse amended with paper residuals to minimize precipitation infiltration mitigating acid mine drainage production. A cost assessment on the two proposed reclamations will be performed to compare and contrast the benefits of adopting the proposed reclamation design.

1.4 Objectives

The broad objectives of this research include the following two main goals:

- 1) Develop a three dimensional analysis of seepage and slope stability for the Royal Scot by a finite element method based software to evaluate the seepage reduction between land cover reclamation and barrier cover.
- 2) Measure the economic viability of the project by developing and comparing a cost estimate of two different reclamations: 1) a Land Cover reclamation and 2) A Barrier Cover reclamation. This will include expensing the AMD treatment for the both designs to approximate a time for a cost payoff of the two reclamation proposals.

The following work scope activities are proposed to accomplish the goals of this research:

1. Perform an analysis on water flux by a 3D finite element model, simulating a 24 hour 5 year of recurrence rainstorm event occurring at the site;
2. Compare the 2 different reclamation approaches seepage reduction;
3. Evaluate slope stability of the two proposed approaches under occurrence of a 24 hour duration with 100 year recurrence rainstorm;
4. Develop a construction agenda organizing the construction services in a manageable time for execution;
5. Estimate the total construction cost utilizing unit price description of services specified by R.S. Means® Construction Cost Data, and
6. Calculate the break-even construction and operation costs for the project by contrasting actual costs from AMD treatment and the projected reclamation project cost;
7. Summarize the results.

2. LITERATURE REVIEW

2.1 Acid Mine Drainage (AMD)

Acid Mine Drainage (AMD) is formed when sulfide minerals in the Coarse Coal Refuse (CCR) are exposed to oxidizing conditions (water and oxygen), forming highly acidic solution. Other sources of AMD formation occurs when sulfides are exposed in civil constructions as roads and excavations. Due to the geologic formation of the site, minerals can oxidize and produce high acidity. In coal fields, as found in the Appalachian region, the presence iron di-sulfides oxidizing and producing ferric hydroxide, ferrous iron, sulfate and acidity. The chemical reactions occur as described in the reactions below (Skousen and Ziemkiewicz, 1996).

The acidity of AMD, especially that produced by abandoned mine lands (AML) is likely to seep to rivers and streams. Skousen and Ziemkiewicz (2000) stated that AML are responsible for producing 90% of the AMD in the United States that are discharged in streams and rivers. Since abandoned mine lands have no claimer, the cost of treat this environmental issue relies in to public administration.

Treatment of AMD can be assessed by numerous methods, the most common is to treat with chemicals, which primarily neutralizes pH. Many options are available in market, yet the most famous are the calcium carbonate (limestone), calcium hydroxide (hydrated lime), sodium carbonate (soda ash), sodium hydroxide (caustic soda) and ammonia (Gusek and Figueroa, 2009).

Limestone is more appropriate for low flows due to its low solubility and its cost is considered low when compared to other chemicals. Hydrated lime is the treatment approach used in USA for most AMD remediation. This product is applicable in high flow and acid concentration situation. Hydrated lime has a low solubility in water, requiring an aerator to dissolve it, which increase its

initial cost. Soda ash as Caustic soda is normally used at isolated areas, where energy is not an easy to get resource. Soda is suitable for areas with low flow and acidity. It comes in briquettes size, making it convenient to use, however, it is one of the most expensive ways to treat AMD (Skousen and Ziemkiewicz, 1996).

Caustic soda is suitable for low flows but with high acidity. Compared to the other treatments cited in this work, this is the second most expensive behind soda ash. With a simple application, soda has to be handled careful. One major inconvenience for its use is that it can freeze on low temperatures, forcing the user to use an anti-frost solution or dissolve it (Skousen and Ziemkiewicz, 1996)

Ammonia can elevate the pH of AMD up to 9.0 in some cases, being one of the most effective treatments in use today. It comes liquefied in storage tanks and after mixed with water return to gaseous form, being very soluble and raising the pH of the water really fast. Compared to other treatments (sodium composites) ammonia has proved to be a cost effective however, issues with handling, over application and potential biological applications have to be taken care (Skousen and Ziemkiewicz, 1996).

2.2 Paper residuals

Short paper fiber (SPF) is a waste resultant from the water treatment process used at paper mills. The SPF material components are wood fiber, soil and biologic organisms. Use of paper residuals as a soil amendment is becoming a common practice. Maltby (2005) reported 29 landfill closure projects that used SPF as soil amendment on the cap. Camberato et al. (2006) proposed the use of paper mill residuals for agriculture and found good results on soil remediation, increasing the basic organic nutrients for plants as nitrogen and phosphorous.

Moo-Young and Zimmie (1996) tested short paper fiber geotechnical properties for conformity to ASTM requirements. Hydraulic conductivity tests on undisturbed samples collected in a Shelby tube was performed. Samples were collected in different period of times to check consolidation effects on hydraulic conductivity. Results of hydraulic conductivity vary from 1.06×10^{-7} cm/s to 4.50×10^{-8} cm/s, increasing as sitting time at the pile increased. This results lead to the conclusion

that after natural process of consolidation by time, the paper mill sludge reduced the permeability of the cover, suggesting that it can be a potential material to be used in civil engineering construction.

2.3 Cover design

Landfills control flow of gases and liquid into the subsurface and generate waste breakdown when a liquid (normally precipitation) is in contact with waste streams such as municipal solid waste, industrial wastes and sludge. The contaminated liquid is referred to as leachate (Albright *et al.*, 2010). To avoid diluting leachate with precipitation, a cap cover system using hydraulic barriers is used for a regulatory promulgation requirement and an industry standard design approach. Cap and cover systems can be named as alternative covers, store and release covers or water balance covers.

A variety of types of covers can be used depending on the final purpose of the design, availability of materials, and cost of execution. Conventional covers are the profiles that use a barrier layer on the top of the contaminated material, this barrier can be a simple soil cover, a low conductivity soil layer, a geosynthetic clay liner (GCL), a composite or even a combination of all (Figure 2) (Albright *et al.*, 2010).

In order to produce a more ecological and resistive erosion design, the top soil is normally designed to be vegetated by native grass. The major role of the grass is to create resistive forces against erosion, reducing the rain splash effect, runoff velocity and soil particles movement. Another benefits are the maintenance of the water balance, removing water from the top soil layer, consequently reducing infiltration and produces a better aesthetical appearance to the reclamation (Gray and Sotir, 1995).

Figure 2 - Conventional cover designs.

2.4 Unsaturated Soil Mechanics

Unsaturated soil mechanics started to be developed in the late 1970s, when the perception that the majority of engineering problems were taking place on unsaturated soils rather than saturated. The role of water in soil mechanics is well known and the transition process from dry to saturated is

when the unsaturated soil mechanics is important. At unsaturated mechanics, the soil mass is conceived as a multi-stage system, composed of soil, water, air and a contractile skin (Figure 3). The interaction of the air phase with the solids will be different from the water phase, influencing the water flow through a soil, strength parameters, stress-strain and deformation when the proportion of the fluid phases changes. To study a soil mass under an unsaturated condition besides the interaction between soil solids, water and air has to be described. The search for a characterization of the soil-water interaction resulted in the Soil-Water Characteristic Curve, which correlates the water content and the soil suction (Fredlund *et al.*, 2012).

Figure 3 - Unsaturated soil mechanics considered phases

An example of a common geotechnical practice that is critical in earthwork design which occurs under unsaturation condition is compaction. On field operations, it is very important to achieve final dry density as tested in laboratory to achieve final design purposes and for that, soil moisture content is crucial. If design dry density is not achieved, the expected behavior for that project will not be fulfilled and pathologies will be generated (Lu and Likos, 2014).

Unsaturated modeling is now used in engineering for designs associated with compacted, collapsing or residual soils. Water seepage reduces the soil strength when the soil mass is saturated. Soil masses when in the unsaturated state, normally present negative pore pressures at the surface. With occurrence of heavy rainfalls, seepage can change the pore pressure and reduce the factor of safety of the slope. When studying soil saturation process and its effects on a soil mass, unsaturated

soil mechanics is indicated for a better understanding of the soil stresses and fluxes variation (Fredlund *et al.*, 2012).

2.5 Cost Estimation and Break-Even analysis

Cost estimation is the prediction of all costs involved during the process of executing some action. In construction, the most common involved categories to take in account are: material, equipment, labor and facilities. The estimation will use previous services executed data stored in a database. Previous information about the categories will describe the bare cost to execute a service including how long it takes to be executed by a specific crew using an equipment (when applicable). However, each construction site will be unique and will have its particularities, which will require the expertise of a capable engineer to define the better approach to assess the construction plan. (RS Means, 2016)

Normally used in business, the term break-even is used for identify the number of sales that a product will surpass the fixed costs to produce it (Reilly, 2009). For a construction project this term can be understood as the time that the profits generated by an investment will overcome the amount invested. A linear equation can be built to describe it:

$$\text{Break Even time} = \frac{\text{investment}}{\text{total reduction in cost per time unit}} * \text{time} \quad \text{Equation 5}$$

3. MATERIALS AND METHODS

3.1 Geometry

The topography used to model this work was the project elaborated by Lorimer (2016) (Figure 4). The geometry was developed using the GeoFluvTM method of developing a geomorphic landform design aided by the Carlson Natural Regrade Software. Elevations from this design were converted to a relative coordinate system and then imported into Soil Vision® finite element analysis program. Coordinates conversion from Carlson Civil software was made by extracting the X,Y and Z point by creating a grid file and exporting the result to an MS Excel file, where they were made relative to itself, bringing lower left corner of the two modeled area to a 0,0,0 (X,Y,Z) coordinate.

Figure 4 – Royal Scot final watershed design with the modeling areas (adapted from Lorimer, 2016).

3.2 Geotechnical Properties

Laboratory geotechnical properties used in this work were obtained from Stevens (2016) and Tolikonda (2010). Classification, strength and hydraulic properties of coarse refuse, blended coarse and fine and the Mgro™ growth blend design soil properties applied in this work are described in section 4. 3D modeling on SVFlux® and SVSLOPE®.

3.3 Finite Element Analysis Software

The SoilVision Systems LTD softwares SVFlux® and SVSlope® were utilized for the three dimensional seepage and slope stability analysis of this work. SVFlux® is capable of modeling soil response to various weather conditions and perform a 3D seepage analysis using saturated and unsaturated soil mechanics. Weather conditions include: insulation, evaporation, transpiration, runoff, infiltration and inclusion of water heads, fluxes, precipitation (rain and snow) and groundwater. The analysis consists of: water flow in to the soil mass, calculating parameters such as saturation, head, pore water pressure, flow velocity, runoff, infiltration volumes and others.

The slope stability analysis was performed when the SVSlope® was coupled with the SVFlux®. Program coupling imports the pore water values to perform the stability calculations. SVSlope® can perform multiple calculation methods as simplified bishop, Morgenstern-Price, General Limit Equilibrium, etc., using a variety of searching methods as grid and tangent, entry and exit or moving wedges. Mesh generation and refinement for the finite element analysis calculations, also the time-step refinement was automatic created by the program.

3.4 Water balance calculation

The water balance at the cover design, the total infiltration, runoff and the evapotranspiration (where it applies) are to be accounted when a precipitation occurs. Infiltration will be the water that percolate in to the layers and may reach the waste layer, the runoff is the volume of water that flows at the soil surface and the evapotranspiration is the volume of water that is expelled out of the soil by evaporation and vegetation consumption of soil water. For a hypothetical situation of an inclined plane confined at the four edges, Equation 6 describes the change in water budget for a soil mass (Bedient *et al.*, 2013).

$$P - R - G - E - T = \Delta S \quad \text{Equation 6}$$

Where:

P = precipitation,

R = surface runoff,

G = Ground water flow,

E = evaporation,

T = transpiration,

ΔS = Change in water storage for a time period.

Runoff is the water that flows at the surface when the absorption capacity of the soil is reached for a specific rainfall arrangement. SVFlux® calculates the runoff based on an iteratively process. The calculation is a function of precipitation and hydraulic conductivity, being these the only necessary input parameters for the model. The runoff is set in the program at the climate boundary condition, allowing it to happen. The runoff precision coefficient was set to 100 and the transition width as 1 kPa. Precipitation often deliver an increase in soil pore pressure, sometimes greater than zero, which the program interpret as ponding (Thode and Fredlund, 2012).

Evaporation and evapotranspiration were not applied in this modeling in order to find the worst case scenario for the infiltration into the model due to the rainstorm event. Even presenting a ground water table, ground water flow was considered in the analysis since capillarity effect was not noticed to affect the water balance during the modeling evaluation.

3.5 Soil-Water Characteristic Curve

When designing a water balance cover, the major soil properties that are in concern are the flow and stress phenomena. Under unsaturated conditions, every soil will present an affinity for water, which is described as soil suction. For each soil mass, suction will be governed by its gradation and water content. Fredlund and Xing (1994) performed regressions on their experimental testing results that culminated in the unique equation that describes matric suction in function of water content presented on Equations 7 and 8.

$$\theta(\psi, a, n, m) = C(\psi) \frac{\theta_s}{\left\{ \ln \left[e + (\psi / a)^n \right] \right\}^m} \quad \text{Equation 7}$$

$$C(\psi) = \frac{-\ln(1 + \psi / \psi_r)}{\ln[1 + (1,000,000 / \psi_r)]} + 1 \quad \text{Equation 8}$$

Where:

θ = Volumetric water content,

θ_s = Saturated volumetric water content,

$C(\psi)$ = Correction factor for suction = 10^6 kPa at zero water content,

a = Parameter function of the air entry value of the soil (kPa),

n = Parameter function of the rate of water extraction of the soil,

m = Parameter function of the residual water content (θ_r),

ψ = soil water suction,

ψ_r = Suction corresponding to the residual water content.

The SWCC is unique for each soil. Soil composition and grain size distribution are the main parameters that affect the water affinity behavior of a soil. When a coarse soil is evaluated, high values of air entry parameters are found in the curve, resulting in a rapid fall of the slope followed by a long tail. When evaluating finer materials, the water affinity is higher, thus high values of matric suction are observed for lower water contents when compared to coarse soils. Lu and Likos (2014) exemplify water affinity presenting the capillarity effect, where in fine soils the water tension is higher which increases the water affinity and raises the water higher than in a coarse material. Figure 5 exemplifies the parameter variation and its effects on the SWCC.

Figure 5 – Soil-Water characteristic curve modifications due to parameters variation: a) air entry parameter value variation, b) rate of water extraction parameter variation and c) residual water content parameter variation.

Total soil suction in unsaturated soils is a function of the thermodynamic potential of pore water. When neglecting temperature, gravity and inertial effects, (analyzing only the soil-water interaction of suction) the three primary factors that will have an influence on suction are capillary effects, short range adsorption effects and osmotic effects. In literature, capillary and short range effects are combined, and named matric suction. Osmotic effects is the suction produced by dissolved solutes that may be contained in the fluid, originated by external leachate or by internal process that are generated by the contact between water and soil particles (Lu and Likos, 2014). Water flow is coordinated by Darcy's law applied in a three dimensional space as following:

$$q = -k_x(h_m) \frac{\partial h_t}{\partial x} \mathbf{i} - k_y(h_m) \frac{\partial h_t}{\partial y} \mathbf{j} - k_z(h_m) \frac{\partial h_t}{\partial z} \mathbf{k} \quad \text{Equation 9}$$

Where:

$k_i(h_m)$ = hydraulic conductivity function on each coordinate direction,

$\mathbf{i}, \mathbf{j}, \mathbf{k}$ = unit vectors on the x, y and z direction,

$ht = \frac{\Psi_t}{\rho_w g}$, $\Psi_t = \Psi_g + \Psi_m + \Psi_o$,

Ψ_g = suction due to gravity,

Ψ_m = matric suction,

Ψ_o = osmotic suction.

The importance of the Soil-Water Characteristic Curve can be evidenced when the parameters to estimate the soil hydraulic conductivity and the effective stress parameter can be retrieved by the elaboration of the SWCC. Fredlund et al. (1994) established an empirical equation regressed from laboratory testing, resulting in Equation 10:

$$k = k_{sat} \left\{ \frac{\int_{\ln(\psi)}^b (\theta(e^y) - \theta(\psi)) / e^y \theta'(e^y) dy}{\int_{\ln(\psi_{aev})}^b (\theta(e^y) - \theta_s) / e^y \theta'(e^y) dy} \right\} \quad \text{Equation 10}$$

Where:

k_{sat} = hydraulic conductivity at saturated conditions,

$e = 2.7182$,

y = Variable function of the water content,

Ψ_{aev} = Air entry value.

Effective stress also changes with the water content variation, and the equation that governs the effective stress is defined as

$$\sigma' = \sigma - u_a + \chi(u_a - u_w) \quad \text{Equation 11}$$

Where:

σ' = effective stress,

χ = effective stress parameter, varies between 0 and 1 and is a function of water content and contact angle,

σ = total stress,

u_a = pore air pressure,

u_w = pore water pressure.

By changing effective stress, the Mohr-Coulomb shear strength is also modified. Fredlund et al. (1978) noticed that with the increasing of matric suction, the soil friction angle increased as well, and to take that increase in account, they proposed an extension in the shear stress resistance equation, which is written as Equation 12.

$$\tau_f = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad \text{Equation 12}$$

Where:

c' = cohesion at zero matric suction,

ϕ' = effective friction angle,

$u_a - u_w$ = matric suction at failure,

ϕ^b = increase in friction angle associated with the matric suction increase.

For the effective stress parameter, importance of the SWCC shows at parameter equation defined as:

$$\chi = \left(\tan\theta - \frac{1 - \cos\theta}{\cos(\theta + \alpha)} \frac{\cos\theta - \sin\alpha}{\cos\theta} \right)^2 \frac{\tan\theta + \left(\frac{\sin\alpha}{\cos\theta} \right) \frac{(1 - \cos\theta)}{\cos(\theta + \alpha)}}{\tan\theta - \left(2 - \frac{\sin\alpha}{\cos\theta} \right) \frac{(1 - \cos\theta)}{\cos(\theta + \alpha)}} \quad \text{Equation 13}$$

Where:

θ = Water content at soil mass,

α = Contact angle.

The General Limit Equilibrium (GLE) was used in this work as the slope stability limit equilibrium method. This method has the capability of perform factor of safety calculations against sliding for forces (FFOS) and moment (MFOS). An advantage of this method compared to the classical Bishops method, is that shear forces between slices are considered. The equation for Factor of Safety calculation by the GLE is as Equation 14 (Fredlund, 1981).

$$Fm = \frac{\Sigma[c'l + (P - ul)\tan\Phi']}{R\Sigma W_x - \Sigma Pf \pm Aa} \quad \text{Equation 14}$$

Where:

F_m = computed factor of safety,

c' = effective cohesion,

u = pore water pressure,

l = length of the failure surface at the base of each slice,

Φ' = effective angle of internal friction,

P = the total normal force on the base of a slice,

R = radius of curvature,

W_x = the total vertical forces due to the mass of a slice,

A = the resultant external water forces,

a = the perpendicular distance from the resultant external water forces to the center of rotation,

Pf = resulting moment of failing mass, independent from slice to slice.

4. 3D MODELING WITH SVFLUX® AND SVSLOPE®

4.1 SVFlux® modeling set up

Seepage modeling was performed using SVFlux® by creating the Barrier Cover and the Land Cover design layers utilizing the geometry from the final watershed design of the Royal Scot reclamation project. Two models were created: 1) a steep slope model and 2) a flat model, being the steep slopes 1:4 ($\beta=14.04^\circ$) and steeper. Modeling was performed under a transient analysis and using unsaturated soil mechanics theory to solve the hydraulic and strength soil analysis.

Creation of the model consisted in importing the geometry of the areas of interest from the Lorimer (2016) final cap and cover design. A surface grid was generated, which is composed of 20 meters side squares resulting in a projected area of 140 x 160 meters for both the steep and flat models. The weather event selected for the precipitation infiltration at each model was a 24 hours duration and 5 year recurrence interval rainstorm which correspond to an 82 mm rainfall intensity according to the National Oceanic and Atmospheric Administration (NOAA).

The analysis time span for each model lasts until the end of infiltration. The rainstorm was set to occur at day 1 of the analysis. The initial water table was set at 1 meter from the bottom surface. Evapotranspiration was not applied to the model to assess worst case infiltration condition of the unsaturated flow under the applied rainstorm event.

To compare the two proposed reclamation approaches, the flat and steep models were created in accordance to the layering of each proposal. The Barrier Cover reclamation is composed of 3 layers described from the bottom to the top as: 1) the mine refuse layer, 2) a two feet compacted layer using the same soil as in the refuse layer, and 3) an one foot thick blend of paper residuals and *in situ* material in a volumetric proportion of 60% of shale material to 40% Mgro™ blend. Nomenclature of layers and surfaces are described in Table 2 and a schematic design is illustrated on Figure 6. The Hydraulic barrier layer was modeled in 3 different composition: 1) compaction of *in situ* material, 2) controlling the proportion of fines to an 80% coarse refuse to a 20% fine and 3) controlling the proportion of fines to a 60% coarse refuse to 40% fine refuse. Inclusion of fines

is expected to reduce the hydraulic conductivity, as consequence of reduction of the D_{10} (diameter where 10% of the sample is sieved in a grain size distribution test).

Table 2 – Hydraulic Barrier cover proposal modeling nomenclature

Hydraulic Barrier Modeling Description	
Surface 1	Bottom of mine refuse
Surface 2	Top of mine refuse
Surface 3	Top of low permeability Layer
Surface 4	Top of Growth Layer
Layer 1	Mine refuse Layer Material
Layer 2	Low Permeability layer (Hydraulic Barrier)
Layer 3	Growth Layer

Figure 6 - Schematic design of Barrier Cover model layers

The Land Cover proposal differ from the cap and cover by the removal of the compacted layer from the design therefore, containing only 2 layers placed from the bottom to the top as: 1) the

mine refuse layer and 2) A layer of one foot thick blend of paper residuals and *in situ* material in a volumetric proportion of 60% of shale material to 40% Mgro™ blend. Representation of the layer modeling in this proposal modeling is explained at Table 3 and pictured in Figure 7.

Table 3 – Land Cover proposal modeling nomenclature

Land Cover Modeling Description	
Surface 1	Bottom of mine refuse
Surface 2	Top of mine refuse
Surface 3	Top of Growth Layer
Layer 1	Mine refuse Layer
Layer 2	Growth Layer

Figure 7 – Schematic design of Land Cover model layers

For modeling purposes, material properties for the mine refuse and growth layers in both reclamation approaches were assigned the same hydraulic and strength properties. Soil properties applied for each layer are described in Table 4. All soil layers were considered three dimensional isotropic. As the modeling is based on unsaturated soil mechanics, the unsaturated hydraulic conductivity is calculated by the Fredlund and Xing (1994) estimation.

Table 4 – Soil hydraulic and strength properties (Stevens, 2016)

Material	Saturated Hydraulic Conductivity (cm/s)	Porosity	Specific Gravity
Fill	4×10^{-4}	0.45	2.65
Compacted CCR (std. proctor)	2×10^{-5}	0.27	2.19
60% CCR/ 40% Mgro™ blend	1×10^{-3}	0.52	2.00

The unsaturated properties for the soils used in the modeling were assigned by characterizing the Soil-Water Characteristic Curve for it. A grain size distribution based estimation developed by Zapata (1999) was used to predict the Fredlund & Xing (1994) equation parameters. Zapata (1999) defines SWCC parameters based on grain size distribution and plasticity of the material when applicable and no hysteresis is taken in account. For coarse materials, correlation of particle size of 60% passing or D_{60} and the four parameters of the SWCC was established by the following equations:

$$af = 0.8627(D_{60})^{-0.751} \quad \text{Equation 15}$$

$$mf = 0.1772(\ln(D_{60})) + 0.7734 \quad \text{Equation 16}$$

$$nf = 7.5 \quad \text{Equation 17}$$

$$h_r = af \left(\frac{1}{(D_{60} + 9.7e^{-4})} \right) \quad \text{Equation 18}$$

To develop these equations for the SWCC parameters, a regression on 120 soils with a plasticity index equal to zero, using D_{60} as the main variable to correlate SWCC parameters for a coarse soil (Fredlund et al., 2012). However, the upper boundary for those equations is 1.0 mm, which conflicts with the D_{60} for the fill material collected in the field that can be averaged as 6.85mm. The grain size distribution for the field material is presented in Figure 8.

Figure 8 – Combined Grain Size Distribution plots of the in situ, 60/40 and 80/20 barriers.

In this work the Zapata (1999) estimation was performed with a D_{60} of 1.0 mm during the modeling process. Calculation of the Fredlund and Xing (1994) SWCC fitting parameters culminated as: a_f , m_f , n_f and h_r as 0.8627, 0.7734, 7.5 and 0.7325 respectively.

By using these fitting parameters, the resulting Soil-Water Characteristic Curve is presented in Figure 9. The grain size distribution defined by Stevens (2016) and literature, a low value of the air entry parameter ($a_f = 0.8627$) at the SWCC were expected, creating a curve shifted to the left with a drop after reaching the air entry value, with a small residual water content.

Figure 9 - Resulting SWCC for the *in situ* hydraulic barrier.

The estimation for the Soil-Water Characteristic Curve was calculated outside the limits of the estimation but the resulting curve is representative for a poorly graded sand with gravel. Besides the compaction of the *in situ* material, two other barriers were tested with controlling the grain size distribution. The first barrier was set as an 80% coarse and 20% fine refuse and the second controlled GSD barrier is a blend in a proportion of 60% coarse and 40% fine refuse as described in Tolikonda (2010). Soil saturated hydraulic conductivity and D_{10} used as model inputs are described in Table 5.

Table 5 - Controlled GSD barriers properties

Material	Saturated Hydraulic Conductivity (cm/s)	Porosity	D_{10} (mm)
80/20 Hydraulic Barrier	2×10^{-6}	0.18	0.045
60/40 Hydraulic Barrier	10^{-5}	0.21	0.069

Soil-Water Characteristic Curve estimation was performed by using Torres (2011) model, which improved Zapata (1999) for soils with more fine contents and change the soil gradation parameter input to D_{10} instead of D_{60} as used on Zapata's. The Torres (2011) SWCC estimation equations are as the following:

$$a_f = -967.21D_{10} + 218.37D_{10}^{-2.7}$$

Equation 19

$$n_f = 10^{(-0.0075a_f + 0.1133a_f - 0.3577a_f + 0.3061)}$$

Equation 20

$$m_f = 0.0058a_f - 0.0933a_f + 0.4069a_f + 0.3481$$

Equation 21

$$h_r = 100$$

Equation 22

where,

D_{10} = grain size diameter at 10% passing by weight (mm),

$a_f = 1.28$ if $D_{10} < 0.020$ mm.

The fitting parameters a_f , n_f , m_f and h_r were calculated to be 7.76, 7.11, 0.59 and 100 respectively for the 60/40 hydraulic barrier blend and 5.17, 2.81, 0.75 and 100 for the 80/20 hydraulic barrier blend. Resulting SWCC for the 60/40 and the 80/20 mixtures are presented in Figure 10. Table 6 summarize the calculated SWCC parameters for the 3 barriers utilized in this work.

a)

b)

Figure 10 - SWCCs for the hydraulic barriers: a) 80% coarse and 20% fines and b) 60% coarse and 40% fines.

Table 6 - SWCC parameters estimation for the controlled GSD barriers mixtures

Barrier proportion	a_f	n_f	m_f	h_r
60/40	7.76	7.11	0.59	100
80/20	5.17	2.81	0.75	100
<i>In situ</i>	0.86	7.5	0.77	0.73

The steep slope modeling is located at the south west corner of the pile, named Area 1, identified by the red solid outline box in Figure 11. An example of the model ready at the SVFlux® software environment is presented at Figure 12. The flat model is named Area 2, circumscribed in by a dashed outline blue box Figure 11.

Figure 11 – Modeling regions Area 1 and Area 2 locations on the project. Adapted from Lorimer, 2016.

Figure 12 – Area 1 model at SVFlux®, local coordinates in meters.

The flat modeling area contains the beginning of Channel B and is discharging in the east channel of the watershed design. Final modeling result for the Area 2 flat slope modeling is presented in Figure 13.

Figure 13 – Area 2 Model at SVFlux®, local coordinates in meters.

At the sidewall of the models, a “review boundary” condition was applied for an estimation of the ground water exit points. The review boundary can be identified at Figure 12 and Figure 13 as the green sidewalls. Review boundaries are normally used for unknown water exit points at the model, the exit point is calculated in an iterative process to determine the exit point at same height as the head, satisfying the following: head = y (vertical coordinate of the exit point) (Thode and Fredlund, 2012).

To verify the model response to the rainstorm, a flow surface was established at the top of the mine refuse layer in each model, corresponding to Surface 2 to account water volume going into the mine refuse. The flow comparison is performed for the two approaches in order to account for the flow of acid mine drainage which will be neutralized at the treatment ponds in the field.

4.2 SVFlux® results

Defined the model geometry, soil hydraulic properties, time of analysis, boundaries conditions, the seepage analysis for the steep and flat models is ready to be performed.

4.2.1 Land Cover reclamation

The steep modeling with no barrier presented a total precipitation volume of 1993.49 m³ and an infiltration into the mine refuse of 1948.12 m³ after a 70 days period. Figure 14 shows the cumulative water balance during the analysis period.

Figure 14 - Water infiltration into the mine refuse for the Area 1 (steep) land cover model

For the flat modeling with no barrier, total volume of precipitation was 1846.04 m³ and the total infiltration to the mine refuse layer was 1898.16m³ for a 70 days period. Figure 15 shows the cumulative water balance during the analysis period.

Figure 15 - Water infiltration into the mine refuse for the Area 2 (flat) land cover model

The infiltration volume plotted larger as the precipitation is explained by the water content inside the growth layer seeping into the refuse. For both models (steep and flat) the seepage response for the design storm indicated no reduction in the volume infiltrating into the refuse layer.

4.2.2 Hydraulic Barrier Cover reclamation

Similarly as performed for the land cover design, the cap and cover was evaluated by a steep and a flat model. The cap and cover steep modeling results (Figure 16) presented a total precipitation of 1981.05 m³ and an infiltration through surface 2 of 1920.7 m³, representing a 3% reduction for the 70 day analysis. Figure 17 presents the saturation development through the analysis of the steep *in situ* barrier model.

Figure 16 - Water infiltration into the mine refuse for the Area 1 (steep) cap and cover model

Figure 17 - Saturation development through the analysis of the steep in situ barrier model

Flat modeling analysis of the design with a compacted hydraulic barrier had a total precipitation of 1872.13 m³ and a total infiltration to the mine refuse layer of 1817.17 m³ representing 3% reduction in total precipitation for a 70 days analysis (Figure 18). Figure 19 presents saturation development through the analysis of the flat *in situ* barrier model

Figure 18 - Water infiltration into the mine refuse for the Area 2 (flat) cap and cover model

Figure 19 - Saturation development through the analysis of the flat *in situ* barrier model

Comparison of the flat and steep modeling showed that the infiltration reduction was the same, both models presented a reduction of total precipitation in to the mine refuse layer of 3%. When comparing to the design with no barrier, a delay in infiltration is noticed, demonstrating the effect of the hydraulic barrier in the design.

4.2.3 Hydraulic Barrier cover reclamation with fines controlling

In order to achieve a better hydraulic barrier, addition of fines in the composition of the hydraulic barrier was modeled. Tolikonda (2010) performed soil hydraulic conductivity testing in coarse coal refuse. Two blends were tested: 1) controlling the mixture to an 80% coarse and 20% fine coal refuse (80/20) and 2) a mixture of 60% coarse and 40% fine refuse (60/40). The proportions of the material are in weight units. Grain size distribution and soil hydraulic conductivity were extracted and used in this work as parameters for the finite element modeling.

The first mixture modeled was the 60/40 blend. The areas used in this analysis were same steep and flat topographies used for the previous modeling. Analysis was performed for 100 days where the seepage response to the 5 year rainstorm was considered finished.

The steep modeling analysis of the 60/40 barrier design presented a total precipitation of 2000.16 m³ and a total infiltration to the mine refuse layer of 1362.73 m³ representing 31.8% reduction in total precipitation for a 100 days analysis (Figure 20). Figure 21 shows the saturation development during the model analysis.

Figure 20 - Water infiltration into the mine refuse for the Area 1 (steep) 60/40 barrier cover model

Figure 21 - Saturation development through the analysis of the steep 60/40 barrier model

The flat modeling analysis of the 60/40 barrier design presented a total precipitation of 1856.52 m³ and a total infiltration to the mine refuse layer of 1441.05 m³ representing 22.35% reduction in total precipitation for a 100 days analysis (Figure 22). Figure 23 presents the saturation development through the analysis of the flat 60/40 barrier model.

Figure 22 - Water infiltration into the mine refuse for the Area 2 (flat) 60/40 barrier cover model

Figure 23 - Saturation development through the analysis of the flat 60/40 barrier model

The next hydraulic barrier mixture tested was the 80/20 blend. The areas used in this analysis were same steep and flat topographies used for the previous modeling. Analysis was performed for a 150 days where the seepage response to the rainstorm was considered finished.

The steep modeling analysis of the 80/20 barrier design presented a total precipitation of 2001.56 m³ and a total infiltration to the mine refuse layer of 1387.50 m³ representing 30.67 % reduction in total precipitation for a 150 days analysis (Figure 24). Figure 25 shows the saturation development through the analysis of the steep 80/20 barrier model.

Figure 24 - Water infiltration into the mine refuse for the Area 1 (steep) 80/20 barrier cover model

Figure 25 - Saturation development through the analysis of the steep 80/20 barrier model

The flat modeling analysis of the 80/20 barrier design presented a total precipitation of 1936.16 m³ and a total infiltration to the mine refuse layer of 1191.70 m³ representing 38.45 % reduction in total precipitation for a 150 days analysis (Figure 26). Figure 27 presents the Saturation development through the analysis of the flat 80/20 barrier model.

Figure 26 - Water infiltration into the mine refuse for the Area 2 (flat) 80/20 barrier cover model

Figure 27 - Saturation development through the analysis of the flat 80/20 barrier model

An accounting for steep slopes was performed on the Royal Scot design using Carlson® Civil suite 2016. A total of 19.00 acres within the 47.64 acres area boundary are composed of steep slopes (slopes greater than 25% inclination) which represents 39.54% of the total area, identified as blue areas on Figure 28. Areas identified as steep slopes were assumed to perform as the Area 1 finite element modeling while the areas identified as flat slopes in (gray areas in Figure 28) will be assumed to perform as the flat slope modeling. Table 7 shows the percentage of areas calculated from Figure 28 of steep and flat areas.

Table 7 - Site slopes gradation

Slope definition	% of total area	Area (acres)	Average Slope % (β°)
Flat	60.81	28.59	11.1 (6.3°)
Steep	39.19	18.43	36.9 (20°)
Total	100	47.02	

Calculation of total infiltration reduction from one design was performed by interpolation. The values obtained in infiltration reduction from each design were weighted averaged by its area. The percent infiltration reduction was multiplied by its area in the design, and divided by the total area as follows:

$$Total\ red.\ (\%) = \frac{\%red.(steep)*area(steep)+\%red.(flat)*area(flat)}{total\ area} \quad Equation\ 23$$

Figure 28 – Steep and flat slopes area identification

Summary of the calculated values for total infiltration reduction for the design is computed in Table 8.

Table 8 - Reduction in infiltration per each approach

Design	Precipitation (m ³)	Flow through Surface 2 (m ³)	Infiltration Reduction	Total design infiltration reduction
No Barrier steep	1993.49	1948.12	2%	0.82%
No Barrier flat	1846.04	1898.16	0%	
<i>In situ</i> Barrier steep	1981.05	1920.7	3%	3.00%
<i>In situ</i> Barrier flat	1872.12	1817.17	3%	
60/40 Barrier steep	2000.16	1362.72	32%	26.11%
60/40 Barrier flat	1856.52	1441.05	22%	
80/20 Barrier steep	2001.56	1387.50	31%	35.13%
80/20 barrier flat	1936.16	1191.70	38%	

4.2.4 Seepage modeling results discussion

The Land Cover design presented no infiltration reduction in to the pile. The growth layer was modeling as a loose soil as it has to be loose to allow grass growth in it. Moo-Young and Zimmie (1996) studied the properties of short paper fiber residuals, and identified that this material naturally consolidate with exposure to environmental conditions, thus reducing the porosity and consequently decreasing the intrinsic permeability of the soil. So, for a long time the runoff over the growth layer is expected to increase, thus reducing infiltration. This reduction in infiltration due to natural consolidation of the material is expanded for all the designs.

The 80/20 barrier design presented to be the best design for a barrier compared to the *in situ* and the 60/40 barrier. The *in situ* material has a higher effective diameter size (D_{10}) of 0.5mm, when the 80/20 has $D_{10}=0.045$ mm and the 60/40 has a $D_{10}=0.069$ mm. Hydraulic conductivity is related to the effective diameter and void ratio, as described extensively in the literature e.g.: Hazen (1930), Amer and Awad (1974), Chapuis (2004).

The 60/40 barrier has more fines in its composition than the 80/20 barrier, however, for coal residuals Tolikonda (2010) found that after compaction, the fines aggregates together, creating coarse grains, resulting in a consistent shift of the GSD to a larger particle gradation size, increasing all the passing diameters (D_{85} , D_{60} , D_{15} and D_{10}).

The flat areas showed that infiltration occurs slower than the steep models. This can be explained by the runoff occurrence. At the flat area, water will seep in the downward direction equally, saturating the barrier, thus increasing the hydraulic conductivity under the same pressure head resulting in a slower flow. In the steep model, due to the runoff from the crest of the slope, saturation will occur first at the toe of the slope building the pressure head up, resulting in a faster infiltration at the toe.

Even having the same planar area, a difference in precipitation volume between the steep and flat models is noticed. This difference is resultant from the way that the modeling applies the climate variables. Precipitation is applied into the model as a parcel of the climate surface boundary, computed by a unit area. The steep model has a greater surface area due to the elevation, consequently increasing the volume.

4.3 SVSlope® modeling set up

For analysis of the slope stability the steep slope models, named Area 1, were studied. SVSlope® works as a complementary version of SVFlux®, as it imports the geometry, soil properties and soil pore water pressures. A transient analysis is being performed, the pore water pressure along the soil profile is going to change. Analysis of the slope stability was performed by applying a 100 year rainstorm event and retrieving the developed pore water pressure caused by it. Coupling the SVSlope® with the SVFlux®, the strength parameters had to be defined. Soil strength properties used in this analysis are as reported by Stevens (2016) presented in Table 9.

Table 9 – Soil Strength properties (Stevens, 2016)

Material	Internal Angle of Friction (θ) (degrees)	Cohesion (c')(kPa)	Specific Gravity (G_s)	Dry Density (γ_d) (kN/m^3)
Fill	40.54	2.00	2.65	18.02
Compacted CCR (std. proctor)	38.30	2.00	2.19	19.74
60% CCR/ 40% Mgro™ blend	27.90	1.00	2.00	13.36

Where Φ (θ) is the internal angle of friction, c' is cohesion, γ_d is the optimum compacted dry unit weight and G_s is the specific weight of the soil. The search method selected for the analysis was the entry and exit. This method consists in establish a starting point or range and an end point or range for the potential slipping surface. As the analysis is being performed in a three dimensional scale, the area modeled was divided along its “Y” direction into 8 sections. Eight entry points are distributed along each red lines placed at the crest and same for the exit points at the red lines at the toe of the slope (Figure 29). The calculation methods selected for the analysis was the General Limit Equilibrium (GLE).

Figure 29 – Slope entry and exit ranges divisions along the slope.

Figure 30 presents the location of the entries and exits ranges in terms of X and Z coordinates, Y coordinates where the slope is being evaluated, entry and exits number of points along the range (increments), slope division and radius increments for the potential failure slope search.

Definition		Format	
<div> <div> <div>Entry Range(Right Side)</div> <div> ☒ Range ☐ Point </div> <div> <div>Left Point</div> <div> <div>X: 107</div> <div>Z: 59.633</div> </div> </div> <div> <div>Right Point</div> <div> <div>X: 134</div> <div>Z: 65.642</div> </div> </div> <div> <div>Draw</div> <div>Increments: 8</div> </div> </div> <div> <div>Exit Range(Left Side)</div> <div> ☒ Range ☐ Point </div> <div> <div>Left Point</div> <div> <div>X: 43</div> <div>Z: 39.037</div> </div> </div> <div> <div>Right Point</div> <div> <div>X: 67</div> <div>Z: 44.982</div> </div> </div> <div> <div>Draw</div> <div>Increments: 8</div> </div> <div>Radius increments: 8</div> </div> </div>			

Min. Value:

Max. Value:

Total Divisions

Y-Coordinate: 20

160

8

Aspect Ratio: 1

1

1

Apply

XZ View

OK

Cancel

Figure 30 - Entry and exit slope search description

4.4 SVSlope® results

By defining the search method and the potential slipping surfaces, the model was ready to be run. Analysis of the reclamations with a hydraulic barrier and without were performed. The results of 5184 trial slopes analysis for each time step and method are showed in the following sections.

4.4.1 Barrier cover reclamation

The cap and cover design resulted in a Factor of Safety of 2.06 which remained constant during the transient analysis for GLE calculation methods as illustrated in Figure 31.

Figure 31 - FOS of the Barrier Cover design during analysis time

The potential sliding mass for the design was founded to be near the crest of the slope, identified as the orange area in Figure 32.

Figure 32 – Barrier Cover design potential sliding mass

A cross section at the middle of the sliding mass with the trials of the potential sliding surfaces at the slope is presented in Figure 33. The lowest FOS of 2.06 is identified in red color with Table 10 presenting the geometric and physical properties of the sliding mass.

Figure 33 – Cap and cover design sliding surfaces trials

Table 10 - Sliding mass characteristics

GLE Analysis	Results
Factor of Safety	2.06
Total Weight (kN)	4,154
Total Volume (m ³)	255.30
Total Activating moment (kNm)	3.03x10 ⁵
Total Resisting Moment (kNm)	6.25x10 ⁵
Total Activating Force (kN)	1,554
Total Resistive Force (kN)	3,203
Total Active Columns	57
Total Sliding Surface Area (m ²)	585
Center Point (X,Y,Z) (m)	(40.82,80.00,220.29)
Ellipsoid Aspect Ratio	1.00, rx:178.97

4.4.2 Land cover reclamation

The land cover design resulted in a Factor of Safety of 2.02 which remained constant during the transient analysis for GLE calculation methods as illustrated in Figure 34.

Figure 34 - FOS of the land cover design during analysis time

The potential sliding mass for the design was founded to be near the crest of the slope, identified as the orange area in Figure 35.

Figure 35 – land cover design potential sliding mass

A cross section at the middle of the sliding mass with the trials of the potential sliding surfaces at the slope is presented in Figure 36. The lowest FOS of 2.02 is identified in red color with Table 11 presenting the geometric and physical properties of the sliding mass.

Figure 36 - Land cover design sliding surfaces trials

Table 11- Sliding mass characteristics

GLE Analysis	Results
Factor of Safety	2.016
Total Weight (kN)	3,653
Total Volume (m³)	252.4
Total Activating moment (kNm)	1.137x10 ⁵
Total Resisting Moment (kNm)	2.295x10 ⁵
Total Activating Force (kN)	1,379
Total Resistive Force (kN)	2,779
Total Active Columns	46
Total Sliding Surface Area (m²)	478
Center Point (X,Y,Z) (m)	(79.79,80.00,123.01)
Ellipsoid Aspect Ratio	1.00, rx:75.41

By comparing the slipping surfaces characteristics, it can be noticed that the Barrier cover presented a deeper and heavier potential failure surface. Total volume for both approaches are closer (255.3 m³ and 252.4 m³) however the compacted layer being part of the slipping mass increased its weight from 3,653 kN to 4,154 kN comparing to the Land Cover design.

5. COST ESTIMATION AND BREAK EVEN ANALYSIS

After computation of flows through the west boundary of the models, a comparison of the estimated reduction in Acid Mine Drainage can be performed for evaluation of the benefits of a proposal over another. A cost development of the Barrier Cover design was performed and compared to the Land Cover reclamation proposal cost. Based on the AMD production reduction, when facing the reclamations, a break-even analysis of when the construction cost will be surpassed by the savings on treatment.

5.1 Basis of Estimation

5.1.1 Project Coordination:

Overhead and profit for the general contractor will be established on 15% of the bare costs.

5.1.2 Field offices and sheds:

Field office will be a rented container with dimensions of 50' x 10'. Rent will be assessed in monthly stipends. Total cost of it will include telephone bills, with long distance calls, light and heating, ventilation and air conditioning. The shipping of the container with a distance of 60 miles is also included in the total price.

5.1.3 Sanitary Facilities:

Sanitary facilities will be provided by chemical bathrooms type porta potty or similar. Acquisition of 3 baths is being accounted, where one will be designated for the administration and the others will be placed in strategic positions in the field for fast access of the crew in to it.

5.1.4 Temporary access roads:

Due to the construction of the Channel east, a road relocation has to be done. The road is defined of a 3' compacted layer of CCR (Figure 37). Shrub cutting has to be done after surveying locate the edges of the road. With the road place cleaned, excavation and backfilling are going to be executed to reach the final elevation of the road as defined in the project. Final dry density has to

be inside the project acceptance range of 87.0 to 88.5 lb/ft³ for optimum compaction. The services for the road construction are excavation, backfilling and compaction, and their description are in the respective sections.

Figure 37 - Access road profile (adapted from Lorimer, 2016).

5.1.5 Project Signage:

Signals will be placed at the site to identify the major structures and locations during the construction. Safety signs will be placed near to the working locations and areas with accident risk. The cost of the signage will be included at the equipment mobilization

5.1.6 Assessment (Surveying):

Site surveying is one of the critical points in this project; a well done survey will lead to a well-executed project. Surveying will be conducted to stake out the field defining final elevation of critical points for execution of the project. Stakes will be placed based on the recommendation of a professional engineer and the opinion of the contractor if the latter is defined. The cost of the service is estimated using a crew of one chief of party, one instrument man, one roadman and the electronic level. It is expected a productivity of 3.3 acres leveled per day totaling 15 days of service.

5.1.7 Subsurface investigation (drilling, sampling and testing):

It has to be executed to verify the soil layering on the site also to take samples and compare to the previous lab testing. After soil profile description, the project has to be revised in case of major

changes has to be done. The crew for this service is estimated of one driller, two laborers. Drilling and sampling will be executed by a mounted truck auger and samples will be send to a qualified soil laboratory.

5.1.8 Material Transportation:

The cap layer is composed of a volumetric blend with 60% of CCR and 40% of Mgro™ short paper fiber. The Mgro™ has to be shipped from MeadWestvaco Company in Covington – Virginia to the Royal Scot site. This shipping is a 58.5 miles distance and the average time for it is 1 hour and 15 minutes from site to site with no traffic. The sipping will be made by 4 dump trucks with a capacity of carrying 34 cubic yards of material doing 2 trips per day. Total volume of Mgro™ is 29166.00 Cubic yards, each truck doing 68 cubic yards per day, resulting in 108 days of service.

5.1.9 Earthmoving

Excavating Bulk Bank Measure:

The excavation of the CCR pile will be done by 3 excavators with a 2 CY bucket in the areas defined as excavation. The excavated material will be loaded in a 22 cubic yard off-road truck that will haul the material to the filling areas stockpiling it. Each excavator will be served by 2 off road trucks taking in account 15 min of load/unload of each truck. For this service, a crew of 3 equipment operators (cranes licensed) and 6 truck drivers. An output of 1320 cubic yards of excavation per day is estimated for each crew, resulting in 86 days of work. For hauling, 594 cubic yards of coal refuse is anticipated, resulting in 95 days of work to the completion of the job.

Trenching:

The same excavator used to cut the pile can be used to trench the areas that Rip Rap will be placed with a 1 CY bucket. Where needed for the channel and ditches excavation. Thirty days of service is expected to finish the excavation of all channel and ditches by one excavator.

Backfill:

Fill will be done with three 200 hp (or similar) dozer or front end loaders hauling for an average distance of 150' from the excavated pile dumped by the off road truck to the final filling destination. The crew necessary for this service is 3 medium equipment certified operators and 2

laborers. A volume of 325006 cubic yards of backfilling will be executed at a rate of 1225 cubic yard per day for each dozer, resulting in 89 days of service.

Compaction:

Before start the compaction itself, water content has to be guaranteed in the right range according to the project (12.5% to 14.5%). If watering is needed, this will be made by 300 gallon truck spreading water in the layers before compaction. Compaction will be made in 6 inches thick lifts and compacted by a 12 ton. Towed vibratory roller until optimum dry density range (87.0 to 88.5 lb/ft³) permitted in project is acquired. A two passing compaction per lift is being taking in to account, however if two passes of the vibratory roller do not guarantee the final dry density, more passes are to be executed. For compaction, one medium equipment certified operator is needed and a laborer. A volume of 230125.44 cubic yards of soil are to be compacted by a riding vibratory roller which has the capacity of compact 3000 cubic yards per day, resulting in 77 days of compaction.

5.1.10 Growth layer:

The growth layer is designed to allow grass to grow and cover the project, so cap layer cannot be compacted. The blending of Mgro™ and CCR is going to be performed by an excavator mixing the materials together. The spreading of the blend at the site is done with dozers. After the spreading is complete a light tractor (220 hp or similar) will revolve the growth blend to prepare the layer to receive an appropriate grass seeds blend. Hydroseeding will be used to ensure that the whole area will be covered.

5.1.11 Earthwork methods:

Channels have three layers: compacted layer, filter layer and the liner layer. The grain size distribution of each layer has to be as described in project and the soundness of material has to be checked (Figure 38). Rip Rap materials are going to be machined placed (can use the front end loaders used to fill the slopes) in the trenches. Grouting will be done with the grout characteristics described in the project at the confluence/merging points of ditches and side channels by a length of 15 feet (Lorimer, 2016). Before placing, the rocks have to be washed and in the moment of grouting application they have to be wet. Grouting has to fill the joints between rocks completely

Figure 38 - Rip Rap Channel profile (adapted from Lorimer, 2016)

5.1.12 Cost Adjustment:

As the cost estimation was developed following RS Means (2016), the final location adjustments had to be performed because the values that the database use are averaged for the United States. For the geographic corrections that is proposed by RS Means (2016), Lewisburg – West Virginia is the closest city with a correction index, at a distance of 30 miles.

5.2 Cost Assessment

The cost for the reclamation of the Royal Scot refuse pile was calculated based on the RS Means Site Work & Landscape Cost Data. The discrimination of services are as described in Section 0 Basis of Estimation. Total unit price for each required service was consulted, as well as crew dimensioning and daily outputs. The quantities/ volumes were withdrawn from the WVU Geomorphic Landform reclamation submitted to the WVDEP. A creation of a spreadsheet with all services described, quantities and units, unit price and total price was developed for better comprehension of each service individual cost Table 12.

Some of the needed services were not discriminated in RSMeans, therefore they needed their own cost composition or estimation. Those services were the Mgro™ hauling from Westvaco factory at Covington - VA to the Royal Scot site at Anjean - WV, The Mgro™ mixing with the coarse coal refuse in the site and the growth blend plowing with a tractor for softening the soil for grass growth.

Table 12 – Cost Estimation for the Hydraulic Barrier Reclamation

Item #	Description	Quantity	Unit	Unit Price	Total
01 50 00	Temporary Facilities and Controls				
01 52 00	Construction Facilities				
01 52 13	Field Offices and Sheds (rent per month)	14.00	M	612.29	8,572.00
01 52 19	Sanitary Facilities	3.00	EA	672.50	2,017.50
01 54 36	Equipment Mobilization				
01 54 36.50	Equipment Mobilization	1.00	EA	120,000.00	120,000.00
01 55 00	Vehicular Access and Parking				
01 55 13	Temporary Access Roads	406.15	C.Y	6.48	2,633.17
01 57 00	Temporary Controls				
01 57 26	Site Watering for Dust Control + compaction moisture control	682585.20	SY	0.19	129,691.19
02 20 00	Assessment				
02 21 00	Surveys				
02 21 13	Site Surveys	47.01	AC	418.25	19,661.93
02 30 00	Subsurface Investigation				
02 32 00	Geotechnical Investigations				
02 32 13	Subsurface Drilling and Sampling	5.00	EA	2,433.55	12,167.75
02 32 16	Material Testing	5.00	EA	1,354.00	6,770.00
	Material Transportation				
	Mgro™ Short Paper Fiber Hauling				
	Mgro™ Short Paper Fiber Hauling	29166.00	CY	6.79	198,037.14
31 20 00	Earth Moving				
31 22 00	Grading				
31 22 13.20	Rough Grading	227528.40	SY	0.47	106,938.35
31 23 00	Excavation and Fill				
31 23 16.42	Excavating Bulk Bank Measure	337638.50	CY	1.66	559,129.36
31 23 16.13	Trenching	8731.00	CY	4.36	38,067.16
31 23 23.20	Hauling	337638.50	CY	0.14	48,343.69
31 23 23.14	Backfill	325005.80	CY	1.60	520,009.28
31 23 23.23	Compaction	230125.44	CY	0.38	87,447.67
	Mixing Mgro™/CCR in field	72915.00	CY	1.49	108,461.06
31 30 00	Earthwork Methods				
31 37 00	Riprap				
31 37 13	Machined Riprap	8373.00	SY	77.00	644,721.00
32 92 00	Turf and Grasses				
32 92 19.13	Mechanical Seeding, 215 lb./acre	227528.40	SY	0.07	16,745.82
	Blend plowing	455056.80	SY	0.07	31,853.98

The “Item #” is the identification of the service following the RS Means (2016) catalog (which is in conformation with the construction specifications institute MasterFormat), description is the name of the service, and quantity stands for the amount of the service needed in accordance with the unit. Unit price is the summation of the material, labor and equipment cost to develop one unit of the discriminated service. Unit price includes taxes and fees when applicable, however no overhead and profit is taken in account.

For the hauling, a cost composition was elaborated and is described in Table 13. Two options of dump trucks were considered, a 22 cubic yards and a 34 cubic yard volume capacity. Cost composition considers cost of labor, material and equipment. Labor cost was considered as one truck driver, material is the diesel price for fueling the trucks, and equipment was considered the truck maintenance (tires replacements and other minor repairs). No acquisition price or rental was considered for hauling because it is included in the mobilization price.

Table 13 - Cost composition for Mgro™ hauling by truck volume: 22 CY and 33 CY

Volume of Dump Truck (CY):	22
Truck driver hour (\$)	42
Diesel price (\$)	2.39
Mileage (mi/gal)	6
Tire life (mi)	80000
Tire price (\$)	400
Tires/truck	10
Trips/day	8.00
Trip length (mi)	120.00
Driver cost	\$168.00
Tire/ maintenance cost	\$6.00
Gas cost	\$47.80
Total Trips (60/40)	1326
Total Cost (60/40)	\$294,106.80
Total cost/trip/truck	\$221.80
Total days (60/40)	166
Cost/CY for 22 CY truck	\$10.08

Volume of Dump Truck (CY):	34
Truck driver hour (\$)	42
Diesel price (\$)	2.39
Mileage (mi/gal)	5.5
Tire life (mi)	80000
Tire price (\$)	400
Tires/truck	18
Trips/day	8.00
Trip length (mi)	120.00
Driver cost	\$168.00
Tire/ maintenance cost	\$10.80
Gas cost	\$52.15
Total Trips (60/40)	858
Total Cost (60/40)	\$198,151.20
Total cost/trip/truck	\$230.95
Total days (60/40)	108
Cost/CY for 34 CY truck	\$6.79

Cost for an hour of a truck driver was withdrawn from *RS Means* truck driver hour average, including taxes and fees, diesel was established as the average price consulted at Covington – VA and Anjean – WV. Tires lifecycle and prices were averaged on a 385/65R22.5 all position tires. As the Mgro™ is expected to be given and loaded for no cost, it was not considered. The Mgro™ mixing with coarse coal refuse in field is going to be proceeded as described in section 5.1 Basis of Estimation. The cost for that operation was considered as an excavation in loose sand, but revolving soil and Mgro™ together until a uniform blend is formed.

Final Price:

The estimated final price for the construction can be divided in three different final prices category: Final Bare Cost, Total Cost including overhead and profit and the Total Cost geographically adjusted. The total bare cost is the cost involving labor, materials and equipment, the total cost is the bare cost multiplied by the overhead and profit percentage, which was defined to be 15% for that project and the geographic adjustment is an index calculated by *RS Means* that is more accurate to the average price they used for calculations to the desired region. For this project, Lewisburg, WV was the closest city that had a calculated index. The index used to geographic conversion was the weighted average. Table 14 describes the final prices as previously mentioned.

Table 14 - Discriminated final prices

Bare cost	\$2,661,296
Overhead and Profit (15%)	\$399,194
Final Cost	\$3,060,490
City index for Lewisburg	96.7%
Adjusted final cost	\$2,959,494

5.3 Cash Flow Analysis

The estimated time of construction for this project was estimated for 14 months; the total final price for the state is expected to be spent over two years. To analyze the cash flow out, a productivity calculation for each service was assessed and the total number of days needed to finish the task was calculated. As described in Table 15.

Table 15 - Daily output per crew and total days to finish a service

Item #	Description	Quantity	Unit	crew	# of crews	daily output	days
01 50 00	Temporary Facilities and Controls						
01 52 00	Construction Facilities						
01 52 13	Field Offices and Sheds (rent per month)	14.00	M			1	14
01 52 19	Sanitary Facilities	3.00	EA			1	3
01 54 36	Equipment Mobilization						
01 54 36.50	Equipment Mobilization	1.00	EA				
01 55 00	Vehicular Access and Parking						
01 55 13	Temporary Access Roads	406.15	C.Y	B-10Y;B-10B;B-12C	1	1225	1
01 57 00	Temporary Controls						
01 57 26	Site Watering for Dust Control + compaction moisture control	682585.20	SY	B-64	1	20000	35
02 20 00	Assessment						
02 21 00	Surveys						
02 21 13	Site Surveys	47.01	AC	A-7	1	3.3	15
02 30 00	Subsurface Investigation						
02 32 00	Geotechnical Investigations						
02 32 13	Subsurface Drilling and Sampling	5.00	EA	B-55	1	0.6	9
02 32 16	Material Testing	5.00	EA				
	Material Transportation						
	Mgro™ Short Paper Fiber Hauling						
	Mgro™ Short Paper Fiber Hauling	29166.00	CY	B-34D	4	68	108
31 20 00	Earth Moving						
31 22 00	Grading						
31 22 13.20	Rough Grading	227528.40	SY	B-11L	1	36000	7
31 23 00	Excavation and Fill						
31 23 16.42	Excavating Bulk Bank Measure	337638.50	CY	B-12C	3	1320	86
31 23 16.13	Trenching	8731.00	CY	B-12A	1	297	30
31 23 23.20	Hauling	337638.50	CY	B-34F	6	594	95
31 23 23.14	Backfill	325005.80	CY	B-10B	3	1225	89
31 23 23.23	Compaction	230125.44	CY	B-10Y	1	3000	77
	Mixing Mgro™/CCR in field	72915.00	CY	B-12A	2	480	76
31 30 00	Earthwork Methods						
31 37 00	RipRap						
31 37 13	Machined RipRap	8373.00	SY	B-13	2	80	53
32 92 00	Turf and Grasses						
32 92 19.13	Mechanical Seeding, 215 lb./acre	227528.40	SY	B-81	1	20340	12
	Blend plowing	455056.80	SY	B-81	1	20340	23

Crew description and its equipment are described in Table 16.

Table 16 - Construction crew description

Crew	Description
A-06	Instrument man; roadman/chainman; level, electronic
A-07	Chief of party; instrument man; roadman/chainman; level, electronic
B-10B	Equipment operator (medium); 1/2 laborer; 1 dozer 200 hp.
B-10Y	Equipment operator (medium); 1/2 laborer; 1 vibratory roller towed 12 ton
B-11L	Equipment operator (medium); 1 laborer; grader 30,000 lbs.
B-12A	Equipment operator (crane); 1 laborer; hydraulic excavator 1 cy
B12-C	Equipment operator (crane); 1 laborer; hydraulic excavator 2 cy
B13	Equipment operator (crane); 4 laborer; 1 equip operator (oiler), 1 hyd. crane, 25 ton
B-34D	Truck driver (heavy); truck tractor 6x4 380hp; dump trailer 22 C.Y
B-34F	Truck driver (heavy); dump truck off hwy. 35 ton
B-55	Truck driver (light); 2 laborers; flatbed truck, 3ton; truck mounted auger
B-64	Truck driver (light); laborer; water reservoir (300 gallon); flatbed truck, gas 1.5 ton
B-81	Truck driver (heavy); laborer; Equipment operator (medium); 1 hydro mulcher truck mounted 3000 gal.; 1 truck tractor 220hp

By estimating the total number of days to finish a service, a Gantt chart (Table 17) could be developed to illustrate the construction process and define ranges of start and end date of each activity (blue shade). Periods are defined as months and the duration of each task is as defined in Table 15.

Table 17 - Gantt chart of activities for the reclamation construction

5.4 Actual AMD treatment cost and future expenses

To perform a break even analysis and compare the actual AMD treatment expenses with the predicted reduction found in the finite element seepage modeling, a contact with the WVDEP to account the actual expenses on their acid mine drainage treatment. The system used at the site is a passive treatment using caustic soda to neutralize the produced AMD on site. WVDEP reported in a personal interview that for the year of 2015, a total of 105,265 gallons of caustic soda was used at the site (Nathan Parks, personal communication).

The caustic soda price varies during time, therefore, an average of the buying price of \$1.60 per gallon was used to estimate an annual expense. The average yearly cost with chemical totaled \$168,424.00. The other main cost being spent is the cleaning of the sludge on the treatment pond. A yearly cost of \$ 4,900 was provided by the WVDEP that includes the electrical cost to pump the sludge from the treatment ponds to the sludge pit and pump maintenance.

A future expense that the WVDEP has planned for the Royal Scot refuse pile, is the slope reclamation due to erosion damage. The cost estimation for the site reclamation is as described in Table 18.

Table 18 - WVDEP reclamation cost estimation

ITEM	DESCRIPTION	QUANTITY	UNIT	UNIT PRICE	AMOUNT
1.0	Mobilization/Demobilization/Project Sign (Limited to 5% total bid maximum for this permit)	Lump Sum	LS	\$100,000.00	\$100,000.00
2.0	Site Preparation (Limited to 2% total bid maximum for this permit)	Lump Sum	LS	\$40,000.00	\$40,000
3.0	Construction Stakeout (Limited to 2% total bid maximum for this permit)	Lump Sum	LS	\$40,000.00	\$40,000.00
4.0	Utilities	No Bid Item		No Bid Item	No Bid Item
5.0	Regrading of Topsoil/Topsoil Substitute Borrow Material	28	AC	\$1,500.00	\$42,000
6.0	Topsoil/Topsoil Substitute Borrow Material	105600	CY	\$5.00	\$528,000
7.0	Regrading Refuse Material	189300	CY	\$3.00	\$567,900
8.0	Revegetation	28	AC	\$1,500.00	\$42,000
9.0	Storm Water Management-Silt Fence and Hay Bale Dike	7000	LF	\$5.00	\$35,000
10.0	Clearing and Grubbing	5	AC	\$2,000.00	\$10,000
11.0	Vegetative Enhancement	6	AC	\$1,500.00	\$9,000
12.0	Short Paper Fiber Application	70000	CY	\$5.00	\$350,000
15.0	Grouted Riprap Channel	1,800	LF	\$70.00	\$126,000
16.0	Grass Lined Channel	1,000	LF	\$15.00	\$15,000
17.0	Grass Lined Trapezoidal Channel	3,700	LF	\$20.00	\$74,000
18.0	Sumps	50	EA	\$100.00	\$5,000
19.0	Incidental Stone	200	TN	\$30.00	\$6,000
Notes: LS: Lump Sum, AC: Acres, CY: Cubic yards, LF: Linear foot, EA: Each, TN: Tons.				Total	\$ 1,989,900

Final bare cost, overhead and profit of 15% and final total cost are presented at Table 19, where bare cost is the sum of all services price, overhead and profit is the margin for the contractor and the final cost is the sum of bare cost and overhead and profit.

Table 19 – Land Cover reclamation estimation final cost

Bare cost	\$ 1,989,900
Overhead and Profit (15%)	\$ 298,458
Final Cost	\$ 2,288,385

5.5 Break Even Analysis

In possession of estimated cost of the Barrier Cover design reclamation and its benefits in acid mine drainage reduction compared to the Land Cover reclamation costs with no expected reduction in AMD (no infiltration reduction is expected) a break even analysis can be executed and the time for a payback assessed.

Adoption of the 80/20 Barrier Cover to this construction is indicated since it presented lower seepage volumes comparing to the *in situ* and the 60/40 hydraulic barrier. Using a barrier with low hydraulic conductivity will reduce the amount of water infiltrating, thus generating less acid mine drainage, resulting in the state saving money. The 80/20 Barrier Cover was estimated to be \$2,959,493, while the Land Cover is \$2,288,385.

The actual total cost with water treatments is calculated to be \$168,424, meanwhile, after the execution of the 80/20 Barrier Cover project, it is expected a 35.13% reduction in infiltration in the pile, consequently a reduction in AMD production by the same amount, resulting in a cost of \$109,257 per year on caustic soda, a difference of \$59,167.

Considering the year of the beginning of the reclamation being year 0, the total time for the Barrier Cover be a cost effective design is 10 years. These costs are presented on Table 20 and illustrated on Figure 39.

Table 20 - Cost comparison Land Cover vs. 80/20 Barrier Cover

Category	Land Cover Reclamation	80/20 Barrier Cover Reclamation
Total construction cost	\$2,288,385	\$2,959,494
Gallons of Caustic soda/year	105,265	68,285
\$/gallon caustic soda	\$1.60	\$1.60
year expenses on AMD	\$168,424	\$109,257

Figure 39 - Break Even Analysis for the 80/20 Barrier design compared to the Land Cover reclamation. The arrow identifies the moment when the break-even occurs (10 years).

6. CONCLUSIONS

Evaluating the results of the 3D unsaturated seepage and slope stability modeling, cost estimation and the the break-even analysis, it can be inferred that:

1. The seepage model analyzed for the Land Cover design showed that the precipitation will essentially infiltrate in to the refuse layer, consequently there will be no reduction in seepage. The Hydraulic Barrier Cover model presented different behaviors for each different soil gradation utilized. The *in situ* compacted barrier presented an infiltration delay of 20 days for the steep modeling and a 30 day delay for the flat model. This model simulates the worst case scenario of a precipitation infiltration, and the evapotranspiration parcel of the water balance is not applied.
2. The use of controlled fines presented a better hydraulic barrier compared to the *in situ* material. Infiltration reduction averages of 26% for the 60/40 barrier and 35% for the 80/20 barrier were predicted by the seepage finite element modeling. Although the 60/40 ratio had more fines in its composition, the aggregation of fines shifted the GSD curve to a larger particle size, consequently increasing the effective diameter and resulting in a higher hydraulic conductivity.
3. The unsaturated soil mechanics presented to be very suitable on analyzing the seepage modeling. It can be noticed during the saturation process that the slope of the infiltration trough the hydraulic barrier changed, presenting the effect of saturation reducing the hydraulic conductivity thus flattening the infiltration slope.
4. In terms of slope stability, both steep and flat approaches presented a stable slope. The factor of safety remained constant from the beginning to the final of the transient analysis. Difference in FOS from the Land Cover to the Hydraulic Barrier Cover varied at the third decimal, presenting the values of 2.02 and 2.06 respectively.

5. The estimated construction cost for the Hydraulic Barrier Cover proposal is \$2,959,494, for a manageable construction time of 14 months. Reclamation cost for Land Cover design is lower (\$2,288,385), however, this cover system did not reduce the precipitation infiltration into the refuse layer.
6. For a long term scale cost analysis, the maintenance and cost with Caustic Soda to neutralize the acidity of the water will surpass the cost difference (\$671,109) from the Hydraulic Barrier design construction after 10 years.
7. Comparing the post construction cost to treat the AMD, a yearly reduction of \$59,167 on water treatment is estimated. A break even analysis for the Hydraulic Barrier reclamation presented a 10 years period, a reasonable time, as the refuse pile will not be moved and will continue producing AMD. Estimation of a worst-case design scenario resulted in a \$1.18 million savings over a 20 year period. This design implementation can be expanded to other AMD producing coal refuse piles, multiplying the savings for the State and protecting the environment.

7. FUTURE WORK

To develop a better description of the design, some material properties has to be evaluated for future work. First, a Soil-Water Characteristic Curve test for the material to compare and contrast with the estimation of the Zapata (1999) and Torres (2011) equations. SWCC has a major role under unsaturated mechanics, describing the matric suction for the soil as its water content increases, governing the hydraulic and strength properties.

Soil investigations into the mine refuse layer is necessary to evaluate strength and more important its hydraulic properties and state (void ratio, density, saturation, etc.). With this in hand, a better description of seepage, water retention time and volume as well as water table description.

Study on the growth layer long term consolidation, as well as its combination with grass coverage, and how it is going to affect the runoff. Runoff increases will be an important parcel of the infiltration reduction of the design.

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