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Conversion of an evapotranspiration soil cover to a geosynthetic cover for a waste rock facility closure

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Abstract

Earthen water balance covers (e.g., ET covers) are used widely throughout the world to minimize or eliminate meteoric percolation through mine waste facilities. ET covers promote sustainability because they are constructed with natural materials generally available on or near a mine site, and function harmoniously with local hydrological processes. However, percolation from ET covers varies widely, and is dependent on total annual precipitation and precipitation occurrence (rain or snow). At semiarid and arid sites having low annual precipitation, percolation rates through ET covers are typically negligible (i.e., less than 5 mm/yr). In contrast, at humid sites with high annual precipitation, percolation rates can be high (i.e., greater than 100 mm/yr).

In 2002, an ET cover was constructed on a waste rock facility (WRF) at Rain Mine in northern Nevada. The WRF is located at high altitude (2,020 m above mean sea level) where annual precipitation, primarily in the form of snow, is estimated at 442 mm. Mature vegetation was established by 2011 and estimated percolation through the WRF was about 12% of annual average precipitation (2011–2019). The high percolation rate from the WRF occurs because accumulated snow is difficult to manage with an ET cover in a snowmelt hydrology setting. To achieve low percolation rates, a geosynthetic cover is required.

This paper presents a case study, where parts of an existing ET cover are replaced with a geomembrane that is overlain by a geocomposite drainage layer. Existing ET cover soils were salvaged, and then placed on top of the geosynthetic cover. The geosynthetic cover system was constructed on the part of the WRF that receives most of wind-drifted snowfall deposits.

This case study summarizes a performance evaluation of the ET soil cover, characterization data collected, and geotechnical analyses performed in support of the new cover design. Construction experience learned from the execution of the project and performance data of the new cover system collected to date are also presented. Preliminary results indicate that the seepage rate from the WRF has been significantly reduced after the new cover installation.

Keywords: *Waste rock facility closure, earthen water balance cover, geosynthetic cover, cover performance evaluation, geotechnical analyses*

1 Introduction

The Rain Mine site is a closed mine site located approximately 14.5 km (9 miles) southeast of Carlin, in Elko County, Nevada. The subject facility, herein referred to as the North Waste Rock Disposal Facility or the NWRDF, encompasses approximately 73 hectares (or 180 acres) of land. Waste rock placement occurred during active open pit mining during the period of 1987 to 1994. Waste rock placement between 1990 and 1994 was modified to isolate sulfide material using an encapsulation zone by placement of a 46 m (150 feet) thick rind of oxide material around its perimeter and as a capillary break under its base. The referenced facility is located at elevations mostly between 1,950 m (or 6,400 feet) and 2,072 m (or 6,800 feet) above mean sea level (amsl), averaging about 2,020 m (or about 6,627 feet) amsl.

An underdrain collection system was constructed starting in 1991 and expanded in 1996 to accommodate additional seepage observed along the western toe of the facility. The collection system was designed and constructed to report to an acid rock drainage (ARD) collection pond. The expansion of the collection system in 1996 included the construction of interceptor trenches and collection laterals along the toe of the facility as well as a conveyance pipeline. Further expansions of the collection system were constructed to manage additional seepage in 1999 and 2000.

Construction of an evapotranspirative (ET) cover of NWRDF was completed in 2002. The cover consisted of 0.9 m (or 3 feet) of subsoil cover material along with 0.3 m (or 1 foot) of topsoil and vegetation. The intent of the ET cover was to impede vertical infiltration of meteoric waters, allowing established vegetation to transpire accumulated moisture within the cover.

With continued ARD flow from the NWRDF, the performance and effectiveness of the ET soil cover was observed to be inadequate. Nevada Gold Mines LLC (NGM) had identified an approximate 30-hectare (75-acre) area located along the eastern portion of the NWRDF for targeted cover improvements to reduce infiltration of meteoric waters contributing to the generation of ARD, which prompted the need for the cover improvement project involving conversion of the cover system in a portion of the NWRDF from a soil cover to a geosynthetic cover. Refer to Figure 1 for a general site layout of the Rain Mine site along with a vicinity map.

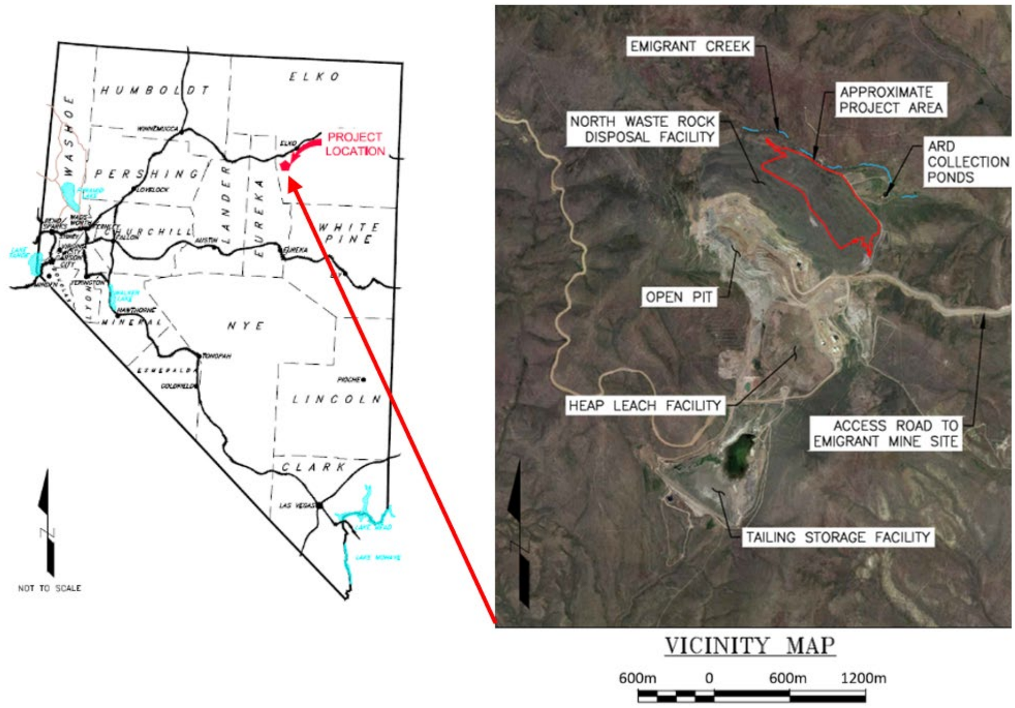


Figure 1 Rain Mine site layout and vicinity map

2 Project setting

2.1 Climate

The site is characterized as a semi-arid, high-altitude environment typical of the northeast region of Nevada. Precipitation data have been collected onsite since 1991. A recent summary of precipitation data based on review of climate data since 1980 in support of the project design estimated an average annual precipitation of 442 mm (or 17.4 inches), and annual potential evapotranspiration of 1,168 mm (or 46 inches).

In addition, considerable snow drifting has been observed on the north facing slopes of the NWRDF, which became the primary focus for cover improvements within the NWRDF. These drifts are believed to contribute significantly to the observed ARD collected from the toe of the facility. Numerous snow surveys were performed at the NWRDF with the greatest snow depths ranging from 0.6 m to 0.9 m (or 2 to 3 feet).

Climatological data utilized in this study was mainly based on historical precipitation data collected at the site from all previous site studies. Figure 2 presents constructed annual precipitations recorded for the Rain Mine.

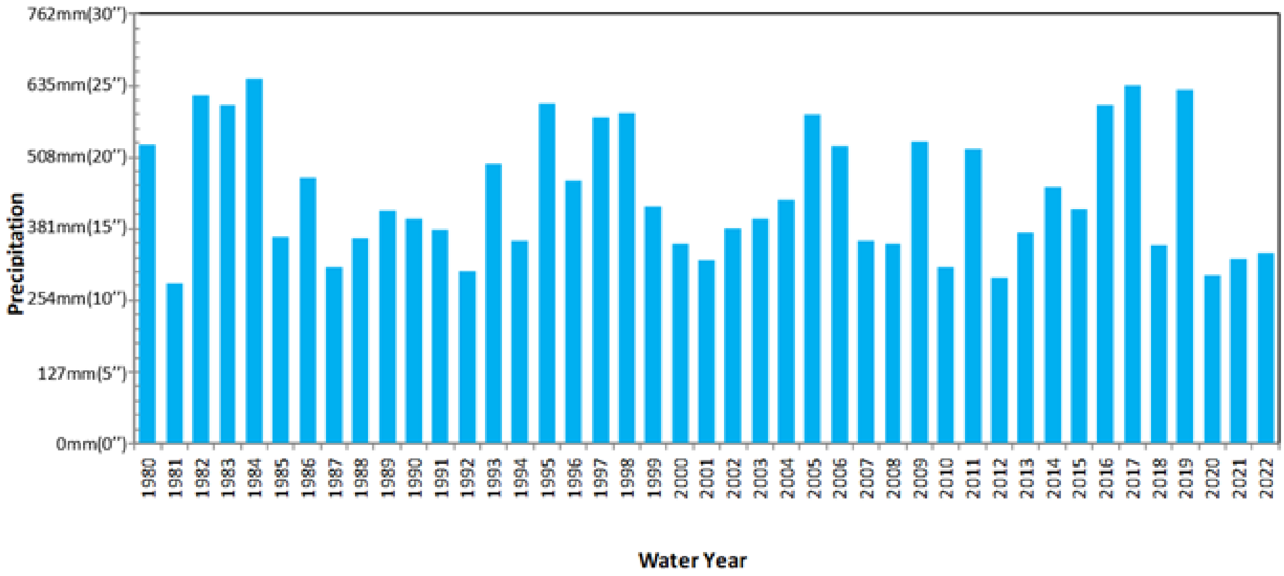


Figure 2 Rain Mine water year annual precipitations

2.2 Site geology and seismicity

The site is located on the eastern limit of the Pinion Range which includes the southern limits of the Carlin Trend. The area is characterized as being dominated by fault block tectonics and includes sediment filled basins between the north-south trending ranges. In addition, major faulting near the site is composed of west and northwest trending, high angle normal and reverse faults. Exposed lithologies across the site were noted to mostly consist of the following:

- Mississippian Webb formation: mudstone, siltstone and sandstone; or Mississippian Chainman formation: conglomerates, sandstone, and mudstones.
- Devonian Devil's Gate limestone.
- Colluvium.

The United States Geological Survey (USGS) through the National Earthquake Hazards Reduction Program (NEHRP) has evaluated the general seismic characteristics of the conterminous United States, particularly the western United States. Design ground motions for the project were derived using the online "unified hazard tool" published and managed as part of the National Seismic Hazard Mapping Project within the USGS's earthquake hazards program. The output data are probabilistic peak horizontal ground accelerations associated with site locations mapped on a grid system, which were used in support of the stability analyses. Review of published data on earthquakes and mapped fault traces with evidence of latest Quaternary displacement does not suggest the NWRDF is located over any reported traces of Quaternary faults.

3 Existing ET soil cover and performance review

Prior to the improvements project, the ET soil cover constructed in 2002 utilized soils borrowed from the adjacent areas for use as both subsoil and topsoil material. The placed soil cover, from the bottom to the top, consists of (1) 0.9 m (or 3 feet) of subsoil, and (2) 0.3 m (or 1 foot) of topsoil and vegetation, as shown in Figure 3.

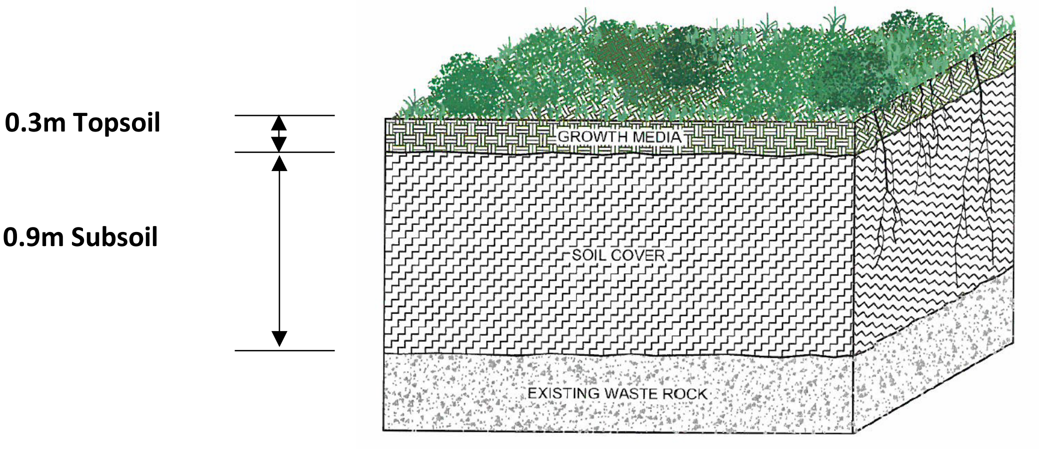


Figure 3 Existing ET soil cover

3.1 ET cover performance evaluation

An implicit assumption in cover design is that the evapotranspiration (ET) for the cover will ideally remove nearly all of the available stored water each year, leaving an empty "sponge" that is ready to store infiltrated water during the following wet season. The "sponge" concept is illustrated on Figure 4.

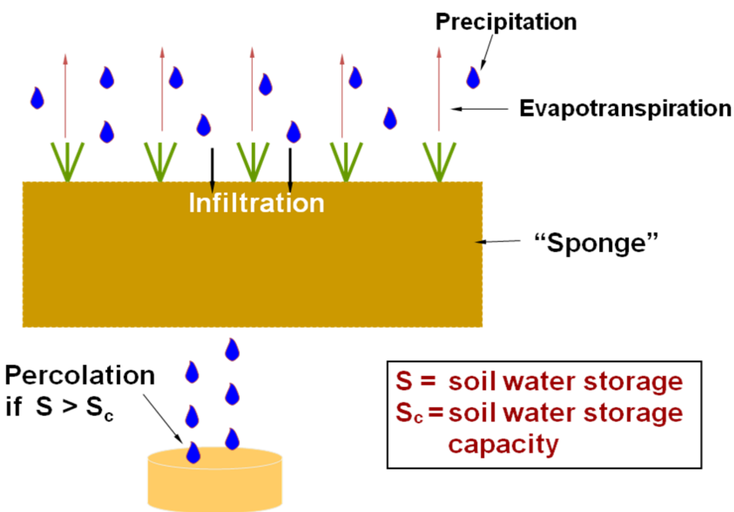


Figure 4 ET cover design – sponge concept

Ideally, the required water storage (S_r) of a cover should equal the net infiltration during the wetter period of the year when precipitation exceeds ET. Cover design can be based on numerical modelling and/or field test plots. In this evaluation, a water balance approach is used for its simplicity and practical application.

A semi-empirical method to estimate the required storage for a cover was first developed during the US EPA-funded Alternative Cover Assessment Program ACAP (Albright et al, 2004) using site data collected from test facilities in the US. The monthly accumulation of soil water storage (ΔS) can be determined using Equation 1 when the precipitation/potential evapotranspiration, or P/PET, threshold is exceeded:

$$\Delta S = P - \beta\ PET - \Lambda \qquad (1)$$

Where P is the monthly precipitation (mm), PET is the monthly potential evapotranspiration (mm), β is a fraction which represents actual ET, and Λ is a lumped loss term.

A summary of P/PET threshold, β and Λ under different climate conditions is shown in Table 1.

Table 1 Parameters for Equation 1 under different climate conditions (AlbriqhtAlbright et al, 2004)

Climate type	Season	P/PET threshold	β (-)	Λ (mm)
No Snow & Frozen Ground	Fall-Winter	0.34	0.30	27.1
	Spring-Summer	0.97	1.00	167.8
Snow & Frozen Ground	Fall-Winter	0.51	0.37	0
	Spring-Summer	0.32	1.00	167.8

Based on review of historic studies by multiple parties, records of the site weather station, as well as published climate data such as the Climate Engine, the following average monthly precipitation and PET of Rain (Figure 5) were used for the project design.

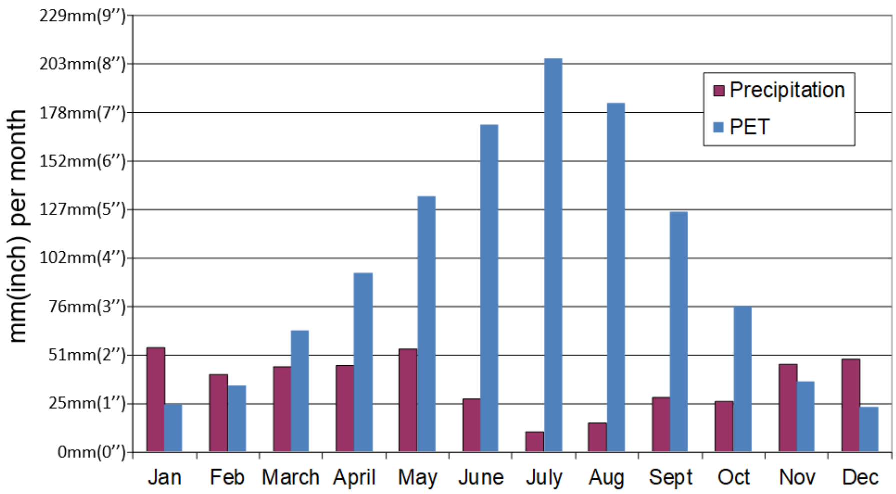


Figure 5 Estimated average rain monthly precipitation and PET

Based on Table 1 and monthly inputs as summarized in Figure 5, it is determined that the ET cover needs to have a required annual water storage (S_r) of 166.5 mm (or 6.6 inches) to effectively minimize meteoric percolation through the cover (Table 2), which indicates the following:

- During the hot season (April through October) precipitation in these months will be virtually lost to ET as PET far exceeds P.
- As PET is small during the cold season (November through March), little precipitation in these months is lost and the majority amount of precipitation needs to be stored in the cover.

Table 2 Computation of required cover water storage

Month	Precipitation (mm)	PET (mm)	Snow/Frozen Ground?	Season	P/PET	Threshold (P/PET)	Threshold Exceeded?	Beta β (-)	Lambda Λ (mm)	*Δ* S (mm)
Jan	54.3	25.0	Y	Fall/Winter	2.17	0.51	Y	0.37	0	45.0
Feb	40.7	34.6	Y	Fall/Winter	1.18	0.51	Y	0.37	0	27.9
Mar	44.8	63.9	Y	Fall/Winter	0.70	0.51	Y	0.37	0	21.2
Apr	45.2	93.4	N	Spring/Summer	0.48	0.97	N	1.00	167.8	0.0
May	54.2	133.8	N	Spring/Summer	0.41	0.97	N	1.00	167.8	0.0
Jun	27.7	171.2	N	Spring/Summer	0.16	0.97	N	1.00	167.8	0.0
Jul	10.4	206.2	N	Spring/Summer	0.05	0.97	N	1.00	167.8	0.0
Aug	14.9	182.6	N	Spring/Summer	0.08	0.97	N	1.00	167.8	0.0
Sep	28.4	125.6	N	Spring/Summer	0.23	0.97	N	1.00	167.8	0.0
Oct	26.7	76.2	N	Fall/Winter	0.35	0.34	Y	0.30	27.1	0.0
Nov	45.9	36.6	Y	Fall/Winter	1.25	0.51	Y	0.37	0	32.3
Dec	48.6	23.3	Y	Fall/Winter	2.08	0.51	Y	0.37	0	40.0
Total (mm)	**441.8**	**1,172.2**	Total Required Storage (mm) =							**166.5**

Storage capacity (S_c) of a cover profile represents all soil water present when percolation is incipient (or negligible) and is determined by integrating the field capacity (θ_c) over the cover thickness. Therefore, the storage capacity is computed as:

$$S_c = L\,\theta_c \tag{2}$$

Where L is the thickness of the cover.

Not all of the storage capacity is available for storing water because plants cannot remove some of the water stored in soil. The water that cannot be removed is defined by the wilting point (θ_m). The available storage capacity (S_a) of a soil layer is the total storage capacity less the water content remaining at the minimum water content:

$$S_a = L\,(\theta_c - \theta_m) \tag{3}$$

By convention, field capacity (θ_c) is normally assumed to be the water content corresponding to a suction of 33 kPa. The minimum water content (θ_m), or wilting point, is normally assumed to correspond to a suction of 1,500 kPa. In the desert plant communities in the Great Basin, it is common for the wilting point to correspond to a much higher suction, i.e., 4,000 kPa, to account for their higher salt tolerance (Zhan et al, 2006). Benson (2007) indicates that most arid region plants can extract water from the soil at suctions up to 5,000 to 8,000 kPa. θ_c and θ_m are usually derived from water retention curves (WRCs) showing the relationship between water content and suction of a soil, commonly determined in laboratories.

In order to monitor the movement of meteoric water in the cover profile, nine moisture monitoring stations were installed in the cover of the NWRDF. Each monitoring station incorporated moisture monitoring probes and temperature probes, installed in both the topsoil and subsoil. Based on field measurements, as well as characterization and modelling, a range of available water contents between 8% and 10% was used for the project, with consideration of 10% being more representative of site conditions with higher suction as discussed above.

Based on the above calculation, the total required storage is 166.5 mm (6.6 inches), and actual storage of the 1.2m (or 4-foot) cover is 95.0-121.9 mm (3.7- 4.8 inches), resulting in a storage deficit of 44.6-71.5 mm (1.8-2.8 inches). The above calculation can also be used to estimate deficiency in the ET cover thickness. If the ET soil cover was designed to hold the infiltrated water during the wet season (with precipitation totalling 167mm or 6.6 inches), the required cover thickness would be between 1.7m and 2.1m (5.5 and 7.0 feet), higher than the current thickness of 1.2m (or 4 feet).

3.2 NWRDF ARD seepage modelling

To evaluate the cover system efficiency, a monthly time-step, spreadsheet-based water balance model was created. The model considers the close inter-relationship between precipitation, ET, and cover net infiltration on a monthly scale with continuous feedback of water movement in the soil-plant-atmosphere continuum. While the NWRDF cover was installed in 2002, ARD seepage has been collected since March 1991. Figure 6 shows the recorded seepage rates and site precipitations summarized. By examining the seepage trend and baseflows (lowest flows in September and October), it appears that the cover performance became dynamically stable around year 2011 after vegetation became mature and/or after completion of draindown of stored moisture in the waste rock material.

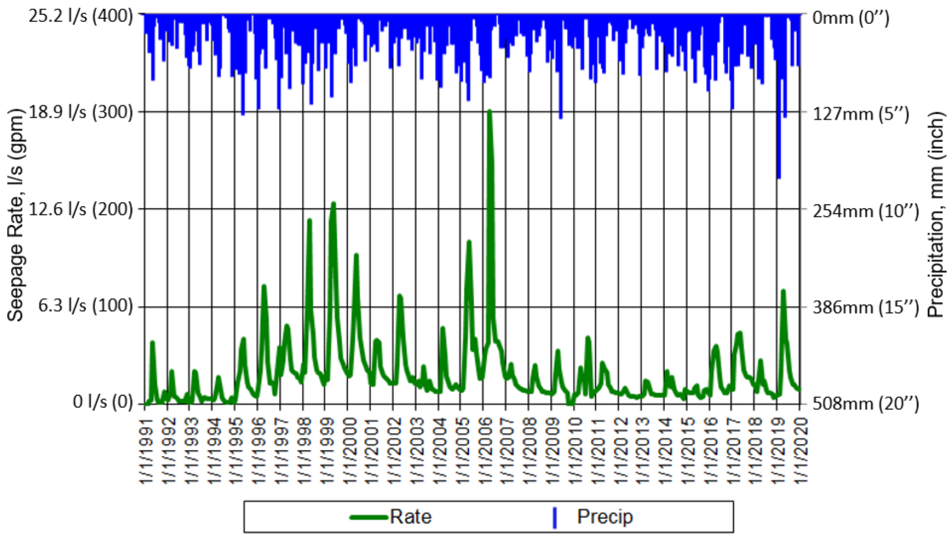


Figure 6 Recorded NWRDF ARD seepage and the site precipitation

Figure 7 shows the simulated recharge rates from water balance modelling, which closely reproduced the recorded seepage rates for the monitoring period after pedogenic processes and cover vegetation reach stable conditions. The simulation of historic ARD recovery rates supports the cover performance evaluation discussed previously.

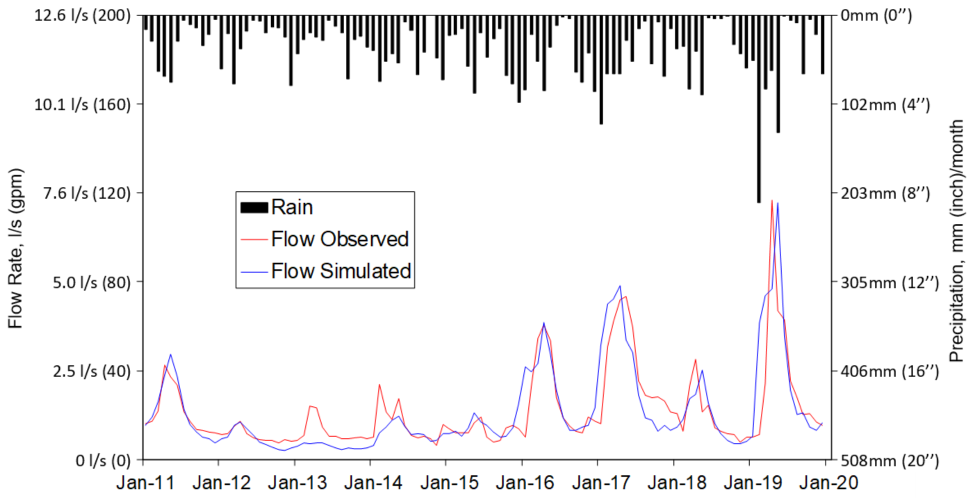


Figure 7 Monthly measured and modelled ARD seepage from NWRDF

For the period of Jan 2011 through Dec 2019, the average annual precipitation and seepage rate are 508 mm (20 inches)/year and 1.4 liter/sec (or 22 gallons per minute/gpm), respectively. Considering the NWRDF footprint of 73 hectares (180 acres), the unit percolation rate is 61mm (2.4 inches), closely matching the estimated storage deficit range of 44.6-71.5 mm (1.8-2.8 inches) discussed above. The calculation also indicates that seepage rate is about 12% of precipitation, which is within the range of values commonly seen in the literature for ET covers. This exercise further validates cover performance discussions in Section 3.1.

3.3 Findings from cover performance evaluation

The seepage rates as discussed in Section 3.2 exceed the flow limits that can be sufficiently managed by the existing ARD collection system and prompted the need for cover improvement to reduce ARD flows.

Based on the above ET cover performance evaluation, a geosynthetic cover was proposed for the areas that had been identified to collect more snow and incur more ARD flows, primarily based on considerations of the following:

- Deficiency in thickness of the existing ET soil cover.
- Constraints of project boundaries due to adjacent features, such as roads, natural drainages, and ponds. Addition of geosynthetic materials does not increase thickness of cover compared with the existing system thus minimizes the impact on these features where relocation or modification may involve substantial effort.
- Effectiveness of geosynthetic covers, in comparison with other cover options.
- Opportunity in salvaging existing soil cover materials for use in the new cover system.

The intention of the improvements is to reduce long-term ARD flows to be below 0.63 liter/sec (10 gpm) from the currently flow of 1.4 liter/sec (22 gpm).

4 Geosynthetic cover design

A geosynthetic product, referred as Super Gripnet® geomembrane by AGRU America, was used for the project. Figure 8 shows a typical profile of installation which involves a geotextile and overlying soils to be used in conjunction with the geomembrane. With the assembly proposed, the application is deemed appropriate for the project mainly considering: (1) high interface shear strength and capability of use in relatively steep slopes; (2) incorporation of an integral drainage system (IDS) above the geomembrane which will impede and convey infiltration through the overlying soil cover along the interface. This section presents the design of the new cover system along with supporting geotechnical analyses performed.

Figure 8 Typical Super Gripnet® installation profile (reproduced from www.agruamerica.com)

4.1 Site characterization

To support the design of the lined cover system, field investigations were conducted to obtain representative samples of the existing ET cover and identify potential borrow material. These investigations consisted of test pit excavation, soil sampling, laboratory analysis to define index properties and engineering characteristics of the subsurface materials. The intent of the field sampling effort was to:

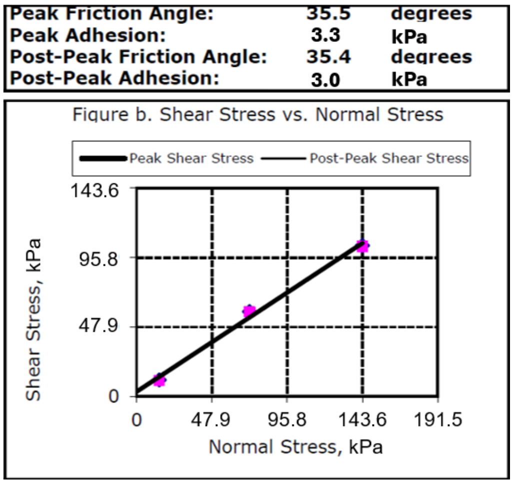
- Evaluate the suitability of the existing NWRDF ET cover soils for re-use as liner cover material referred to as Overliner).
- Identify additional sources of borrow material to use as liner bedding and makeup cover materials if required.
- Evaluate adjacent materials as a possible borrow source for liner bedding if and where needed.

In addition to the above, the site characterization is also based on historic work by various parties. A total of thirteen (13) test pits were excavated and sampled. Bulk and bag samples of soils were collected from spoils excavated from each test pit and sent to laboratories for testing.

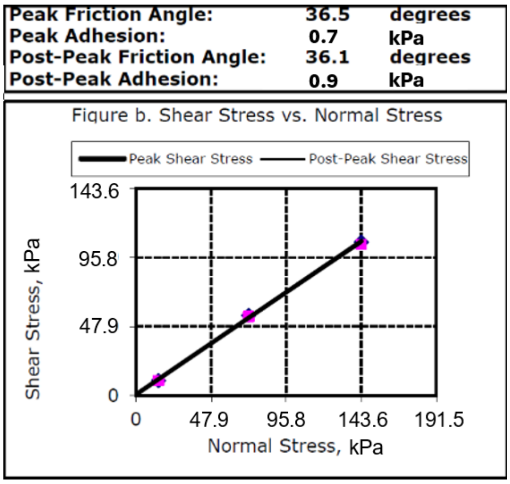
Geotechnical laboratory tests have been performed on the bulk samples in support of soil characterization and engineering analysis. The purpose of the laboratory testing was to assess the physical and engineering properties of various samples collected in the field and to evaluate characteristics (both puncture resistance and interface shear strength) of liner interface under planned applications. Geotechnical laboratory testing was completed on selected bulk soil samples collected from the test pits. Laboratory testing performed included the following:

- Index testing including Sieve Analysis (ASTM D422), Moisture Content (ASTM D2216), Atterberg Limits (ASTM D4318).
- Modified Proctor (ASTM D1557) was completed for compaction characteristics of soil using modified effort.
- Liner Puncture testing was completed to determine puncture resistance under two different overburden pressures, utilizing an 80-mil HDPE Super Gripnet® and 16oz nonwoven geotextile, along with soil material sourced onsite. The tests were performed under two different loadings corresponding to 1.5 to 3 times of maximum construction loads.
- Standard Test Method for determining the Shear Strength of Soil-Geosynthetic and Geosynthetic-Geosynthetic Interfaces by Direct Shear (ASTM D5321). A total of three sets of liner interface shear

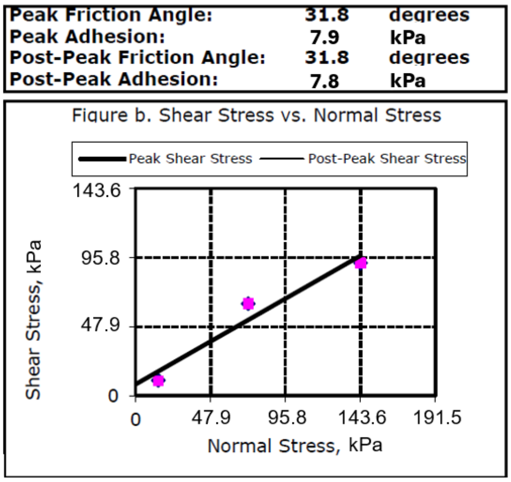
tests have been performed using the subsoil of the existing cover as the Overliner, with the results presented in Figure 9.



(a) Interface Shear Test 1



(b) Interface Shear Test 2



(c) Interface Shear Test 3

Figure 9 Liner interface shear strength testing results

4.2 Proposed new cover design

The NWRDF cover improvement project was carried out in accordance with relevant regulatory and permitting requirements, particularly Nevada Administrative Code (NAC) 445A "Water Controls" and NAC 519A "Reclamation of Land Subjected to Mining Operations or Exploration Projects."

The NWRDF cover improvement design strategy includes the following elements:

- Identifying and evaluating on-site borrows for different construction materials as needed.
- Removal and stockpiling of existing cover materials for re-use.
- Regrading of the surface of the NWRDF as needed to facilitate stormwater drainage.
- Mass grading involving a balanced cut and fill; therefore no waste rock and cover materials will be exported from the NWRDF as a result of construction.
- Design of a synthetic and impermeable liner cover with integrated drainage system (IDS) within the targeted improvement area.

- Design of stormwater controls to meet requirements of the NAC 445A.350-445A.447 in the targeted improvement area.

The design was prepared with the following key features:

- Average regraded slopes no steeper than 2.5H:1V (horizontal to vertical).
- Removal of most of the existing benches and reconstruction of two new benches to promote stormwater drainage; a perforated piping system (consisting of a 6-inch-diameter corrugated polyethene pipe or CPE pipe) was proposed on each bench to collect seepage reported from the upper slope and provide drainage relief to the IDS.
- Lined cover system over the improvement area, from bottom to top, consisting of: (1) prepared subgrade (and liner bedding fill layer if needed); (2) an 80-mil high density polyethylene (HDPE) Super Gripnet® by AGRU or equivalent, (3) 16oz non-woven geotextile, (4) 2-foot overliner material using salvaged existing subsoil, and (5) 1-foot growth medium using existing salvaged topsoil.
- Stormwater diversion channel along the crest of the improvement area to facilitate drainage to manage a 500-year, 24-hour event as required by NAC 445A; newly constructed bench and stormwater diversion channels that tie-in to existing site-wide stormwater management facilities.
- The design is implemented in a fashion, and with necessary precautions, to avoid impact on and disturbance of the ARD collection system.

A site layout with major improvements is shown in Figure 10, along with a typical new cover detail.

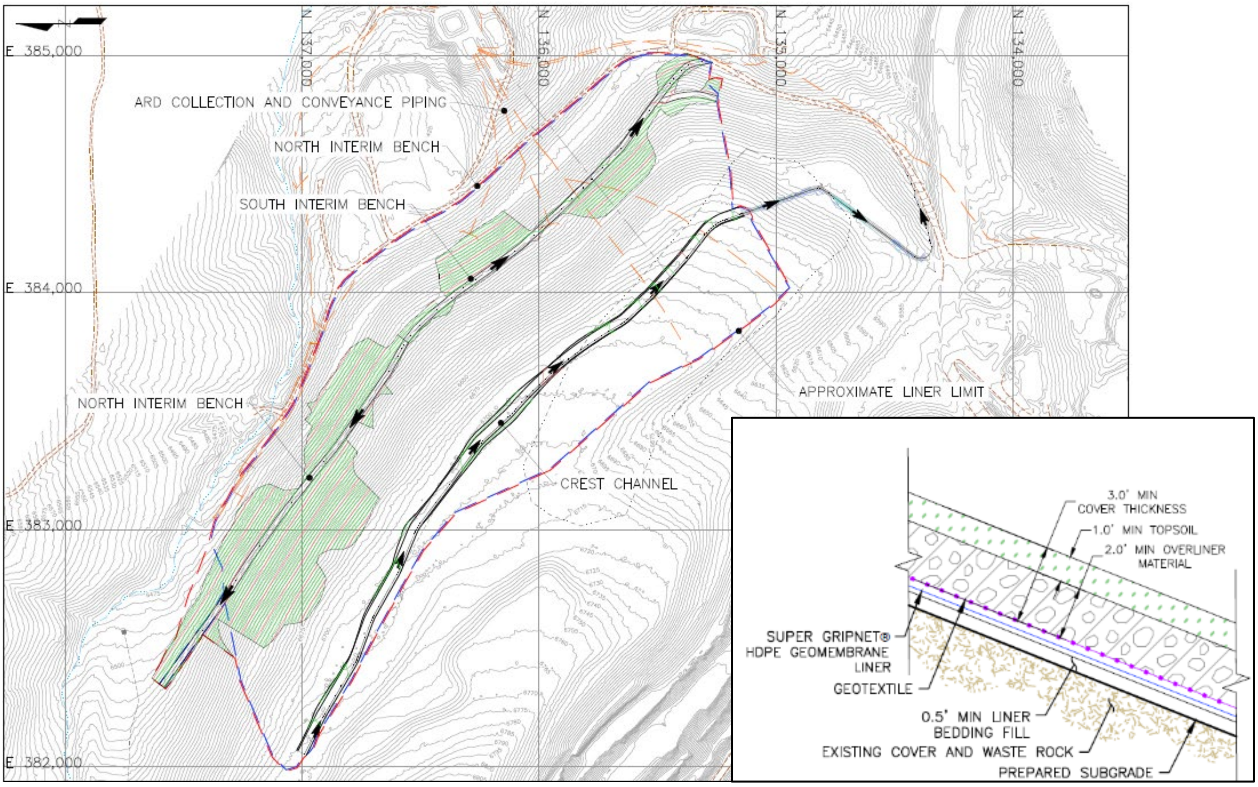


Figure 10 New cover improvements layout with typical cover detail

(grid line labels and dimensions shown in feet; 1 foot = 0.305m)

4.3 Supporting engineering analyses

The following geotechnical analyses have been performed in support of the design. The main focuses of geotechnical analyses are to (1) evaluate flow capacity of the IDS versus the cover filtration to ensure adequacy of the IDS system above the geomembrane; and (2) perform veneer stability (or surficial stability) of the cover system and global stability analyses of slopes.

4.3.1 Infiltration analysis

The infiltration analysis was carried out based on ARD flows discussed in Section 3, in order to:

- Estimate the amount of seepage reporting to the IDS and check against design conductivity of the proposed IDS for different cases of flow.
- Evaluate the adequacy of 6-inch CPE pipe to receive infiltrated water through the cover system.

Conservatively assuming all ARD seepage is through the targeted improvement areas of 30 hectare (75 acres), the following two cases of seepage were evaluated, accounting for reduced thickness of soil materials in the new cover:

- Case 1: Average observed seepage = 2.2 liter/sec (or 35 gpm).
- Case 2. Maximum recorded seepage = 18.9 liter/sec (or 300 gpm).

These above scenarios are considered in evaluating the efficacy of the IDS. Rates of unit seepage were compared against calculated flow rates for the Super Gripnet®, using the following equation,

$$\theta = \frac{q}{iw} \tag{4}$$

where θ = transmissivity of the Super Gripnet®, 4x10^{-3} m^2/sec (published by AGRU America); q = flow rate (m^3/sec); i = hydraulic gradient or slope of IDS, which is 4% across inter-slope benches and about 40% along overall slopes; w = width of geomembrane (m), which, on this project, is about 158 m (or 520 feet) for the longest horizontal run of single lifts above or below inter-slope benches, and about 244 m (or 800 feet) for the greatest horizontal length of overall slope.

The calculations, as summarized in Table 3, shows that the transmissivity of the liner IDS is much greater than the estimated unit seepage for each case with design slopes. Relief of the proposed CPE piping system which is anticipated to add additional redundancy for conveyance of seepage flow at inter-slope benches. The calculated capacities of IDS transmissivity are one to two orders of magnitude higher than the flows of both cases, indicating abundant adequacy in the IDS.

Table 3 Summary of results from infiltration analysis for improved cover design

Scenario	Inter-slope bench flow (4%)		
	Unit seepage rate - bench liter/sec/m(gpm/ft)	**Design flow capacity - bench liter/sec/m(gpm/ft)**	**Acceptable (Yes / No)**
Case 1 – Average Seepage Case	0.001 (0.006)	0.160 (0.77)	Yes
Case 2 – Maximum Seepage	0.010 (0.048)		Yes
Scenario	**Overall NWRDF flow (~40%)**		
	Unit seepage rate - overall liter/sec/m(gpm/ft)	**Design flow capacity - slope liter/sec/m(gpm/ft)**	**Acceptable (Yes / No)**
Case 1 – Average Seepage Case	0.002 (0.009)	1.602 (7.73)	Yes
Case 2 – Maximum Seepage	0.015 (0.074)		Yes

Considering the new NWRDF cover involves a nearly impermeable geomembrane liner, infiltration through the plastic liner is anticipated to be minimal, and seepage from the cover improvement area due to precipitation will be significantly reduced to a level that is negligible.

4.3.2 Slope stability analyses

Slope stability analyses were performed to evaluate the veneer and global slope stability of the proposed cover improvements. The critical cross-sections for analyses were developed coinciding with locations that were used for stability analyses of previous permits and where the height and inclination of the proposed regraded slopes was the greatest. Table 4 presents material properties that were used for slope stability analyses.

Table 4 Material properties for slope stability analyses

Material	Unit weight (γ)	Shear strength parameters (effective stress)		Reference for derivation of parameters
		Cohesion (c)	Angle of internal friction (Φ)	
	kN/m^3(pcf)	kPa(psf)	(degrees)	
Waste Rock	21.2 (135)	0 (0)	35.5	Previous studies
Liner Bedding/Interface	20.1 (128)	0 (0)	34	Site characterization
Overliner/Liner Interface	19.6 (125)	0 (0)	32	Previous studies and site characterization
Growth Media (Topsoil)	18.4 (117)	0 (0)	30	Previous studies
Native Soil Foundation	18.8 (120)	33.5 (700)	20	Previous studies
Bedrock Foundation	23.6 (150)	0 (0)	40	Assumed conservatively

Global slope and cover stabilities were evaluated with limit equilibrium methods using SLIDE Version 6.0 software (RocScience, 2016) to identify potential least stable failure surface via a critical surface search routine for critical failure mode. SLIDE iterates through a variety of failure surfaces to determine the surface with the minimum factor of safety (i.e., critical surface). For failure mechanisms considered in the analyses, slope stability was evaluated using limit equilibrium methods based on Spencer (Spencer, 1967). Spencer's method is a method of slices which satisfies both moment and force equilibrium. A "factor of safety" is calculated from the ratio of the available shear strength and the shear strength required for equilibrium. Factors of safety in excess of 1.0 indicate stability and those less than 1.0 indicate instability, while the greater the mathematical difference between a safety factor and 1.0, the larger the "margin of safety" (for safety factors in excess of 1.0), or the lower probabilities of failure. Circular and block failure surfaces were considered in these analyses.

Stability analyses using SLIDE were performed assuming static and pseudo-static loading conditions. Pseudo-static-based analyses are commonly used to apply equivalent seismic loading on earth fill structures. In an actual seismic event, the peak acceleration would be sustained for only a fraction of a second. A horizontal seismic load coefficient for pseudo-static analyses was adopted corresponding to 50% of the peak horizontal acceleration of the modelled seismic event which could affect the site with a probability of exceedance of 2% in 50 years (or a design earthquake event with a return interval of 2,475 years). All calculated factors exceed 1.5 under static conditions and 1.05 under pseudo-static static conditions.

Moreover, veneer stability of the improvement area was evaluated using the method recommended by AGRU for IDS. As discussed earlier, the IDS is a layered configuration consisting of Super Gripnet® geomembrane and nonwoven geotextile to provide increased interface frictional stability and to promote drainage of overlying soils. The IDS was assumed to convey meteoric waters infiltrating the cover soils sufficiently to avoid development of piezometric head within the cover soils. Similar to that of the limit equilibrium analyses, the baseline scenario in the evaluation of veneer stability assumed the IDS was properly functioning and assumed the absence of any piezometric head within the cover system, which has been supported by the infiltration analysis of Section 4.1. Veneer stability for the cover system was evaluated using procedures defined in AGRU Engineering Bulletin 2015-3 (AGRU, 2015). Factor of safeties of the veneer stability calculations are satisfactory and generally consistent with that of the limit equilibrium analyses.

In addition to the above geotechnical analyses, a hydraulic analysis for the proposed stormwater management features in support of the NWRDF Final Cover Design was also performed. The proposed stormwater management features are to include a stormwater diversion channel at the crest of the NWRDF northern facing slope crest, and two inter-slope bench drainages shown in Figure 10. Each of these proposed bench drainages were designed as a V-ditch and/or a trapezoidal channel down gradient. The stormwater diversion channel along the crest of the slope is to manage and divert runoff flows away from the proposed cover improvement area and to minimize runoff on the slope face. The northern and southern bench V-ditches and channels are intended to minimize potential cover erosion as well as reduce infiltration into the soil cover. All stormwater diversion channels were designed with erosion protections. Rip rap linings are used for each of the stormwater management features; and for steeper portions of the stormwater diversion channels, articulated concrete block (ACB) lining is used to prevent erosion.

Other analyses in support of the design also included pipe sizing calculation and post-construction settlement evaluations.

5 Project execution and initial performance check

The project design was completed in 2020 and a permit application for an addendum to the Final Plan for Permanent Closure (FPPC) was submitted in early 2021. The construction started in March 2021 and it took two construction seasons to complete the construction. Upon completion of reseeding, all contractors were demobilized prior to or in October 2022. Regardless of challenging conditions for construction including steep terrains, space constraints, windy construction seasons, and requirements for winter closure, the project achieved zero recordable safety incidents and was completed on schedule and within the project budget. NGM served as the project manager throughout the construction, supported by a Construction Management (CM) team and Construction Quality Assurance (CQA) team, and has achieved all construction milestones successfully.

Figure 11 (Zhan, G. et al, 2022) presents early indicators of the new cover performance which suggested reduction of long-term ARD flows, well below the previously recorded 1.4 liter/sec (22 gpm) as discussed in Section 3.

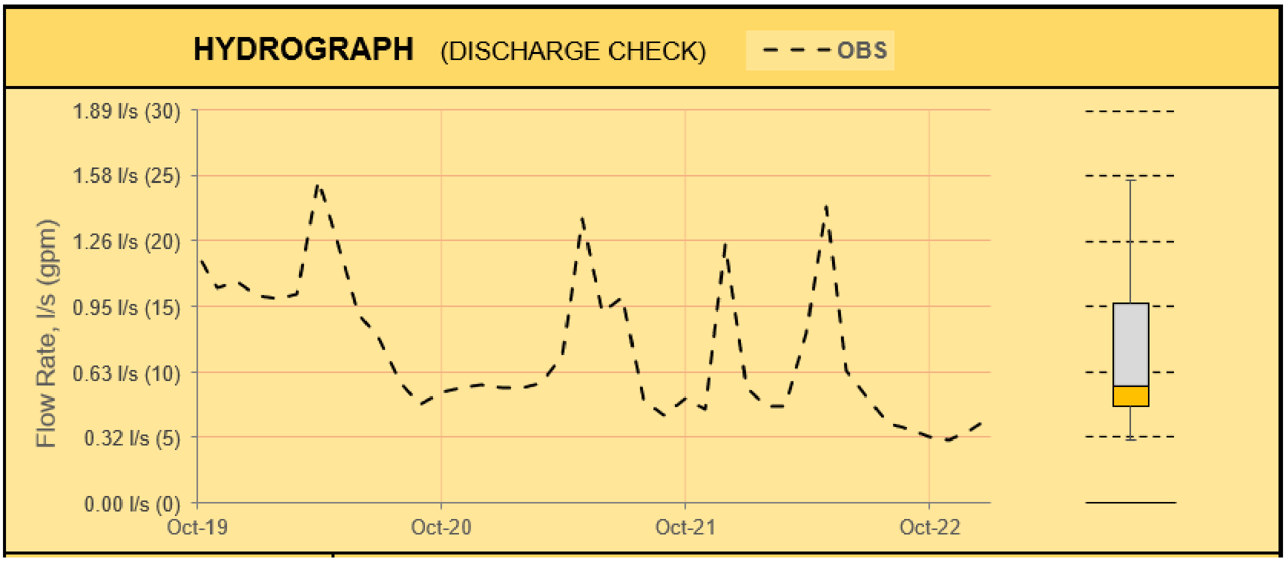


Figure 11 Initial indicators of ARD flow reduction (Zhan, G. et al, 2022)

The 2022-2023 season was extremely wet as record precipitations were measured at many locations in California and northern Nevada. Regardless of wet months of 2022-2023, reduced ARD flows from the project improvement area continued. Minor erosion repair and improvement work will be required near the perimeters of the project area, which are to be the subject of future work.

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