Investigation and Mitigation Design for a Highwall Rock Slope in Southwest Virginia

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ABSTRACT

In 2015 - 2016, a solid waste facility in southwest Virginia mitigated rockfall hazards associated with an old mine highwall adjacent to a lined leachate pond by removing loose rocks from the highwall, stabilizing large metastable blocks in place, and designing and installing a wire mesh rockfall drape. The work was completed in response to frequent rockfalls and raveling of portions of the highwall that could potentially injure personnel working next to the leachate pond, damage a perimeter drainage ditch at the toe of the highwall or damage the pond liner. A portion of the highwall was constructed during past open-pit coal mining, and past blasting exhibited backbreak up to 30 feet (ft) into the highwall. The maximum highwall height is on the order of 320 ft, and the highwall slope is 1,000 ft long, with eight benches and an overall slope angle of 50 degrees. Rockfall mitigation design was initiated in late 2014 consisting of geologic/geotechnical data collection, ground-based light detection and ranging (LiDAR) topographic surveying, and rockfall trajectory modeling to establish a basis for design.

Slope mitigation was started in mid-2015 and consisted of hand and mechanical scaling to remove loose rocks from the slope, along with stabilization of large rock blocks and dental/structural shotcrete placement to fix blocks too large to be safely scaled down to the leachate pond in place. Scaling was performed with a fifteen-foot-high, temporary, movable rockfall barrier placed along the edge of the lined leachate pond to protect the pond liner. Analysis of controlled rockfall trajectories during scaling indicated two rockfall mitigation approaches could be considered: a rockfall drape placed over the entire slope, and a hybrid rockfall barrier placed at the toe. In September 2015, 50% design packages were developed for each option to allow pricing of each alternative. While the hybrid system was about half the cost and could ostensibly be constructed faster, it did not provide as much worker protection from a large rockfall event as the drape alternative. Based on the reduced performance of the hybrid, a need for barrier post foundation support in blast-damaged ground, and the operator’s desire for more comprehensive worker protection, the drape system was selected. GeoBrugg’s 4mm high corrosion resistant Supercoating® high-strength steel Tecco™ wire mesh material was chosen for the drape. This heavier-gauge mesh provides the strength to control larger rock blocks, has mesh spacing sized for smaller rock pieces, obviated the need for a smaller secondary mesh, and could be deployed in one pass. From late November 2015 when materials were ordered through June 2016, the drape system anchors and mesh were installed. The completed system includes 144 wire rope anchors and about 372,000 ft² of wire mesh drape over the slope. The wire mesh panels were installed using a heavy lift helicopter over ten days in April 2016 and were finish-seamed together after placement. The length of the 11.5-ft wide panels hung with the helicopter ranged from 25- to 225-ft long, averaging about 200-ft. The panels were hung in 187 flights (i.e., “picks”), and weighed between 430 and 1,617-lbs. The helicopter averaged panel placement cycle times on the order of 13 minutes, a testament to the teamwork of the ground crew and the military training of the pilot. Approximately 500,000 clips, placed by hand on rope rappel, were used to finish seam the panels to one another.
INTRODUCTION

A portion of a solid waste facility in southwest Virginia included construction of a leachate containment facility at the toe of a highwall slope that was part of an historic coal mine (Figure 1). Past production blasting and mining activities left ragged slopes that were prone to rockfall generation. The constructed leachate pond and drainage system were subject to repeated rockfall strikes requiring rockfall mitigation to protect the facility and site workers responsible for facility maintenance. Rockfalls striking the facility could not only cause damage to the facility and impact site workers, but could also damage the pond liner and release of leachate into the environment. To prevent rockfalls from impacting the leachate facilities, the facility commissioned geotechnical studies and construction of rockfall mitigation measures between January 2015 and June 2016.

The solid waste facility constructed the rock slope above the Final Leachate Pond (FLP) in 2013 and 2014 using production blasting for rock removal and excavation. The rock slope was designed using ¾ horizontal to 1 vertical (3/4H:1V) slopes between benches placed at roughly 50 ft elevation intervals (Figure 2). The benches had a design width of about 10 ft, producing an overall rock slope cut angle of about 50 degrees from horizontal. The overall rock slope vertical height is about 320 ft. Perimeter control blasting techniques were not used to construct the final rock slope grade. A concrete lined diversion channel was constructed in 2014 at the toe of the rock slope on the first bench (Bench #1) to collect and divert runoff around the FLP. A 20-ft wide gravel roadway was constructed around the perimeter of the FLP for access and

Figure 1 – Site location map.

Figure 2 – Pre-construction FLP rock slope condition panorama from west side of FLP. View from northeast (left) to southeast (right).
maintenance purposes. The FLP liner system consists of a 4-inch (in) thick grouted fabriform armor layer, underlain by a 16-ounce non-woven geotextile and 60-mil high density polyethylene (HDPE) membrane liner. The HDPE liner lies on a double-sided geocomposite drainage layer and 6 inches of crushed drainage stone. The FLP is designed to hold up to 75 million gallons of leachate generated from storage of coal-ash waste.

Shortly after construction of the concrete-lined perimeter channel on Bench #1 in late 2014, rockfall debris started to accumulate in the channel, requiring removal (Figure 3). Rockfalls continued to occur, filling the benches and accumulating within the channel, on the gravel roadway, and occasionally reaching the FLP. The rock block sizes ranged up to 3 ft in longest dimension. Based on site observations and review of blasting logs and videos, it appeared that the combination of uncontrolled blasting and other mining disturbance, and the lack of perimeter control blasting techniques led to extensive backbreak within the final rock slope, loss of benches, and to generation of rockfalls. Additionally, the previous bench design elevations were not based on lithology, which led to formation of overhangs of more resistant sandstone overlying less resistant siltstone, shale and coal due to differential erosion.

The facility operator was concerned that rockfall could damage the perimeter ditch and FLP liner, present a hazard to personnel, and inhibit required operation and maintenance of the FLP facilities. Hence, in late 2014, institutional controls were established to prohibit personnel working at the toe of the slope. The facility started filling the FLP with leachate in April 2015. If rockfall strikes occurred on the FLP liner while filled, and a leak developed, repairs and mitigation would be difficult to conduct, and site operations and environmental permit requirements could be hampered. The facility then fast-tracked rock slope mitigation design and construction to reduce the potential for rockfall impacts on the FLP.

Figure 3 – Rockfall debris accumulating in drainage ditch, perimeter roadway, and concrete liner. Note ponded water in ditch dammed by debris on far left side of photo.
EXISTING CONDITIONS

Geology

The project is located at the margin between the relatively flat-lying Appalachian Plateau and the folded/faulted Valley and Ridge physiographic provinces (see inset map in Figure 1). Regional geologic mapping indicates the project highwall slope consists of the Middle Pennsylvanian-aged Norton Formation, including strata from below the Raven No. 1 coal bed stratigraphically upward to above the Aily coal bed (Figure 4; Evans and Troensgaard, 1991; Nolde, J.E., 1996).

The lithology of the Norton Formation consists of cyclothetic coarsening-upward sequences of coal, shale, siltstone and sandstone of various thicknesses and extents. The Norton Formation consists of cyclothetic sequences of sandstone, siltstone, shale and coal. The sandstone is light-to medium-gray, fine-grained, thin- to medium-bedded, contains feldspar and mica, with large fragments of plant fossils, and has local conglomeratic lenses. The siltstone is medium- to dark-gray, and laminated, containing siderite nodules and lenses. The shale is dark-gray and laminated. The coal is black, slightly iridescent, and brittle, and forms a local hydrogeologic barrier perching groundwater above. The total thickness of the Norton Formation ranges from 270 to 420 ft. The project rock slope contains at least two coal riders known as the Raven Nos. 2 and 3. Locally, the thick sandstone beds above the Raven No. 3 coal are known as the Dismal and McClure Sandstones (Englund, 1981; Nolde, 1989; Whitlock, 1989). The coal beds are typically 1 to 5 ft thick, and the sandstone beds range from about 3 ft to over 50 ft thick.

Locally, the Norton Formation claystone, mudstone and shale weathers rapidly to clayey soils highly susceptible to landsliding. Additionally, the formation is mapped as the source of numerous active and inactive landslides, debris flows, debris avalanches, and areas susceptible to rockfall. The latter areas contain steep and locally vertical slopes and cliffs, formed dominantly of sandstone, limestone, sandy shale, mudstone, and claystone. The interbedded finer grained shale, mudstone and claystone weather rapidly leaving the more competent sandstone and limestone rock faces unsupported (Outerbridge, 1982).

Open-pit and auger mining methods were active at the site into the 1970’s. The mining methods included quarry blasting without perimeter control, and construction of adits, shafts and drilling of horizontal auger holes for coal extraction. These subsurface disturbances likely contributed to the slope conditions causing rockfalls.

Overall bedding strikes roughly north-northeast to south-southwest, and dips gently to the east. Several joint sets are present within the sandstone and siltstones (at least four sets exist).
Additionally, highly weathered dikes of very fine grained diabase (likely of Mesozoic age) and/or clastic debris, up to about 0.5 ft thick are present within a north-south trending vertical joint set. The diabase and/or clastic dike debris has weathered almost completely to a clay in some exposures.

The sandstone has an estimated field strength of 15,000 to 36,000 psi (R5 rating, very strong rock), while the shale and coal have much lower estimated field strengths of 35 to 725 psi (R0/R1 ratings, extremely weak to very weak rock). This difference in strength leads to differential weathering, causing the less resistant rocks to weather quickly compared to the more resistant sandstones, leading to rockfalls primarily due to undercutting of blocks and toppling. The extensive backbreak caused by production blasting and past mining activity also contributes to rockfall generation.

STABILIZATION DESIGN DEVELOPMENT

Conditions Requiring Stabilization

The slope above the FLP was cut into the old mine highwall in 2013-2014 as part of the site development plan, with an overall design slope angle of 50 degrees and a series of six benches as shown in Figures 2 and 3. The layout of the slope and benches was based on overall slope geometry and was not designed to account for bedrock lithology by building benches in weak units underlying hard units to limit subsequent undercutting and possible rockfall generation. During production blasting, several prominent joint sets were encountered and the slopes between the benches broke along those joints; however, the dip of the joints was steeper than the bench face angle and daylighting joint faces were not created. Some variation in bench width and in some cases complete loss of benches occurred as a consequence of the backbreak along these joint sets (Figure 5).

During initial site inspections in early 2015, an upper series of hard sandstone beds with undercut shale beds were observed in the middle and upper portions of the slope. In many locations the bench width varies widely, and several benches have collapsed due to the lack of perimeter control and extensive backbreak. A large amount of loose rock and debris was present on the slope that apparently was not removed during excavation of blasted rock, or not scaled after completion of each bench. In consequence, many rock blocks were falling from the full length of the slope and accumulating in the FLP perimeter channel, on the perimeter gravel roadway below, and some rocks rolled down into the FLP. Most of the benches on the slope had
accumulated falling rocks from the slopes above, and were filling with debris (Figure 6). Surface water emanating from an adjacent wetland northeast of the highwall drains through strata along the bottom half of the slope at the north end, and is locally perched on the more impermeable cleats at the base of the coal seams. Icefalls and rockfalls are common in these areas throughout the winter season.

To aid rockfall mitigation design, in March 2015 the facility commissioned geologic and geotechnical mapping of the base of the FLP rock slope. This effort included data collected from an adjacent rock slope excavation area to support rockfall bounce analyses and evaluation of potential rockfall remedial design approaches. Geologic mapping was supplemented by initial 3D terrestrial LiDAR survey scans of the slope.

Observations and analysis indicated rockfalls on the FLP highwall fell into three categories:

- **Type 1** - Blocky rockfalls that comprised harder competent medium to thick bedded sandstone and siltstone strata formed by differential erosion and undercutting of weaker shales, mudstones and coal strata until individual blocks could fall out of the face.

- **Type 2** - Intermediate-sized blocks derived from broken and slaking thinly bedded siltstones, shales and coal that exist in blast-damaged zones; broken benches; blocks that had already fallen; and from joint/weathering controlled blocks that could break up as they fell into smaller pieces (6-in to 10-in size).

- **Type 3** - Small shards of slaking shale, commonly from the lower half of the slope, that flaked off the face in small pieces in response to wetting and drying of the shale causing expansion and contraction of the wetting surface. The small shale shards fall nearly continuously during periods of precipitation and during winter months as the face freezes and thaws daily.

The liner of the FLP was considered susceptible to damage by falling rocks of the Type 1 category of rockfalls discussed above. Long term operations could be susceptible to ongoing rockfalls occasioned by weathering of shale strata - either undercutting hard sandstone blocks (Type 1) or generating the second and third types of rockfalls noted above.
Consideration of Alternatives

Golder developed two alternative mitigation approaches to the 50% design phase to provide sufficient detail to conduct a cost comparison between the options. The first option consisted of a 4 millimeter (mm) Tecco™ rockfall drape system mantling the FLP rock slope, using approximately 120 wire rope anchors around the perimeter of the drape (Figure 7A). The drape was designed to intercept falling rocks and control their trajectory to direct them to the concrete lined drainage ditch. The second option consisted of a hybrid rockfall barrier/drape positioned on the outboard edge of the first bench (originally the second bench but the second bench was not stable and was missing in places), with a short “tail” constructed of ring nets extending from the top of the barrier to the inboard FLP access road shoulder (Figure 7B). The hybrid drape system was designed to extend approximately 950 linear ft along the edge of the concrete lined drainage ditch on Bench #1. The hybrid barrier/drape would be constructed with 15 ft high posts spaced horizontally every 30 ft with a hybrid rockfall barrier/drape composed of ring nets and 3 mm Tecco™ mesh, requiring approximately 55 wire rope anchors for support. The hybrid barrier/drape was designed to intercept falling rocks at higher velocity and deposit them on the gravel road that surrounds the FLP for removal.

To make conditions safe to work under for both options, the condition of the slope required both mechanical and hand scaling, and installation of spot rock dowels and dental shotcrete to stabilize large sandstone rock blocks in the middle and upper portions of the slope that could not safely be brought down. These areas contained large rock blocks (exceeding 4 ft) that could compromise the integrity of the FLP liner if they fell from the slope. Rock blocks of this size would have an estimated energy of 4,300 kilojoules (kJ), which would also compromise the drape and hybrid systems, and were therefore stabilized in place.
Selected Slope Treatment and Stabilization System

In April 2015 the facility decided to begin work with rock scaling and the installation of the dental shotcrete and dowels. The selection process for the permanent rockfall mitigation method progressed to the 50% design level and occurred simultaneously with the scaling, dental shotcrete and rock dowel activities, with approximate construction costs for both alternatives estimated in September 2015. While the hybrid system was about half the cost and would be faster to build, it did not provide sufficient protection if a large rockfall event were to occur. Based on the reduced performance of the hybrid, its need for foundation support for barrier support posts in questionable ground, and a need for more comprehensive protection of workers, the facility chose to move forward with the drape system option.

Rockfall Drape Design

The rock drape system consists of Tecco™ mesh manufactured by GeoBrugg® Protection Systems (GeoBrugg). The Tecco™ system is constructed of high-tensile steel (256 ksi) coated in a proprietary aluminum-zinc anti-corrosion coating and arranged in a diamond shaped pattern. The drape is secured to the rock slope by primary cable anchors and intermediate anchors used to secure the top, side and bottom cables.

The major components of the rock drape are:

- GeoBrugg Tecco™ mesh, consisting of 0.157-in (4 mm) diameter steel wire, single twisted into diamond-shaped meshes, with a nominal unstrained opening of 3.3 by 5.4-in. The wire is coated with a proprietary zinc-aluminum coating for corrosion protection.

- 3/4-in diameter, galvanized 6x19 extra improved plow steel (EIPS), independent wire rope core (IWRC), double-leg wire rope anchors with a cementitious grout bond zone of at least 15-ft for top anchors and at least 5.5 ft for bottom anchors. The wire rope anchors are constructed using galvanized thimbles and wire rope clips.

- 7/8-in diameter galvanized 6x19 EIPS IWRC wire rope was used for upper and side support ropes, and galvanized 6x19 EIPS IWRC 3/4-inch diameter wire rope was used for the bottom support rope.

- 5/16-in diameter galvanized 7x19 wire rope for seaming the perimeter of the drape to the top, side and bottom support ropes, wrapping the seaming rope through each Tecco™ mesh diamond and around the support ropes.

- Two GeoBrugg® 4 mm diameter T3 connection clips connecting Tecco™ drape mesh at every other diamond overlap. Generally, the mesh was overlapped by at least 6-in between vertical panels.

The mesh design consisted of an evaluation of potential rockfall particle size, rockfall modeling, slope condition, interbench and overall slope angles, interface friction angle, potential debris.
load, and snow/ice loads. Rockfall modeling and observation of the scaling operations indicated that the average rockfall block diameter is about 1.5 ft, and at most, 10 cubic yards (CY) of rockfall materials are anticipated to fall in any one event. The analysis indicated that a ring net drape system with an overlain finer mesh would adequately retain rockfalls of this size. However due to the very large area requiring drape materials (estimated at 403,000 ft², including a 25% contingency), and the difficulty in installing the relatively heavy ring nets on a restricted-access rock slope, the use of lighter drape materials was evaluated. The larger gauge Tecco™ system mesh was chosen as it could hold the assumed rockfall, is lighter than a ring net/mesh system, and could be rapidly deployed by heavy-lift helicopter in relatively long lengths (up to 225 ft) in limited access areas. Additionally, the drape could be installed in one pass, as opposed to a ring net/light drape design which would require installation of the ring nets first, followed by a lighter mesh (e.g., double-twist wire mesh), requiring two passes.

**CONSTRUCTION**

Construction activities started in April 2015, and included:

- Temporary rockfall barrier installation
- Mechanical and hand scaling
- Rock dowel and shotcrete installation
- Cable anchor drilling and installation
- Cable anchor testing
- Rockfall drape installation

The paragraphs below provide brief summaries of these activities.

**Temporary Rockfall Barrier Installation**

Prior to implementing mechanical and hand scaling operations, a 120-ft long, 500 kJ capacity temporary rockfall barrier was installed at the toe of the north end of the slope, just inboard of the FLP (Figure 8). The barrier consisted of 4 mm Tecco™ wire mesh supported by steel I-beams, 10- to 15-ft tall mounted on steel plates, and anchored by concrete blocks. The barrier was designed to be moveable with minimum disassembly, such that the barrier could be dragged along the FLP slope toe by a front-end loader and placed into position below the area to be
The temporary rockfall barrier was used in tandem with rubber tire blasting mats that were laid along the top of the concrete lined drainage ditch on Bench #1 to dampen the kinetic energy of falling rocks (Figure 9). The barrier and mats were moved from a north-to-south direction as the scaling operation moved across the rock slope.

**Scaling**

The rock slope was scaled to remove loose rock and soils from the rock face and benches (Figure 10). The majority of the rock slope was hand scaled using standard 4-ft long steel mine scaling bars; however, some larger unstable rock blocks were broken apart on the slope using a “boulder buster” and scaled using compressed air bags. The boulder buster uses a small propellant charge placed within a water-filled drill hole and then initiated. The pressure pulse initiated by the propellant charge is directed via a water-tight barrel at the collar of the hole into the incompressible water, resulting in an expansion and hence breakage of the rock in tension. The resulting charge is strong enough to break the rock, but not enough to produce fly-rock. The air bags were rated to produce jacking forces of up to 70 tons, and when coupled with scaling bars are able to push rocks off the slope in a controlled manner.

The northern 100 ft of slope was scaled using a specialized mining slusher. The slusher consists of a compressed-air powered 3-drum hoist, with cables running up to pulleys attached to wire rope anchors at the crest of the slope, and connected to a mini-dragline excavator bucket. The drum hoists are controlled by clutches, which direct the bucket up and down and across the slope, which is in turn used to pull down loose debris to the toe of the slope. Four temporary wire rope cable anchors were installed at the top of slope to support the slusher pulleys: one into the soil and rock on the east side of the soil slope, and three in the rock face above Bench #5 to the west of the soil slope.

![Figure 9 – Scaled debris in concrete ditch resting on blasting mats and contained by temporary barrier.](image)

![Figure 10 – High scalers scaling rock face.](image)
Dental Shotcrete and Rock Dowel Installation

Following completion of the scaling, inspection of the slope face was conducted to identify rock blocks that needed to be stabilized in place. Ten (10) areas containing medium- to thick-bedded sandstone layers that contained large dilated rock masses (blocks 4 ft or larger) that could not be scaled from the slope without risking damage to the FLP were identified during the rope rappel inspections. The rockfall energy of these masses was calculated to be too great for the temporary rockfall barrier as they may bounce over the barrier or pass through the barrier and thus impact the integrity of the FLP liner. As these rock masses had the potential to fall in the near future, area-specific stabilization was designed, incorporating untensioned rock dowels and fiber-reinforced dental shotcrete (with drainage) to support these rock masses. There were several variations of the specified repairs depending on the degree of reinforcement required. The materials specified for use in the repairs included rock dowels, geotextile drainage board, steel welded wire fabric, and steel fiber reinforced shotcrete.

Rock dowels, shotcrete support dowels, and shotcrete were installed from July 9 to August 27, 2015. The rock dowels were drilled using either a hand held “plugger” drill or a wagon mounted down-hole hammer drill (Figure 11). The dowel spacing and depths were selected to address specific areas of the FLP rock slope where rock blocks were too large to be safely scaled or retained by the Tecco™ rock drape. The rock dowels were separated into two categories: rock dowels used to pin large rock blocks into place, and rock dowels used to provide support to the areas repaired using buttressing shotcrete. The rock dowels used to pin the large rock blocks were designed to be 8 to 15 ft long and fully grouted along their entire length. Rock dowels used to provide support for the shotcrete buttress areas were designed to be 4-ft long and fully grouted.

Figure 11 – Drilling shotcrete support dowels.
Many of the rock masses had overhangs for which the shotcrete formed a filling buttress for structural support (Figure 12). Dry-mix fiber-reinforced shotcrete was specified due to the large distances between the potential shotcrete plant staging and the application areas, and the difficulty in getting concrete wet-mix trucks close to the slope. Shotcrete was also applied to further stabilize and armor loose portions of the rock slope and limit further crumbling and erosion of the slope. In areas exceeding 5 CY of shotcrete, a welded wire fabric was used to provide additional support for thick layers of shotcrete (generally exceeding 6 in). Additionally, based on field conditions, drainage elements such as geotextile-backed drainage board (Mirradrain®) and PVC pipe drains were used to ensure water would not build up behind the repairs.

**Cable Anchor Drilling and Installation**

The cable anchors for the top and lateral support ropes for the drape system were installed during winter conditions. The primary cable anchors were installed at roughly 16-ft spacings at the crest, intermediate anchors (three each) at roughly 80-ft spacings at the top, and cable anchors at roughly 50-ft spacings on the sides. The anchors were installed using wagon drills (see Figure 13), and ranged from 15.5 to 25.5 ft in length. Most of the wire rope cable anchors consisted of premanufactured anchors, but for instances were weak rock and/or soil were encountered, longer anchors were fabricated in the field, using an identical design as the premanufactured anchors. Cable anchors for the bottom support rope were placed at roughly 50-ft spacings, using a John Henry-style top hammer drill mounted on a mini-excavator. The excavator accessed the bottom anchor locations from the concrete lined ditch on Bench #1.
Cable Anchor Testing

To verify the design pullout strength value for the cable anchors, 13 tension tests on representative anchors were conducted using a calibrated hydraulic jack and pressure gauge. Most of the anchors chosen for testing were based on drill hole logs that had suspected zones of weaker, disturbed rock. Two anchors had to be abandoned, redrilled, reinstalled and retested.

Rockfall Drape Installation

Between March to mid-April, 2016 the as-delivered Tecco™ rolls (11.5 x 100 ft) were unrolled, and reassembled to panel lengths ranging from about 25 to 225 ft long to stage the rolls for placement on the slope (see Figure 14). The rockfall drape mesh was installed on the FLP rock slope in mid- to late-April 2016 via airlift using a modified Sikorsky S55(T) helicopter (Figures 15 through 17). The helicopter used a proprietary lifting/ spreader bar attached to the cargo hook, which was attached to the bottom of the drape panel. The panel weights ranged from 430 to 1,670 pounds (lbs). The helicopter lifted the unrolled panels from the staging area and flew them to the drape area, where workers on slope would then secure the panels to the top support rope or other deployed panels using temporary pin screw shackles. Additional workers then guided the panel edges as the helicopter flew down the slope so that the mesh could be laid on the slope and properly overlapped. Once most of the mesh had been laid on the slope, the pilot released the remotely controlled cargo hook, which opened the lifting/spreader bar from the end of the panel, and the remaining panel length fell onto the slope in a controlled manner.

Figure 14 – Drape panel assembly.

Figure 15 – Drape assembly/staging area and pick.

Figure 16 – Helicopter pick
Flights per day ("picks") depended on wind and weather, and ranged from 4 to 27, with daily deployments of 9,200 to 62,940 ft². A total of 187 flights were completed to install 371,846 ft² of drape. After hanging the mesh, workers clipped the panels together with Tecco™ clips with a lateral overlap of 6-in or greater. A seaming rope was then used to attach the drape to the top and side border ropes. The design included a fold of mesh over the bottom support rope to form a hem. Drape construction was completed on in June 2016 (Figures 18 and 19).

**CONCLUSIONS**

The success of this project relied on the collective specialty design and construction experience from the owner, geotechnical design team, specialty rock slope mitigation contractor, general contractor, helicopter operator, and material supplier. Through careful evaluation of the rockfall problem, and evaluation of several alternative approaches, an effective solution was designed and constructed to address a complex rockfall problem. Field design and construction activities were completed on site with no injuries or lost time accidents, contributing to a critically important operations metric to the facility operator. Additionally, the project involved one of the largest helicopter-deployed Tecco™ drape installation projects in the United States.
REFERENCES:


