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## Lining Steep Rock Slopes with a Geomembrane Liner To Facilitate Tailings Facility Expansion

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**ABSTRACT:** Geomembrane liners are increasingly used to provide containment in tailings storage facilities. Typically, geomembrane liners are installed in successive stages with an expanding impoundment footprint and subsequent dam raises, and may require significant impoundment grading to provide suitable slope angles and subgrade for conventional liner deployment. Impoundment grading difficulty is increased in mountainous areas where bedrock may be shallow and, due to steep topography, grading limits for conventional geomembrane lining (typically 2H:1V) may daylight well beyond a facility's boundaries. This paper presents an innovative approach to lining steep to vertical rock faces with a geosynthetic system consisting of slope reinforcement, liner cushioning, and geomembrane, for an expansion of an existing tailings storage facility. Additionally, this paper presents recommendations gleaned from both design and construction experience to advance the application of geomembranes in the mining industry.

**INTRODUCTION:** Mine facilities are located in every climate and topographic region. Constructing mines, and particularly tailings storage facilities (TSFs), presents unique challenges including fixed facility locations, sequential construction schedules, construction season and weather related constraints, and difficulties in sourcing specialized materials and contractors. Successfully engineering and constructing TSFs under these circumstances requires navigating host country regulations and implementing industry best practices, all while ensuring that the finished product can be economically constructed on schedule using local materials, labor, and equipment. The engineering process requires creating a site-specific design that accounts for local factors including climate, geology, hydrogeology, seismicity, and vegetation; optimizing the target site for its intended purpose; meeting the client's operational objectives; and tailoring the construction methods for the available expertise and technology.

TSF design methodology has developed over the past several decades with technology advancement and experience. Through experience, the mining industry and TSF designers have learned

that failures (e.g., dam failures, uncontrolled discharges, or environmental contamination) pose environmental, financial, and even public relations and political risks (Vick 2000). Once constructed as an afterthought with little detailed engineering, TSFs are now designed with the intent of returning the land to a sustainable, beneficial use following closure. TSF designs employ operational and decommissioning strategies to mitigate unacceptable risk to public health and safety and the environment while reducing the need for ongoing maintenance.

Liner systems are constructed to provide both physical and environmental containment of tailings and process solutions. Historically, compacted fine-grained, low permeability soils have been used to provide containment in TSFs. However, geosynthetic liners are increasingly used to provide containment due to construction ease, a lack of available or suitable on-site sources for a soil liner, and effective long-term performance (Blight 2009).

Typically, after dam construction, the greatest expense incurred in constructing a TSF is the earthworks required to construct a suitable subgrade for geosynthetic liners (as well as the costs for the liner components). Conventional liner deployment typically requires grading slopes to no greater than 2:1 (horizontal:vertical). While these grades may be attainable at every site, they can come at high costs if the TSF is located in a mountainous region. Furthermore, given the sequential, phased construction nature of TSFs, construction grading can present risks to the integrity of installed liners where later-stage grading can result in rock instability, or denuding slopes can increase erosion and landslide potential, onto previously installed liners. In these cases, unique liner solutions should be developed to economically provide the necessary containment while reducing environmental and construction risks. This paper presents an innovative approach to lining steep to vertical rock faces with a geosynthetic system consisting of slope reinforcement, liner cushioning and geomembrane to expand an existing geosynthetically lined TSF. Additionally, this paper presents recommendations gleaned from both design and construction experience to advance the application of geomembranes in the mining industry.

**PROJECT BACKGROUND:** Mina El Mochito is located in a mountainous region of north-central Honduras. The topography is dominated by steep, fault controlled ridges and valleys (horst and graben) where steep to near-vertical rock faces are common. The Soledad TSF is located in such a valley.

The Soledad TSF was designed to be constructed in four stages

– a starter facility followed by three expansions. The Stage 1 starter facility was constructed between 2003 and 2006 and consisted of a 42-m-high zoned earth-/rock-fill embankment and an impoundment basin graded to facilitate conventional geomembrane liner placement. Future phases of facility construction were planned and included extension of the liner system up the valley walls.

Grading beyond the limits of the Stage 1 impoundment was not completed due to topographic and budgetary constraints. As a result, near vertical (55 to 90 degree), blocky limestone slopes were left in situ within 3 m of the lined Phase 1 facility (Fig. 1).



Figure 1. View of steep-walled canyon within the Soledad TSF.

**DESIGN CHALLENGE:** The Soledad TSF challenge was two-fold, encompassing both engineering and construction considerations. A geomembrane liner system needed to be developed to provide the necessary containment dictated by regulatory permits while facilitating the construction process and mitigating the potential for damage to previously installed geosynthetic liner during construction.

The selected design solution is a fairly unique application of liner system design and construction. Whereas a few publicly documented projects present similar lining conditions, none (to the authors' knowledge) required construction within such close proximity to an existing lined area (Blum 1999, Breitenbach 2008).

**ENGINEERING DESIGN:** The Soledad TSF expansion engineering design required a multi-disciplinary approach, including aspects of geotechnical, mining, and structural engineering. The first step in the design process required a thorough geotechnical review of the slopes surrounding the existing Phase 1 TSF. Field slope mapping included identifying slope angles, geology, topography, and geologic hazards. Data collected during the field investigation was used to segregate the slopes into three broad categories: slopes that could be lined using conventional lining methods (Zone 1), steep slopes that would require slope stabilization and liner protection prior to lining (Zone 3), and transitional slope areas where a mixture of conventional and steep slope lining technologies would be required (Zone 2). This paper focuses on the Zone 3 (steep slope) liner system design and construction.

The steep slope (Zone 3) liner design needed to address the following factors:

- Slope reinforcement;
- Liner protection/cushioning;
- Liner anchoring;
- Liner performance;
- Liner deployment; and
- Existing liner protection.

Each of these factors is discussed in the following sections.

#### 4.1 Slope Reinforcement

Before a geomembrane liner could be installed, a slope reinforcement system was required to ensure the fractured and blocky limestone rock faces remained stable for the foreseen facility life, i.e., approximately 12 yr, after which the rock faces will be buttressed by the tailings impounded within the facility.

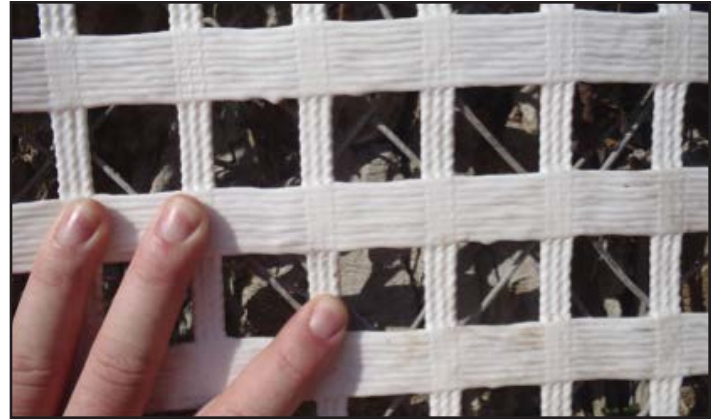


Figure 2. Close-up of Tensor MineGrid™.

Tensor's MineGrid™ slope reinforcement material, coupled with a 5 m x 5 m rock-bolt pattern was selected as the preferred option to retain loose blocks in situ, protecting the liner from rock fall damage. Tensor's MineGrid™ is a reinforcement mesh fabricated with high tenacity polyester fibers with a PVC coating (Fig. 2). The material grade selected (Tensor's MineGrid™ 200 x 200) has a 200 kN/m tensile strength, comparable with most wire and cable rock-slope re-inforcement systems.

#### 4.2 Liner Protection/Cushioning

The effective 30 mm x 30 mm grid opening of the Tensor MineGrid™ reduces liner exposure to small sharp or pointed protrusions. To further protect the geomembrane liner from protruding rocks and angular edges, a heavy duty geocomposite, Agru America 8-250-8 (a 250-mil HDPE geonet with 8-oz non-woven geotextile fused to both sides), was specified as a cushioning layer between the Tensor MineGrid™ and the geomembrane liner.

#### 4.3 Liner Anchoring

Shallow bedrock precluded using a standard anchor trench for the lining system. A structural concrete anchor plinth, connected to the rock mass using #8 rock bolts (DYWIDAG #8 Thread-bar), was designed to anchor the geocomposite and geomembrane liner at the top of the slope (Figs. 3-4). The geocomposite and geomembrane liner were attached to the concrete plinth using a ¼-in-thick, 2-in wide stainless steel bar anchored every 0.15 m with ½-in stainless steel bolts.



Figure 3. Concrete anchor plinth.



Figure 4. Geomembrane and geocomposite anchored to plinth.

#### 4.4 Liner Performance

A 60-mil linear low density polyethylene (LLDPE) liner was chosen as the primary impermeable barrier (Agru America Micro Spike). LLDPE was selected due to its excellent elongation properties and compatibility with the existing Stage 1 LLDPE liner. As an added layer of protection against UV exposure, a thin, sacrificial 6-oz non-woven geotextile (Agru America Agrutex 061) was specified as over-liner protection.

#### 4.5 Geomembrane Liner Deployment

Due to the anticipated difficulty and safety concerns with deploying a liner on steep slopes, geomembrane panels were pre-cut in the staging area. This reduced the quantity and complexity of high-angle work required and facilitated liner installation by dividing the liner into manageable pieces, obviating the need for the heavy equipment typically needed to support conventional liner installation.

#### 4.6 Existing Liner Protection

The typical working bench width between the Stage 1 liner and the new construction was on the order of 3 m. In order to protect the Stage 1 liner from damage resulting from rock fall, equipment, and workers, rock-fall fences and sandbag berms were constructed at the base of the steep slopes.

**CONSTRUCTION:** 5.1 Pilot Program - A pilot construction program was initiated to refine the liner system design and construction approach.

The pilot program consisted of a 25-m-long (approximate) section of a 25-m-high, near vertical rock face (Fig. 5).



Figure 5. Pilot program slope (approximate limits outlined).

The staging areas at the top and bottom of the pilot program slope were narrow and precluded the use of man lifts or cranes. Therefore, manual liner deployment techniques were developed that considered the difficulties in working on high angle slopes in windy or wet conditions. The experienced technicians from the contractor, rock-bolt drillers, and local laborers were trained in high-angle work and rappelling to support the liner system installation and ensure a safe work environment.



Figure 6. Pilot program slope during construction (geocomposite being installed over Tensar Mine-Grid™).



Figure 7. Completely lined pilot program slope.

During the pilot program, the owner, design engineer, driller, and liner installation contractor worked as a team to refine the liner system design and construction techniques. As a result, the pilot program was completed successfully (Figs. 6-7).

#### 5.2 Construction

Following the successful completion of the pilot program and the resulting design modifications, full-scale construction was initiated. Construction included slope preparation, rock-bolt installation, anchor plinth construction, Tensar MineGrid™ installation, geocomposite deployment, and LLDPE liner installation. Figures 8-10 depict the construction progress from the original slope through liner installation.

Labor-intensive slope preparations began six months before liner installation. This work included:

- Constructing sandbag berms and a temporary rock fall fence below the work area to protect the existing liner below;
- Removing vegetation;
- Scaling loose rocks;
- Blunting rock protrusions that could not be removed; and
- Filling voids with sandbags.

Once slopes were prepared, labor crews constructed the anchor plinth and the drilling contractor installed rock bolts on the specified grid spacing. The rock bolts were proof tested and then cut to within 0.3 m of the rock face.



Figure 8. Soledad TSF slope prior to slope preparation.

The Tensar MineGrid™ was deployed in pre-cut sections. The top of each panel was folded over and stitched using a diamond weave pattern specified by the manufacturer to create a sheath for an anchor cable that was connected to dedicated rock anchor bolts along the anchor plinth. The sections were then adjusted to ensure proper contact with the slope, proper anchoring with the rock bolts, and the correct overlap with adjacent panels. Adjacent panels were stitched together using the same diamond weave specified for the top sheath. Retention plates were then installed on the rock bolts. Any excess bolt was cut off, a grout cap was cast over the plate and bolt head, and sections of conveyor belt were installed to further protect the liner system from the bolts. Vertical cables were installed as needed to ensure proper contact between the Tensar MineGrid™ and the rock face. Finally, cable sheaths were created at the lateral extents and base of the Tensar MineGrid™ and cables were installed to effectively tie the reinforcement system together.



Figure 9. Soledad TSF slope following slope preparation and Tensar MineGrid™ installation.

After the Tensar MineGrid™ slope reinforcement was completed (Fig. 9), the geocomposite was anchored to the plinth and deployed down the rock face in pre-cut panel sections. The panels were then adjusted to ensure good contact with the slope and correct overlap with adjacent panels and then connected using zip ties.

Once anchored to the plinth using a stainless steel compression strip, the LLDPE liner was deployed in pre-cut sections. The panels were then welded to the adjacent panels and the existing liner (Fig. 10). The welds and liner were inspected using industry accepted QAQC controls and test procedures.



Figure 10. Soledad TSF slope completely lined

Finally, a sacrificial, 6-oz non-woven geotextile (Agru America Agrutex 061) was installed over the LLDPE liner to provide UV protection. The geotextile was anchored to the anchor plinth and connected to adjacent panels using heat adhesion.

**RECOMMENDATIONS:** Based on design and construction experience, the authors present the following recommendations to successfully design and install geomembrane liner on steep, rocky slopes:

- Teamwork is key to developing an innovative geosynthetic lining solution. Design engineers should work closely with owners, geosynthetic manufacturers, installers and the owner to develop a constructible liner system that meets the owner's needs. This process can mitigate costly design changes.
- A detailed topographic survey of the slope should be performed to facilitate the design process and geosynthetic panel layout. This survey will aid in rock bolt pattern development, geosynthetic panel sectioning, deployment staging, and reduce the waste material quantities.
- A rock-depth contour map of the slope, generated following a shallow drilling/probing program, will help identify areas where slope reinforcement is required, thereby refining the design process and reducing project costs.
- All work crews, drillers, installers, and inspectors should receive high-angle work and safety training. Well trained crews are safer, more comfortable, and work quicker.
- Completing a pilot program ahead of construction helps identify necessary design modifications and allows the contractor to work out the methodology for liner system installation, both these activities lead to a more efficient installation during the full-scale program.
- Rock-face surface preparation activities and rock bolting should be initiated weeks ahead of the lining program. Coordination between the contractors (surface preparation, rock bolting, and geosynthetics installer) is critical to creating a detailed work schedule and efficiently completing the project.
- Access and working benches must be well ordered and staged to support the lining activities. This activity is especially critical when these areas are small or narrow. Daily reviews of site conditions, personnel, and materials will improve installation efficiency.
- The installation team should have a clear understanding of the predominant wind direction(s) and develop the liner system panel staging plan accordingly.

– Rubber pads (conveyor belt sections) provide excellent barriers between rock bolts and the liner system. They also enhance construction speed as they allow liner system deployment to continue uninterrupted while the grout cap over the rock bolt cures.

– High-angle liner system installation is slow. The contractor completed approximately 400 to 600m<sup>2</sup> per day with a 17-person work crew. This installation rate should be considered when scheduling the construction program.

**CLOSURE:** The successful completion of the steep slope lining system at Mina El Mochito has shown that steep, rock faces can be effectively lined. This paper presented an innovative approach to lining steep to vertical rock faces with a geosynthetic system consisting of slope reinforcement, liner cushioning, and geomembrane liner, for an expansion of the Soledad TSF.

A successful pilot program and full-scale installation program were completed. After a year of wind and rain, the lining system is performing as designed and all indications are that it will continue to perform as intended. Furthermore, the construction was performed within budget and with zero lost-time accidents.

The success of the project was founded on teamwork. A key team of representatives of the owner, design engineer, geosynthetic manufacturers, geosynthetic installers, and contractors facilitated

the design and construction process. Working closely together, the design team identified the materials and methodologies necessary to complete the project on-time and within budget.

While not applicable everywhere, the successful completion of the Soledad TSF lining program has resulted in both design and construction experience that advances the application of geomembrane liners in the mining industry.

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***“Our Clients are First, the Team is Second, and I am Third.”***



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