Tailings dam raise with reinforced walls

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ABSTRACT

This paper presents the design of a tailings dam raise with reinforced walls lined with geomembrane, in which the right abutment of the dam raise was designed with a reinforced structure on the upstream side. The main reason for choosing this system was the close proximity of the property limit to the downstream toe of the dam, resulting in a steep upstream dam slope that would be practically vertical.

The engineering design considered the site conditions, such as seismic hazards, tailings characteristics, and local stability of the reinforced earth structure, as well as the condition of the existing tailings dam and the geotechnical characteristics of the materials used for construction. The existing dam was made with granular materials from borrow sources near the site. The geotechnical analyses considered that the impounded tailings were saturated and an eventual tear of the geomembrane liner would generate an internal piezometric level inside the dam due to the infiltration of the tailings decant water. This rise in phreatic level would affect the geotechnical stability of the reinforced wall and dam materials and also the long term stability analysis of the dam.

The analysis and design allowed for 2m of freeboard between the dam crest and the tailings. The stability analysis considers drained and undrained parameters of the materials, as well as seismic conditions of the site.

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INTRODUCTION

The purpose of this study was to provide the client with the necessary technical information to construct the tailings dam expansion project in order to prevent cyanide migration from the tailings impoundment. This mine is a silver project with underground operations located in Mexico. The mine has an approximate elevation from 2,300 to 2,400 m.a.s.l.

This tailings dam expansion design was performed according to the design criteria provided by the client and with the consultant's design and recommendations. Review of the previous phases of the design was performed, including the site seismicity; 0.19g was used as the maximum acceleration expected in the project area based on a deterministic criteria. From this acceleration, a seismic coefficient of 0.10 was recommended for the pseudo-static slope stability analysis of the tailings dam.

The tailings dam raise had to be constructed within a limited space on the right abutment downstream toe of the dam, because of the mine property boundary and the existing tailings impoundment. A reinforced wall on the upstream dam slope was proposed on the right abutment in order to reduce the impacted area and maintain the dam raise inside the mine property boundary and avoid constructing into the tailings impoundment which would require an expensive and complicated the reinforcement of the fine tailings.

The upstream face of the tailings dam expansion will have a composite liner system consisting of a non-woven geotextile underlying a low permeability soil layer which will receive an LLDPE double-sided textured geomembrane of 1.5 mm thickness and a geocomposite liner. In the area of the reinforced wall, the low permeability soil will be replaced by a GCL, because of the steep upstream slope, which would not allow placement and compaction of a low permeability soil.

The geotechnical analyses considered that the tailings of the impoundment were saturated and an eventual tear of the geomembrane liner would generate an internal piezometric level inside the dam due to the infiltration of the tailings decant water.

METHODOLOGY

The design of the reinforced wall was divided into two parts: (1) the geotechnical design that defined the material geotechnical properties and analyzed the internal and external stability conditions; and (2) the civil design that defined the structure geometry, analyzed the liner system on the internal face and designed the external slopes for satisfying the project criteria and restrictions.

Geotechnical design considerations

The geotechnical analysis included static and pseudo-static cases for both the internal and local stability of the wall. The methodology is described below.

Seismicity and seismic coefficient

The most conservative approach with respect to seismic design of tailings dams is to use the Maximum Credible Earthquake (MCE) for the site. This represents the largest possible earthquake that could reasonably be expected to occur given the seismic-tectonic setting. Although a deterministic value, the MCE can be roughly approximated as the 1 in 10,000 year return period seismic event.

The maximum recorded earthquake within a 200 km radius of the mine site was M 4.5. An MCE of M 6 therefore seems a reasonable (and probably conservative) selection for the site. Therefore, the seismic design criteria recommended for the tailings dam is to use are an event of M 6, with a PHA value of 0.19g.

According to the existing technical literature widely accepted internationally, it is recommended that the seismic coefficient be considered in the analysis of the pseudo-static condition of slope design, be obtained as a rate between 1/3 to 1/2 of the maximum expected acceleration. This recommendation is consistent with the recommendations of the U.S. Army Corp of Engineers (U.S. Army Corps of Engineers, Hynes and Franklin, 1984), who suggest the use of a pseudo-static seismic coefficient equal to 50% of the peak design acceleration.

The recommendation of the Corp of Engineers is based on the application of the Newmark Method to calculate permanent displacements in earth dams using more than 350 seismic records, concluding that these structures analyzed by the pseudo-static method with factors of safety greater than 1.0, using an horizontal seismic coefficient of 0.5 PHA, do not develop deformations greater than 1 meter, which is an arbitrary value that can be tolerated by earth dams, without representing a risk to the integrity of the impoundment. Therefore, a seismic coefficient of 0.10 was used for the pseudo-static analysis of the slope design of the tailings dam raise projected.

Design of the reinforced wall with geogrids

The stability analysis of the reinforced structure used the limit equilibrium theory, and is divided into the following tasks:

External stability analysis

The external stability analysis corresponds to the reinforced wall as a single element and depends of the following conditions:

- Geometry of the reinforced wall.
- Soil geotechnical characteristics.
- Geogrid design characteristics.

Internal stability analysis

The internal stability analysis corresponds to the behavior of the internal elements of the reinforced wall and the main analyses to be performed are:

- Over-strength failure analysis.
- Tearing failure analysis.

Stability analysis methodology

In general, the stability analyses were performed using the SLIDE® software (Rocsience, 2013) version 5. The analysis for calculating the factor of safety is 2-D using the limit equilibrium approach, approximating the problem to a plane strain state. The failure criteria used was Mohr-Coulomb theory and Spencer Method was selected for the calculation of the failure surfaces. The analysis hypothesis considered that the properties of the materials are homogeneous and isotropic and the collapse would occur as a result of simultaneous failures along the sliding surface.

For the pseudo-static analysis, the mass involved in the failure is subjected to a horizontal acceleration equal to the seismic coefficient multiplied by the acceleration of the gravity, taking into account the effect from the inertial forces produced by the design earthquake. As described above, the horizontal seismic coefficient was 0.10.

Design criteria

The design criteria for optimal safety factors are:

- Minimum safety factor against toppling greater than 1.5
- Minimum safety factor against sliding greater than 1.5
- Minimum safety factor against settlement greater than 2.0
- Minimum safety factor against sliding on the first layer greater than 1.5
- Long term global minimum static factor of safety equal to 1.4; and
- Long term global minimum pseudo-static factor of safety equal to 1.0; or
- Induced displacements by earthquake that does not involve the tailings dam safety or the liner system integrity.

A pseudo-static factor of safety greater than 1.0 does not mean that the dam will not move during an earthquake, what probably will happen is that the displacements will be minimal with no permanent damages in the liner system associated with the design earthquake.

Material properties

The material properties are based on the available information regarding laboratory test on representative samples and designer experience about each material involved in the analysis. A summary of the material properties are shown in Table 1.

Table 1 Summary of material properties

Material	Total unit weight (kN/m^3)	Saturated unit weight (kN/m^3)	Su* (kPa)	Cohesion (kPa)	Angle of friction (º)
Fine tailings (to be stored)	16	18	50	-	-
Structural fill (dam)	20	22	-	5	35
Compacted tailings (dam)	18	19	-	0	34
Rockfill	20	22	-	50	36
Weathered bedrock	16	18	-	0	40

** Su: Undrained Shear Strength*

Reinforced wall location - plan view

The figure 1 shows the zone where the reinforced wall was be constructed. As we can observe in this figure, there were two restrictions in order to perform the design; property limit shown in magenta line and the existing tailings impoundment, which push to design of a reinforced wall in order to reduce space and perform the dam raise.

Analyzed conditions

The following conditions were analyzed:

- The analysis considered the most critical conditions represented by the highest section of the dam in the area of the reinforced wall;
- Only circular type failure surfaces were considered in the evaluation of the stability of the analyzed structures. No block type failure surfaces were analyzed due to interface conditions;
- The seismic coefficient used for the pseudo-static analyses was 0.10;
- For the entire tailings dam facility (reinforced wall and compacted tailings), the analyses were performed, assuming that the tailings are saturated and a phreatic level through tailings dam exists by infiltration due to a potential geomembrane breach (Bishop, 1973). This phreatic level will act mainly as a piezometric level affecting the properties of the structural fill; and
- The long term static and pseudo-static analyses for the tailings dam raise has been modeled considering the drained and undrained shear strength parameters of the materials involved in the analyses.

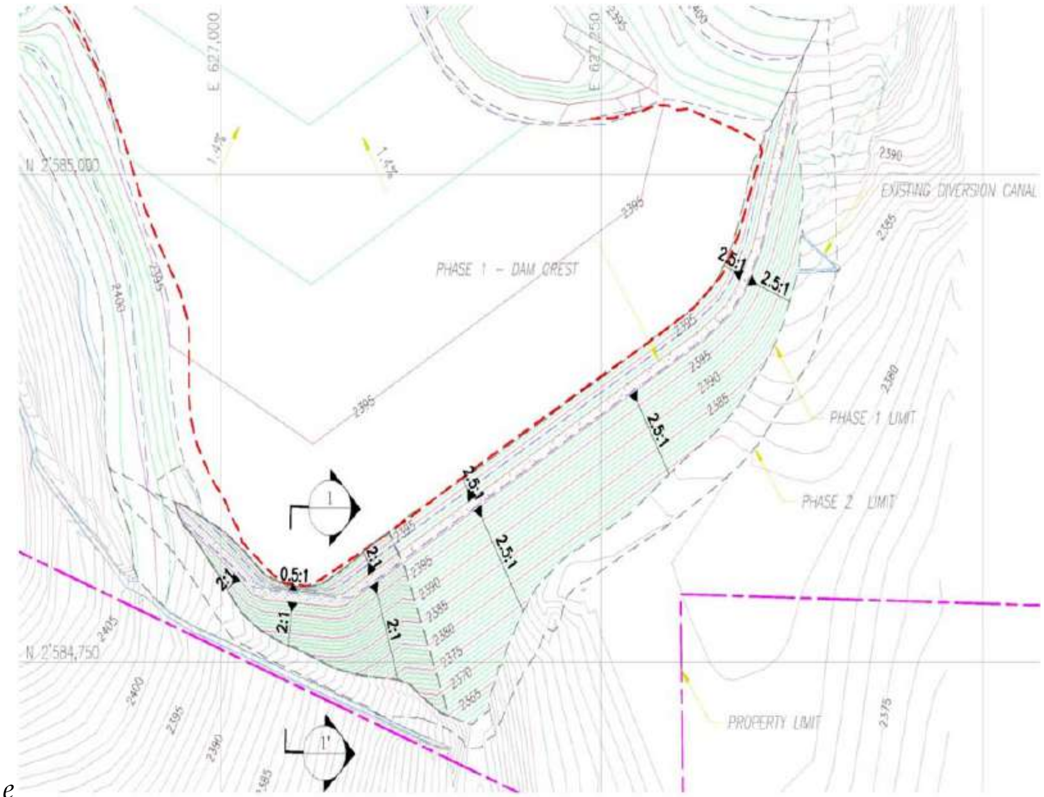

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Figure 1 Reinforced wall with analyzed section - plan view

Results and discussion

A summary of the obtained stability analysis results is shown in Table 2 which shows the results in terms of factor of safety for internal analysis of the reinforced wall. Also the static and pseudo-static cases for the tailings dam section with reinforced wall in the upstream face are shown in this table.

Table 2 Stability analysis results

Structure	Analysis case	Static factor of safety	Pseudo-static factor of safety
Reinforced wall	Topple failure	1.64	-
Reinforced wall	Sliding failure	1.89	-
Reinforced wall	Settlement failure	4.28	-
Reinforced wall	Sliding on the first layer	2.18	-
Tailings dam section with reinforced wall	Circular failure	1.65	1.32

The SLIDE® program result outputs are shown in Figures 2 and 3, which contain information of analyzed geotechnical sections, material properties, phreatic level and location of the critical surface with the lowest factor of safety.

Table 3 Material color legend

Material
Fine tailings (to be stored)
Structural fill
Compacted tailings
Rockfill
Weathered bedrock

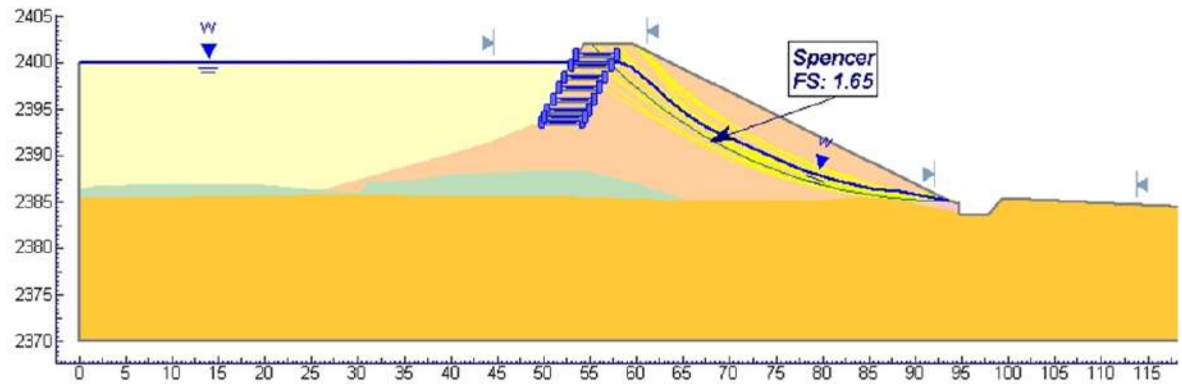

Figure 2 Static stability analysis of the tailings dam

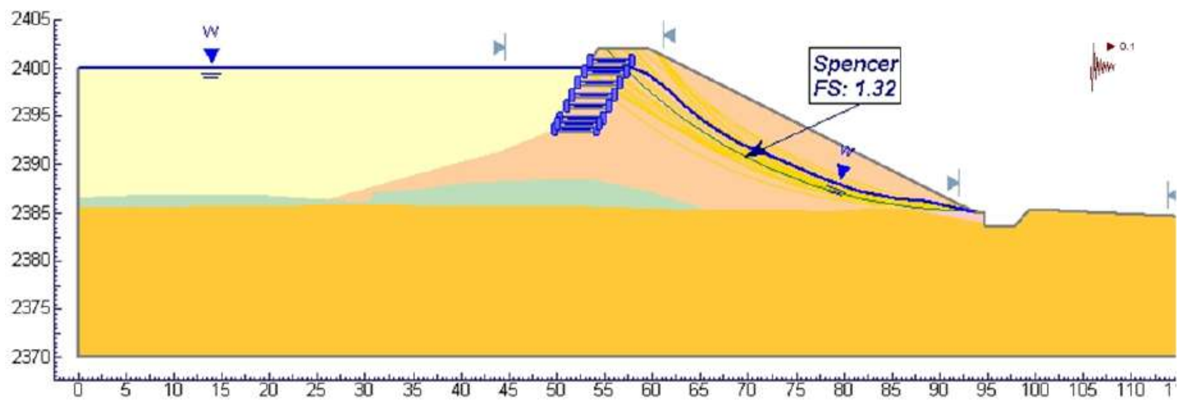

Figure 3 Pseudo-static stability analysis of the tailings dam

According to the results, the factors of safety are greater than the minimum recommended value in the assumed design criteria; therefore, we conclude that the proposed tailings storage facility will be stable.

Civil design

Geometrical configuration

The reinforced wall configuration is shown in Table 4:

Table 4 Final civil configuration

Item	Description
Total dam height	40 m
Total reinforced wall height	8.4 m
Upstream angle slope	63°, 1H:0.5V
Geogrid reinforcement	100 kN/m uniaxial
Geogrid reinforcement	1.2 m spaced, 4.0 m length
Geotextile reinforcement	270 g/m² non-woven
Geotextile reinforcement	0.3 m spaced, 2.5 m lower length, 1.0 m upper length

The final geometrical configuration of the structure is shown in Figure 4, the previous tailings dam was constructed with granular material with same characteristics of that used for the tailings dam raise, from near borrow source

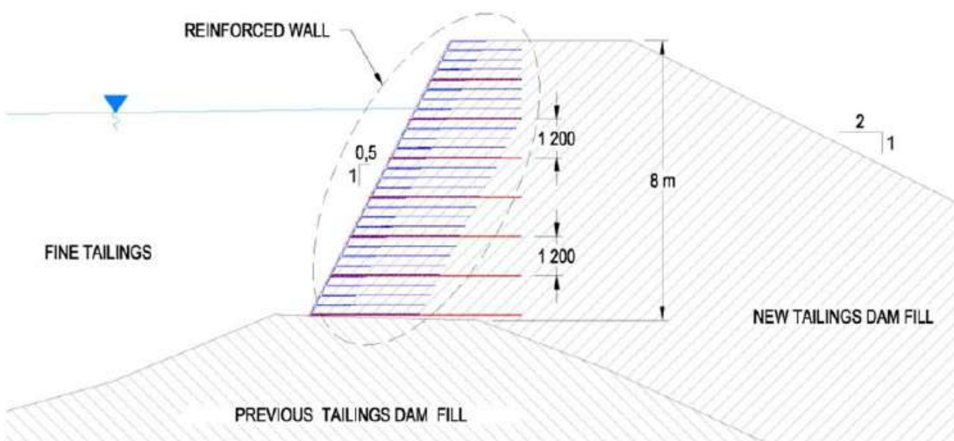

Figure 4 General section of the reinforced wall

Upstream reinforcement wall liner design

The design of the reinforced wall also includes a liner system on the upstream face, which is composed of three layers with different functions:

- *Geosynthetic clay liner (GCL) liner:* a composition of bentonite layered between 2 external non-woven geotextiles, the function of the GCL layer is to provide secondary containment behind the geomembrane liner.
- *LLDPE Geomembrane layer:* The geomembrane is the primary containment being an impermeable layer that protects the wall against seepage (Koerner, 1999).
- *Geocomposite:* The geocomposite will consist of one geonet with non-woven geotextile joined on both sides by heat, and the main function is to drain the water from the tailings to the main drainage system of the tailings impoundment.

Figure 5 shows a typical section of the reinforced wall.

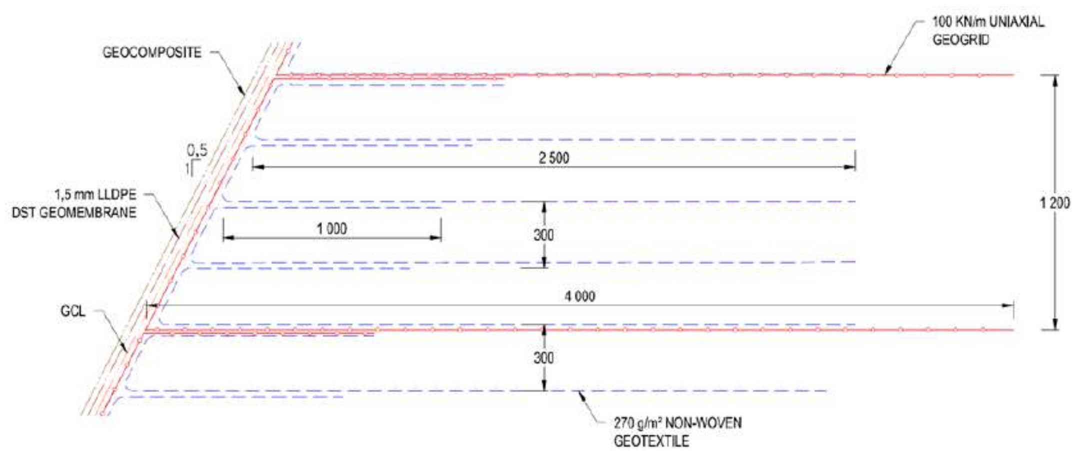

Figure 5 Design of the reinforced wall with geogrid

CONCLUSION

- It is possible to construct tailings dam raises with reinforced walls, which do not involve higher cost and additional work.
- Necessary precautions should be considered in the stability analysis to assure proper behavior of the facility; this is achieved with external and internal analysis of the entire structure.
- Being a reinforced wall which will retain cyanide tailings, a liner system with an impermeable layer is necessary in order to prevent cyanide migration and potential stability issues. However, the analysis has been modeled considering a phreatic surface which will occur in case the liner system is punctured and damaged.
- The problem was analyzed considering a plane strain state (2D) which is conservative, a real 3D analysis would show higher factors of safety.

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NOMENCLATURE

M	Mercalli Scale

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