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Design, Construction and Operation of a Centerline Rockfill Tailing Dam with Low Permeability Core Zone

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Abstract

Gold Fields La Cima (GFLC) owns the Cerro Corona gold and copper mine in the Cajamarca district of Peru, which has gold-equivalent Mineral Reserves of 5.5 million ounces and has been in production since 2008. It produces about 400,000 gold-equivalent ounces a year. MWH Global has been providing design and construction support services to GFLC since 2006.

The Tailing Storage Facility (TSF) includes a rockfill centerline constructed dam with a low permeability core zone. The dam is currently at a height of approximately 100 meters and has a planned ultimate height of 160 meters. The mine is located in a seismically active zone within Peru that has a history of significant earthquake events. In the design of the dam, special consideration was given to maintaining the integrity of the core zone during operations and under earthquake loading.

This paper presents a summary of the facility design and the approach adopted for the limit equilibrium slope stability analyses that were performed to evaluate both upstream and downstream failure modes. The results of field investigations of the tailing beach materials and the properties adopted to characterize the tailing materials are also included. In addition to design considerations, the paper discusses the construction and operation of the facility and presents the results of field monitoring of the facility to date.

Introduction

Project Overview

The Cerro Corona mine is located in northern Peru in the province of Cajamarca, approximately 760 km north-northwest of Lima. The mine is located approximately 80 km by road from the Regional capital of Cajamarca and approximately 30 km from the provincial capital of Bambamarca. The mine location is shown in Figure 1. Gold Fields La Cima S.A.A. (GFLC), a subsidiary of Gold Fields Limited, owns the Cerro Corona mine, a copper mine with significant gold content. The deposit is a diorite porphyry with an average grade of 1.0 gram per tonne of gold and 0.5% copper. The mine has gold equivalent mineral reserves of 5.5 million ounces and has been in production since 2008, producing about 400,000 gold-equivalent ounces per year. The life of mine is expected to be approximately 15 years, extending to 2024 (GFL, 2009). Since 2006, MWH has been providing design and construction support services to GFLC.

Figure 1: Location of the Cerro Corona Mine

Site Characteristics

The site is located on the eastern slope of the western mountain range of the Peruvian Andes. The local topography ranges from shallow valley floors to steep rock bluffs with elevations ranging from 3500 to 4000 m. The regional geologic structure is characterized by Cretaceous-aged sedimentary units, predominantly limestone, with open folds that are steeply dipping to the southwest. The northern part of Peru in the Cerro Corona project area is characterized by significant seismicity.

The site climate is defined by two distinct seasons, a dry and a wet season. For construction purposes, these seasons have been divided into a dry season from April through September and a wet season from October through March. The average annual precipitation is approximately 1,400 mm with approximately 80% of the annual rainfall occurring during the wet season. A 24-hr probable maximum precipitation (PMP) of 250 mm has been calculated for the site.

Site Layout

The Cerro Corona mine site is relatively compact, covering an area of approximately 200 ha, restricted by the Tingo River north of the site and property boundaries around the rest of the site. The mine produces gold and copper by conventional open pit mining methods, utilizing an 18,000 tonne per day (tpd) copper-gold flotation metallurgical processing plant. The site includes other ancillary infrastructure such as rockfill quarries, the waste storage facility (WSF), the upstream containment blanket (UCB), surface water diversion structures, and seepage mitigation structures. The WSF contains waste from mining operations and the UCB is a compacted clay barrier placed upstream of the WSF to reduce seepage flows from the TSF. Seepage mitigation structures, termed Low Volume Underflow (LVU) facilities, have been designed to collect seepage from the TSF. Tailing produced by the Cerro Corona processing plant is deposited in the Tailing Storage Facility (TSF) which is located northwest of the plant site and overlies the Quebrada Las Aguilas, Las Gordas, and La Hierba valleys. The Las Gordas and Las Aguilas valleys are separated by the Las Flacas ridge. The ridge divides the two portions of the TSF as separate impoundments up to an elevation of approximately 3732 m, above which the impoundment is combined. The TSF is currently at a height of approximately 100 m and has a planned ultimate height of approximately 160 m. Figure 2 presents the downstream side of the Cerro Corona site, looking south from a hillside located north of the Tingo River.

Figure 2: Cerro Corona Site

The TSF stores both rougher scavenger tailing (RST), which is deposited sub-aerially, and cleaner scavenger tailing (CST), which is deposited sub-aqueously to reduce the potential for acid generation. RST makes up approximately 95% of the tailing stream. It is thickened to a solids content of approximately 55% prior to deposition. The RST tailing is then conveyed to the TSF via HDPE tailing delivery lines and deposited into the TSF through a number of spigots which run along the upstream (US) face of the TSF dam. Water is removed from the TSF impoundment and reclaimed in the mine process circuit by a floating decant barge located in the impoundment. An overview of the mine site is presented in Figure 3.

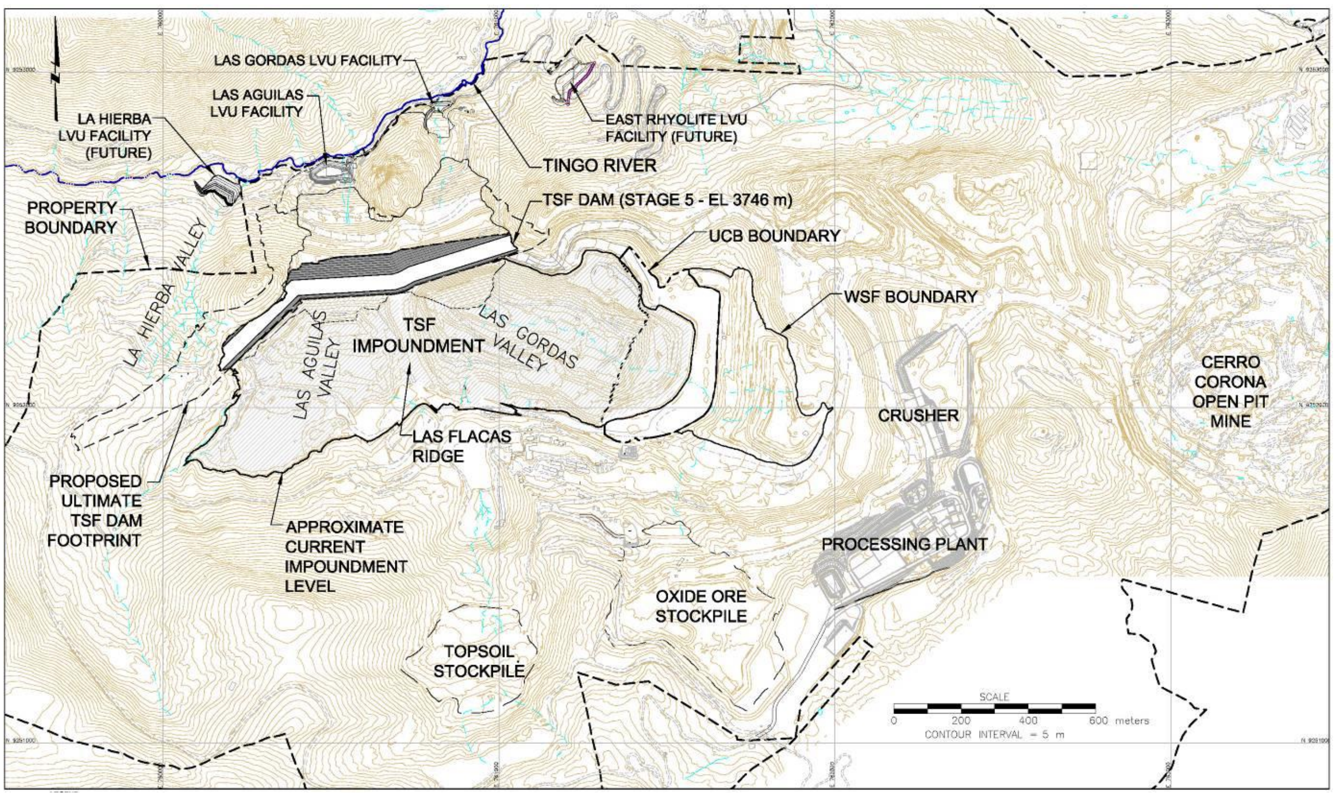

Figure 3: Cerro Corona Site Layout

Facility Design

Design Criteria

The overall goal of the design of the Cerro Corona TSF is to store tailing produced as a result of mineral processing in an environmentally responsible manner. The facility was designed in accordance with relevant international and local regulatory requirements, including those of the Peruvian Ministry of Energy and Mines (MEM), the Mining Association of Canada (MAC), the Canadian Dam Association (CDA), and the International Commission on Large Dams (ICOLD).

Site specific design objectives included:

- Provide storage for a minimum of 100 million tonnes (Mt) of tailing material
- Allow for construction considering the seasonal rainfall conditions
- Account for the relatively high seismic activity in the region
- Account for the relatively small size of the site, considering the location of the Tingo River and the property boundaries
- Allow for the use of locally available borrow materials in the construction of the facility to the extent possible

Background

Considering the design requirements presented above, a centerline (CL) rockfill dam with low permeability core design concept was adopted for the TSF. This design concept consists of the construction of starter dams in the Las Aguilas and Las Gordas valleys, followed by the raising of the starter dams to the proposed ultimate dam elevation of 3800 m utilizing the CL method. The CL raise method consists of constructing vertical raises of the dam, thus maintaining the location of the dam CL. This concept utilizes locally available clays and quarried rockfill and limits seepage from the facility. The design also provides storage for the required amount of tailing within the limited site area. The footprint area is a significant consideration at the Cerro Corona site as the location of the Rio Tingo significantly limits the dam construction footprint, especially in the Las Aguilas valley.

Due to the unique TSF dam design concept, special significance was given to incorporating the observational engineering approach as a part of the dam design, by observing and instrumenting the dam during construction and operations to evaluate its performance and provide feedback on the dam design. The design approach also included the evaluation of a variety of potential failure modes which were incorporated into the dam engineering design analyses. Additionally, a high level of independent review of the dam design was included to provide feedback on the dam design from internationally recognized engineering experts.

To accommodate the climatic conditions at the site, and provide capacity for the tailing material produced during the life of the mine, the TSF dam was designed to be constructed in stages, with conceptual-level designs completed to support for the overall TSF design and final-level designs developed for the intermediate raises, as needed. The use of this staged design and construction concept is well suited to the observational approach adopted as a part of the dam design, allowing the dam design and construction to be optimized to account for items such as feedback from field observations and instrumentation and variations in tailing and borrow material properties during the life of the facility. Figure 4 presents a view of the TSF, looking north from the southwestern portion of the Cerro Corona site. The Las Flacas ridge is visible, which separated the Las Aguilas and Las

Gordas portions of the TSF impoundment during initial operations. Since that time, the ponded water has risen above the ridge, creating a combined impoundment, as seen in Figure 7.

Figure 4: Cerro Corona TSF

Dam Configuration

The typical TSF dam section consists of low-permeability core materials (Zone 1 and 5) placed between US and DS rockfill (Zone 2, 2B and 2C). The core and rockfill materials are separated by drain and filter zones (Zone 3 and 4) placed immediately DS of the low permeability materials to serve as transition zones to reduce the potential for migration of the core materials into the rockfill. To decrease seepage rates from the facility, a grout curtain has been installed in the foundation materials along the axis of the dam.

The following provides a brief description of the characteristics of each of the TSF dam zones:

- Zone 2/Zone 2B/Zone 2C: Zone and Zone 2 materials are similar, specified as well-graded 914.4 mm minus material, with Zone 2 material having slightly more restrictive gradation requirements. Zone 2C material has an increased fines content with a maximum D_{15} of 1.35 mm.
- Zone 1 and 5: Zone 1 and Zone 5 materials are locally derived fine graded materials with a specified in-place saturated hydraulic conductivity of $1x10^{-6}$ cm/s or less. The main difference between the materials is their chemical content, with the Zone 1 material having a restricted copper and sulphur content.
- Zone 3 and 4: Zone 3 and 4 materials are processed aggregates placed to serve as drain and filter zones in the TSF dam. Zone 3 material is a 19.05 mm minus material while Zone 4 material has a maximum particle size of 25.4 mm. The gradation limits for Zone 3 and 4 materials were developed to satisfy filter criteria.

An effective width of 24 m was adopted for the Zone 2B and 2C materials placed upstream of the core materials as a part of the Stage 5 TSF design. This width was selected based on the results of the engineering analyses. To allow for this US width, an approximately 20 m width rockfill bench was placed over the impounded tailing beach at the upstream face of the dam in the Las Gordas valley portion of the TSF. Figure 5 presents the TSF dam section through the Las Gordas valley while Figure 6 presents a detail of the TSF dam crest. Both figures present the proposed ultimate TSF dam design to elevation 3800 m (Stage 14). As presented in Figures 5 and 6, the Stage 14 TSF dam raise includes a 2 m tall parapet wall. Figure 7 presents the Cerro Corona TSF dam and dam zones, looking westward from the east abutment of the dam.

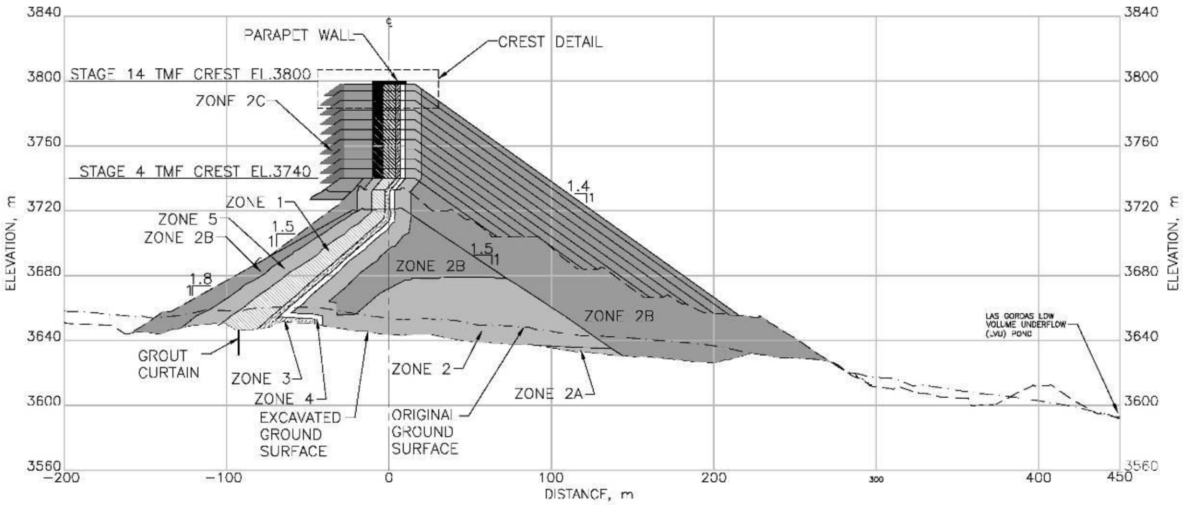

Figure 5: Ultimate TSF Dam Section – Las Gordas Valley

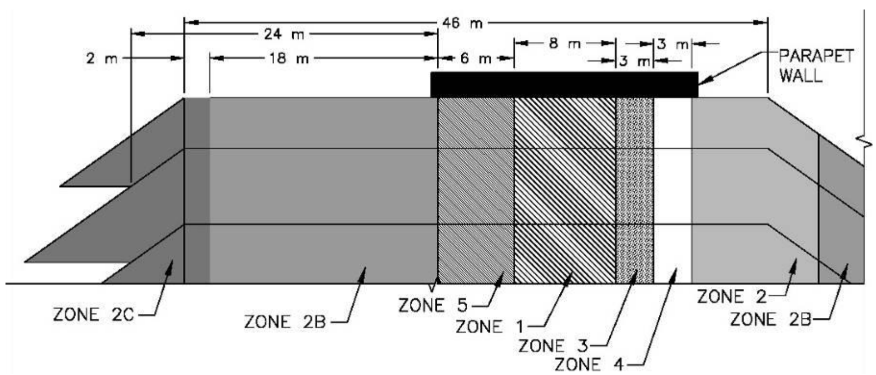

Figure 6: Ultimate TSF Dam Crest Detail

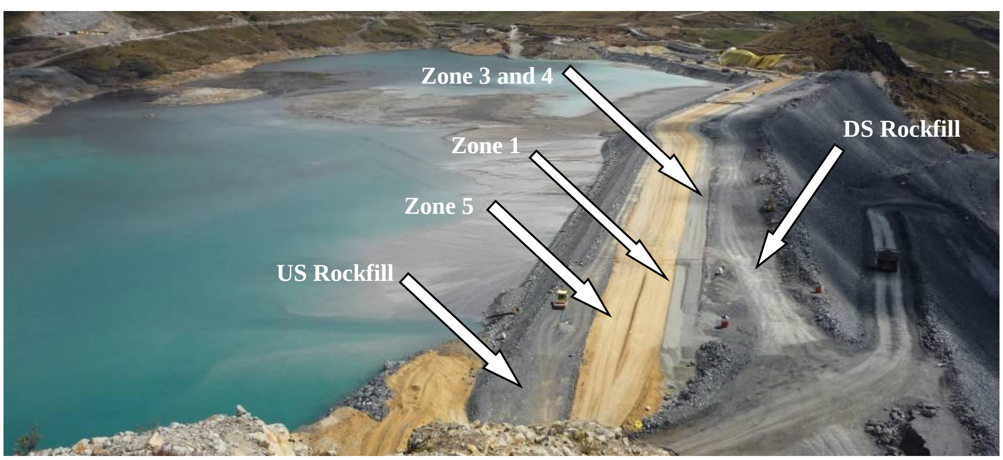

Figure 7: TSF Dam Crest During Stage 5 Construction

Tailing Investigation and Characterization

Tailing investigation programs were performed in September 2009 and September through October of 2010 on tailing material impounded in the Las Gordas portion of the TSF. These investigation programs were termed Campaign 1 and Campaign 2, respectively. The testing performed included cone penetration testing (CPT), vane shear testing (VST), flow penetrometer and tailing sampling for index testing. The test results from the investigation programs were utilized to develop strength parameters to characterize the tailing material. The results of the investigation programs indicate increases in the static shear strength of the impounded tailing material between the Campaign 1 and 2 programs, correlating with site observations.

The Campaign 1 program was performed using a floating barge to access the deposited tailing materials, due to the relatively weak beach conditions at the time. Figure 8 presents the Las Gordas portion of the TSF in September of 2009, during the Campaign 1 testing program. Visible in the impoundment is the floating barge used to test the tailing material.

Figure 8: Las Gordas Tailing Beach – September 2009

As a result of the increased beach strength and beach size in 2010, a tracked rig was utilized in the Campaign 2 tailing investigation program to access the tailing beach and perform the testing. Four roads were constructed across the tailing beach using geotextile overlain with a layer of rockfill to improve access for the Campaign 2 investigation program. Figure 9 presents the same view of the TSF in September of 2010, during the Campaign 2 testing program. Also shown are the roads constructed to access the tailing and the CPT rig used to perform the testing.

Figure 9: Las Gordas Tailing Beach – September 2010

The following parameters were estimated for the tailing based on the results of the Campaign 1 and 2 tailing investigation programs:

- Soil Behavior Type Index (I_c)

- Undrained Shear Strength (Su) and Undrained Shear Strength Ratio (Su/σ_v')
- Liquefied Undrained Shear Strength Ratio ($SuLIQ/\sigma_v$')

The calculated soil behavior type index was used in combination with the normalized CPT soil behavior type chart (Robertson and Cabal, 2010) to characterize the encountered soil deposit. Using this methodology, the material encountered during Campaign 1 can generally be classified as a clay to silt mixture. The calculated soil behavior type index values for the Campaign 2 material are generally lower, indicating coarser tailing material. The tailing material encountered during Campaign 2 can generally be described as a sand to silt mixture with some clay material. It is inferred that these results indicate increased segregation in the Campaign 2 beach. This result is consistent with the increasingly sub-aerial environment under which the tailing was being deposited in 2010.

The undrained shear strength of the encountered tailing material was estimated using the results of CPT, VST, and flow penetrometer testing. Relatively close agreement was observed between the undrained shear strength values estimated using the three testing methods. The undrained shear strength ratio for the material was then estimated by dividing the estimated undrained shear strength by the calculated effective overburden stress at the test location.

The liquefied undrained shear strength ratio of the encountered tailing material was estimated based on correlations using the results of CPT testing. Three correlations were used to estimate the liquefied undrained shear strength ratio of the encountered tailing materials: Olson and Stark (2003), Idriss and Boulanger (2007), and Robertson (2010). All three methodologies involve correlations that utilize back-analyses of historic liquefaction flow failures.

Strength parameters, as presented in Table 1, were estimated for the tailing materials encountered in the Campaign 1 and 2 tailing investigation program by selecting the approximate 20^{th} percentile value from the results obtained in the tailing investigation programs.

Table 1: Tailing Characterization Parameters

Estimated from Campaign 1 and 2 Tailing Investigation Program Results

Campaign	Undrained Shear Strength Ratio (S_u/σ_v')	Liquefied Undrained Shear Strength Ratio (S_{uLIQ}/σ'_v)
1	0.13	0.033
2	0.25	0.035

Engineering Analyses

Engineering analyses were performed in support of the design of the Cerro Corona TSF. To evaluate the stability of the TSF dam, limit-equilibrium slope stability analyses and finite element deformation and slope stability analyses were performed. The finite element analyses were performed for both static and dynamic conditions. The limit equilibrium analyses were performed for a number of dam sections and elevations for US and DS failure modes considering short-term (ST), long-term (LT) and post-earthquake (PE) loading conditions. Evaluations of US stability were deemed a particularly important consideration in the design analyses and analyses were performed to consider the potential for cracking of the low permeability core.

Two sets of analyses were performed to evaluate the US stability of the TSF dam. The first utilized the tailing strengths estimated from the Campaign 2 tailing investigation program, as presented in Table 1, while the second set included sensitivity analyses to evaluate potential issues of concern regarding US stability, as discussed below:

- Tailing Downdrag: The tailing material is deposited into the TSF impoundment in slurry form at relatively low solids content. The consolidation of the deposited tailing has the potential to induce a drag force on the upstream face of the TSF dam. To consider the effects of these potential downdrag forces on the calculated factors of safety, sensitivity analyses were performed with point loads placed at the upstream face of the TSF dam. These point loads were developed in a conservative manner by multiplying the at-rest earth pressure coefficient, Ko, by the static effective vertical stress in the tailing material and then resolving this into a force perpendicular to the US dam face. The downdrag forces were then estimated by multiplying this force by the tangent of the effective friction angle of the tailing. The effective friction angle was approximated as the inverse tangent of the tailing strength ratio. The point loads were applied to the US face of the TSF dam face at 1 m intervals.

- Strain Incompatibility: The stress-strain characteristics of the relatively loose impounded tailing material are expected to vary from that of the compacted materials placed to construct the TSF dam. However, as limit equilibrium methodology does not explicitly incorporate stress-strain behavior, sensitivity analyses were performed in which the impounded tailing material was removed from the analysis and replaced with a phreatic surface to represent the impounded water and point loads to represent the impounded tailing material. These point loads were developed to represent the estimated horizontal effective at-rest earth pressure acting upon the US face of the TSF dam due to the impounded tailing material. The at-rest earth pressure condition is viewed as a lower bound condition where the system is in a state of equilibrium and was developed to serve as a "trigger" analysis to identify scenarios where finite element deformation analyses of the TSF dam should be performed.

  Jaky's equation was used to estimate the coefficient of earth pressure at-rest, which was utilized in combination with the effective vertical stress to estimate the horizontal at-rest earth pressure point loads (Jaky, 1948). Testing performed by Krizek (2004) on slurried kaolin clay samples indicates that Jaky's equation provides a reasonable estimate of the horizontal effective at-rest earth pressure for a slurried material.

  A minimum factor of safety of 1.3 was adopted to evaluate analyses performed considering the Ko condition, with factors of safety below this value indicating that deformation analyses should be performed. This value was selected based on feedback from the Independent Geotechnical and Tailings Dam Review Board (IGTRB, 2010), an independent group of experts who meet regularly to discuss and review the TSF dam design.

Minimum factors of safety of 1.5, 1.3, and 1.2 were selected for long-term, short-term and post-earthquake loading conditions, considering the tailing strengths developed from the Campaign 2 tailing investigation program results. These factors of safety are as recommended by the United States Army Corps of Engineers (2003) and the Canadian Dam Association (2007).

The results of the limit equilibrium analyses indicate that, for all conditions utilizing the tailing strengths estimated from the Campaign 2 tailing investigation program, the calculated factors of safety meet or exceed the minimum values selected for the project. The US sensitivity analyses indicate that the addition of the tailing downdrag forces has a generally limited effect on the calculated factors of safety. However, representing the tailing with at-rest earth pressure forces does have a noticeable effect on the calculated factors of safety, with many of the calculated factors of safety below the minimum value of 1.3 adopted for this condition. Accordingly, it was concluded that strain compatibility represents a significant concern and that static deformation analyses of the TSF dam to evaluate US stability would be required in addition to the dynamic deformation analyses that were being performed to evaluate the seismic behavior of the TSF dam.

Construction

A plan was developed for future construction of the TSF dam. This plan, which utilized material placement rates obtained from TSF construction performed to date, was developed based on the following criteria:

- Maintain a minimum dam freeboard of 2 m in addition to that required to accommodate the PMF
- Restrict earthwork construction to the dry season, to the extent possible
- Reduce the maximum freeboard of the dam to the extent possible (to limit the height of US dam material supported by the tailing beach)

Considering these criteria, a construction plan was developed that utilizes 6 m raise heights for all future construction. Under this plan, it is anticipated that future construction will generally occur on an annual basis during the dry season, with the exception of the final two dam raises which are scheduled to be constructed at two year intervals.

To date, construction of the TSF dam has been performed by local contractors using borrow materials generally obtained from the site. Material sourcing and placement can be summarized as follows:

- Rockfill materials, obtained from drilling and blasting at on-site quarries, are hauled to the point of placement and end-dumped using dump trucks or haul trucks. The rockfill material is then spread using dozers to approximately 1 m thick lifts and compacted using a 19 ton vibratory steel drum roller.
- Zone 1 and 5 materials have been obtained from a variety of sources around the site, including the mine open pit and local glacial alluvial sources. The majority of the Zone 1 and 5 materials placed to date have been borrowed from the open pit, where the materials are obtained from the below economic grade waste portions of the pit. The origin of these materials in the open pit is hydrothermal, containing portions that have undergone meteoric weathering. The weathered portions of the clays have been the most desirable for Zone 1 borrow materials due to their superior geochemical properties (i.e. reduced sulphur contents).. The Zone 1 and 5 material is placed in approximately 25 to 30 cm lifts and compacted with a 19 ton sheepsfoot vibratory roller or a vibratory plate compactor at the abutments.
- Zone 3 and 4 materials are produced in the on-site aggregate processing plant from rockfill material obtained from drilling and blasting in on-site quarries. These materials are compacted in 30 cm lifts using a 10 ton vibratory steel drum compactor or a vibratory plate compactor at the abutments..

A comprehensive quality assurance (QA) and quality control (QC) program has been conducted throughout the construction of the TSF dam. This program includes testing of the construction materials using nuclear moisture density gage, sand cone and in-place rockfill density methods as well as permeability testing using the Guelph permeameter. A laboratory is located onsite for geotechnical testing.

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