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Influence of tailings deposition environment on deposit homogeneity and interpretation of cone penetration test data – A case study from the Cerro Corona Mine

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ABSTRACT

Gold Fields La Cima S.A. (GFLC) owns the Cerro Corona gold and copper mine in the Cajamarca district of Peru. MWH has been providing design and construction support services to GFLC since 2006. The Tailing Storage Facility (TSF) includes a centerline constructed rockfill dam with a low permeability core zone and a proposed ultimate height of 160 meters. Upstream stability of the dam was a specific focus of the design and required characterization of the impounded tailings near the upstream face of the dam.

The tailings deposition environment at the facility has varied with time, being largely subaqueous during initial facility filling, then fluctuating between subaerial and subaqueous due to variations in pond level, and more recently achieving a subaerial beach of increasing length.

Three investigation programs, which included sampling, vane shear testing (VST), and cone penetration testing (CPT), have been performed to characterize the impounded tailings for design purposes. This paper presents a summary of these programs and their influence on the design. It also discusses the apparent influence on the deposition environment on the deposited tailing characteristics and the development of a variable, site-specific cone factor (N_{kt}) for use in estimating peak undrained shear strength (S_u) from the CPT data.

Key words: cone factor, CPT, tailings shear strength

1 INTRODUCTION

1.1 Project Overview

Gold Fields La Cima S.A.A. (GFLC), a subsidiary of Gold Fields Limited, owns the Cerro Corona mine, an open-pit copper mine with significant gold content. The mine is located in northern Peru in the province of Cajamarca, approximately 600 km north-northwest of Lima, approximately 80 km by road north of the departmental capital of Cajamarca and approximately 1.5 km west-northwest of Hualgayoc. The elevation of the mine site ranges from approximately 3,600 to 4,000 m. The mine has been in production since 2008 and it is estimated that the current mineral reserve will be depleted in 2023 (GFLC 2014). MWH has been providing design and construction support services to GFLC since 2006.

1.2 Cerro Corona TSF

Tailings produced by the Cerro Corona processing plant are deposited in the Tailing Storage Facility (TSF) which is located northwest of the plant site. The TSF stores both rougher scavenger tailing (RST), which is deposited sub-aerially, and cleaner scavenger tailing (CST), which is generally 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.

During initial operations of the TSF, a layer of extra fine tailing (EFT) was observed in the upper portion of the impoundment, just underlying the upper supernatant water layer. To reduce the sediment content of this zone and to increase the clear supernatant water available for pumping back to the plant, the EFT material was pumped from the impoundment (using a separate slurry pump) to a small lined pond located along the southern edge of the Las Gordas impoundment. Within this pond, a flocculant was added to the EFT material and the resulting clear water was pumped to the processing plant for reuse. However, as increasing beach lengths have been developed at the facility, significantly decreased amounts of this material are present within the facility and the EFT removal process is no longer being used.

The TSF dam is currently at an elevation of 3768 m (an approximate height of 128 m) and has a planned ultimate height of approximately 160 m. The dam was constructed across the 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 dam section consists of low-permeability core materials (Zone 1 and 5) placed between US and DS rockfill (Zone 2, 2B and 2C). The upstream rockfill was incorporated into the design to provide upstream stability based on engineering analyses considering the anticipated dam raise heights and measured tailings strengths. 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.

Figure 1 presents the crest of the TSF dam at an elevation of approx. 3763 m and indicates the location of the various dam zones and each of the three dams along the extent of the dam alignment. Figure 2 presents a section of the Las Gordas dam, including a 2 m tall parapet wall to bring the dam crest to an ultimate proposed elevation of 3800 m.

Figure 1. TSF Dam with Noted Zonation (Approximate elevation 3765 m)

The TSF dam has been designed to be constructed in stages to provide continually increasing containment capacity for produced tailings. Dam construction began with starter dams in the Las Gordas and Las Aguilas valleys. The original TSF dam design developed by MWH utilized the centerline method to raise the dam above the starter dam elevation. The centerline method was adopted to provide sufficient capacity for the life of mine tailings produced at the site while remaining within the property boundaries. Due to the relatively unique TSF dam design concept, special significance was given to incorporating the observational engineering method as a part of the dam design, by observing and instrumenting the dam to evaluate its performance and evaluating the evolving tailings characteristics during the filling of the impoundment to provide feedback on the dam design.

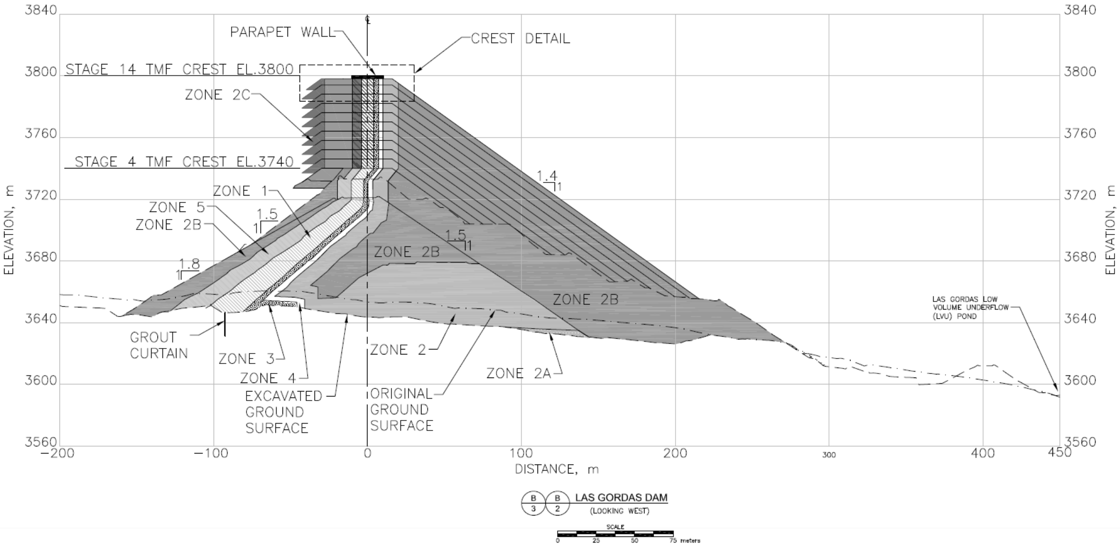

Figure 2. Ultimate TSF Dam Section – Las Gordas Valley

1.3 Evolution of the TSF Dam Design

As discussed further in Section 2, a series of tailings investigation programs were performed to characterize the impounded tailings and serve as inputs to the design of subsequent dam raises.

During the initial operations of the Cerro Corona TSF in 2008 and 2009, there were relatively high pond levels and short beach lengths within the TSF. The initial tailings investigation program performed in 2009 indicated relatively weak tailings material adjacent to the TSF dam. Considering this information, the dam design was updated to provide additional upstream support for the raises of the Las Aguilas and Las Gordas dams constructed in 2009 and 2010. This additional upstream support was incorporated into these raises in various ways: by placing a zone of historically produced tailings material along the upstream face of the Las Aguilas starter dam to serve as an upstream foundation for future raises, the use of the "optimized" centerline raise concept for a raise of the Las Gordas dam (shifting the centerline raise slightly downstream to increase upstream stability), the placement of geosynthetic and gabion reinforcement along the upstream dam face, and the placement of rockfill materials upon the deposited tailings to provide additional upstream support.

A second tailings investigation program was performed in late 2010. The results from this program indicated increasing tailings strengths which were utilized in engineering analyses to support the use of the centerline raise method for future raises. Above elevation 3740 m, all dam raises have been constructed using the centerline method, which includes a 24 m wide zone rockfill upstream of the core zones to provide upstream support. A third tailings investigation program was performed in 2014. The results from this program have recently been evaluated and will be utilized as an input for engineering analyses of future raises. The findings presented in this paper are based on results from this most recent program. Additional information regarding the TSF dam construction materials and design basis and criteria are presented in Corser et al. (2011).

2 TAILINGS INVESTIGATION PROGRAMS AND TESTING

Three tailings investigation programs have been performed at the Cerro Corona TSF to date. The programs were termed "Campaigns". Campaign 1 and 2 were performed in September of 2009 and September through October of 2010, respectively. These programs were performed in the Las Gordas valley portion of the impoundment as the Las Gordas starter dam was constructed first and initial tailings deposition was within this valley. Campaign 3 was performed in September and November of 2014 within the entire TSF basin (Las Gordas, Las Aguilas, and La Hierba). The following sections provide further information on each campaign.

2.1 Campaign 1

Campaign 1 was performed using a floating barge to access the deposited tailings materials due to the relatively short and weak beach conditions at the time. Campaign 1 consisted of CPT and Vane Shear Testing (VST). Due to limitations in the available VST equipment, a rotation rate of only 1 degree per minute could be achieved. This is significantly less than the rate recommended by ASTM D2573 (approx. 0.1 degree/sec) and that recommended by the United States Mine Safety and Health Administration (MSHA) manual for soft, modest permeability mine wastes (rate sufficient to achieve failure within one minute) (D'Applonia Engineering, 2010). Additionally, the observations and measurements indicate barge movement during VST rotation, which is thought to have potentially impacted the test readings.

A total stress cone factor (Nkt) of 15 was calculated considering the VST results and used to estimate the undrained shear strength of the material from CPT measurements. While there was some concern regarding the accuracy of the VST results, the calculated cone factor was within the range of typical values used for normally consolidated clays and considered reasonable.

The calculated undrained shear strength data set was then normalized for use in stability analyses by dividing the calculated strengths by the effective vertical stress to obtain the undrained shear strength ratio, Su/p'. Note that the effective vertical stress was calculated considering hydrostatic conditions (depth below the phreatic surface) and did not consider excess pore water pressures within the consolidating tailings. This was considered appropriate as the value would be utilized in stability analyses which considered a hydrostatic pore pressure distribution for the impounded tailings. A single undrained shear strength ratio of 0.13 was then selected to represent the tailings for analysis purposes. The value was selected through engineering judgment on a visual basis by plotting the data versus depth.

The liquefied undrained shear strength ratio, SuLIQ/p', of the impounded material was calculated based on published literature correlations (Olson and Stark 2003, Idriss and Boulanger 2007, Robertson 2010). A single liquefied undrained shear strength ratio of 0.033 was then selected for engineering analyses using engineering judgment as noted above. The selected shear strength ratios are presented in Table 1.

2.2 Campaign 2

Campaign 2 was performed using a tracked rig via four access roads constructed of rockfill and geotextile running perpendicularly to the TSF dam along the Las Gordas tailings beach. Campaign 2 was performed after construction of the Las Aguilas starter dam was completed and tailings deposition was dedicated to the Las Aguilas portion of the impoundment after construction of the starter dam. At this time, the Las Gordas tailings beach was relatively dry and desiccated as no active deposition was occurring in the area.

Campaign 2 included CPT, VST and soil sampling and laboratory index testing. Sampling was performed at depth using a Shelby tube sampler. Bulk sampling and density testing was performed on the exposed tailings beach by MWH personnel. CPT pore pressure dissipation testing was performed and utilized to evaluate the consolidation characteristics and permeability of the tailings with depth.

While it was initially intended that a full set of VST tests would be performed in Campaign 2, the VST equipment was damaged after performing testing at two locations and no further testing could be performed. As a result, a total stress cone factor (Nkt) of 10 was assumed for the material based on typical literate values and input from the investigation contractor and used to estimate the undrained shear strength of the material from CPT measurements. The undrained shear strength ratio and liquefied undrained shear strength ratio of the material was evaluated as described previously for Campaign 1. A single undrained shear strength ratio of 0.25 and a single liquefied undrained shear strength ratio of 0.013 were then selected to represent the tailings for analysis purposes. These values were selected in a similar manner to the Campaign 1 values, through engineering judgment on a visual basis by plotting the data versus depth. The selected shear strength ratios are presented in Table 1.

2.3 Campaign 3

Campaign 3 was performed using a tracked rig to access the tailings beach via six access roads constructed of rockfill and geotextile running perpendicularly to the TSF dam along the tailings beach in the Las Gordas, Las Aguilas, and La Hierba portions of the impoundment. Campaign 3 included CPT, VST and soil sampling and laboratory index testing. Sampling was performed at depth using a Shelby tube sampler to obtain undisturbed samples for laboratory index testing. Bulk sampling and density testing was performed on the exposed tailings beach by MWH personnel. Index testing included grain size analyses and density testing. A discussion of the grain size distribution results with depth and their relationship to the tailings deposition environment is presented in Section 3. CPT pore pressure dissipation testing was performed and utilized to evaluate the consolidation characteristics and permeability of the tailings with depth.

Fifty five VSTs were performed within the impoundment. VSTs were generally performed between elevation 3750 and 3730 m. Note that elevation 3730 m is the approx. elevation of the tailings in the Las Gordas impoundment at the time of Campaign 2 testing. Accordingly, there is very limited VST strength data available to characterize the undrained strength of the tailings deposited below an elevation of 3730 m in the TSF.

Campaign 3 VSTs were performed at a rate varying between 0.13 and 0.33 degrees per second. This is in general accordance with MSHA recommendations of 0.1 degree per second for soft, modest permeability mine wastes (D'Appolonia Engineering 2011). VSTs were performed in cased boreholes as close to the adjacent CPT location as possible (within 1 to 2 meters). Shear strength results from VST were used to calibrate the CPT data and calculate the cone factor for use in estimating the undrained shear strength from CPT results. A variable cone factor was selected to calculate the peak undrained shear strength from the CPT data. Further discussion on the selection of this cone factor is presented in Section 4.

Undrained shear strength and liquefied undrained shear strength ratios were then calculated from the data in a manner consistent with Campaign 1 and 2. The undrained shear strength ratio results for the Las Gordas portion of the impoundment are plotted in Figure 5. The results indicate that the tailings exhibit a generally linear normalized strength profile with depth and that the strength of the tailing material can be adequately characterized with a linear shear strength ratio. The data also indicates slight variations in the undrained shear strength ratio and liquefied undrained strength ratio within the different impoundment areas of the TSF and with depth in the Las Gordas and Las Aguilas valley (a change in strength observed at approximately elevation 3730 m in the Las Gordas portion of the impoundment and at approximately 3720 m in the Las Aguilas portion of the impoundment). This is attributed to variations in the deposition environment during filling of the TSF and is discussed further in Section 3.

This data was reviewed and single strength ratios were selected to represent the deposited tailings material within the different impoundments and impoundment depths using through engineering judgment on a visual basis by plotting the data versus depth. The selected peak undrained shear strength ratios and liquefied undrained shear strength ratios selected from Campaign 3 are presented in Table 1.

Table 1. Selected Peak Undrained Shear Strength and Liquefied Undrained Shear Strength Ratios from Campaigns 1, 2, and 3

Campaign	Date of Testing	Area	Peak Undrained Shear Strength Ratio (S_u/σ_v')	Liq. Undrained Shear Strength Ratio (S_{uLIQ}/σ_v')
1	Sept. 2009	Entire Deposit	0.13	0.033
2	Sept./Oct. 2010	Entire Deposit	0.25	0.035
3	Sept./Nov. 2014	Las Gordas (Above El. 3730 m)	0.24	0.036
		Las Gordas (Below El. 3730 m)	0.35	0.043
		Las Aguilas (Above El. 3720 m)	0.23	0.038
		Las Aguilas (Below El. 3720 m)	0.27	0.048
		Las Hierba	0.22	0.034

3 IMPACT OF DEPOSITION ENVIRONMENT ON TAILINGS DEPOSIT GRADATION

Sampling and testing of RST tailing has been performed incrementally throughout mine operations. Test results indicate that the RST material has a fines content (percent of material passing the No. 200 (0.075 mm) sieve by mass) that ranges between 52 and 71%. This data was compared with sieve analysis testing results from samples obtained during Campaign 2 and Campaign 3 to evaluate the segregation of the tailings material within the deposit. Campaign 2 samples were obtained from the beach surface at the time of the investigation (approximately elevation 3730 m). Campaign 3 samples were obtained at depth using Shelby tubes samples and from the beach surface at the time of the investigation (approximately elevation 3758 m).

The test results indicate a clear variation in fines content with depth within the Las Gordas and Las Aguilas portions of the impoundment. Figure 3 presents a plot of the measured fines content of tailings samples obtained from the Las Gordas portion of the impoundment versus depth. Below an elevation of approximately 3730 m in the Las Gordas portion of the impoundment and approximately 3720 m in the Las Aguilas portion of the impoundment, test results indicate that the deposited material is notably coarser than the incoming RST tailings. However, in both impoundments, the test results indicate isolated lenses of material within this zone that are significantly finer than the incoming RST tailings. Above an elevation of 3730 m in the Las Gordas impoundment and 3720 m in the Las Aguilas impoundment, the tailings are generally finer with a fines content closer to the incoming RST tailings.

The variation in fines content with depth in the Las Aguilas and Las Gordas impoundment is attributed to variations in the deposition environment with time at the site. Site records and photographs were reviewed to characterize the deposition environment of the deposit with depth. The results of this review for the Las Gordas impoundment are summarized in Figure 3. As presented in Figure 3, the tailings below elevation 3730 m were generally deposited in a subaqueous environment. The relatively low fines content of the sampled tailings is attributed to segregation of fines during subaqueous deposition. This is consistent with field observations which indicate that significant levels of floating EFTs were present during subaqueous deposition in the TSF. The intermittent lenses of high fines content materials are surmised to be zones of flocculated and settled EFTs. Above elevation 3730 m, the deposition environment was generally subaerial with increasing beach lengths. The increased fines content of this material is attributed to fines capture within the tailings beach. This is consistent with observations from the oil sands industry, where field trials indicate that beaches are effective in capturing approximately 20 to 40% of mature fine tailings (MFT) with a particle size of 44 microns or less (COSIA, 2013).

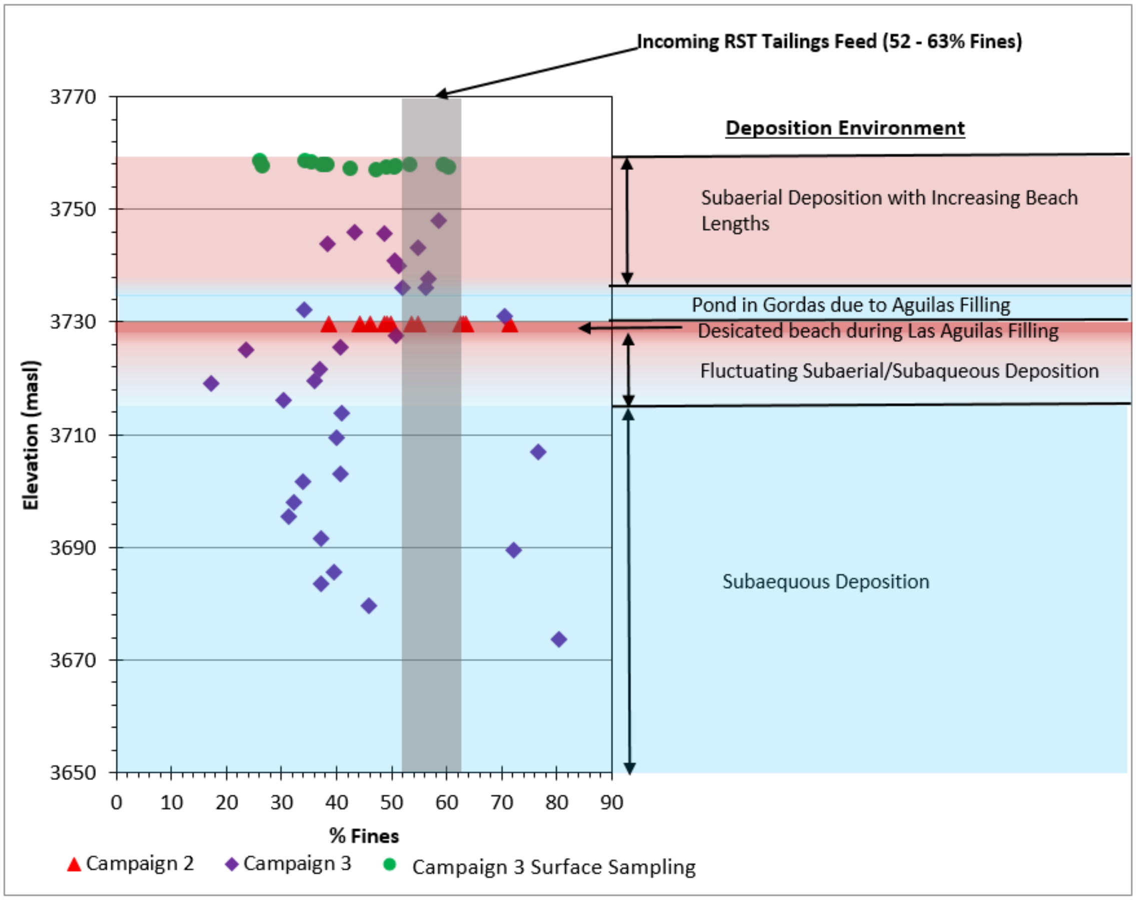

Figure 3. Las Gordas Tailings Fine Content with Generalized Deposition Environment

Note that the sampled tailings material in the La Hierba portion of the impoundment has a fines content that is relatively uniform with depth and consistent with the material observed in the upper portions of the Las Gordas and Las Aguilas impoundments. This is considered reasonable as this impoundment is significantly shallower than the Las Aguilas and Las Gordas portions of the impoundment and deposition was generally subaerial in this area.

While not presented in this paper, the available grain size distribution data was also reviewed to evaluate the variation in segregation with increasing beach length (i.e. distance from the TSF dam face). It was anticipated that coarser materials would be encountered close to the TSF dam and finer materials would be encountered at greater beach lengths. The test results indicate this type of segregation along the Campaign 2 Las Gordas beach (elevation of 3730 m). The remaining test results, including those from the Campaign 3 Las Gordas beach (elevation 3758 m) do not indicate a clear segregation trend with distance from the dam. It is anticipated that future investigation programs will include a beach sampling program to further evaluate the segregation along the beach as the TSF is filled.

These observations are consistent with the Campaign 3 undrained shear strength ratio results which indicate a variation at the approximate elevations of 3730 m and 3720 m in the Las Gordas and Las Aguilas impoundments, respectively, and no clear variation with depth in the La Hierba impoundment.

4 UNDRAINED SHEAR STRENGTH

4.1 Introduction

The undrained shear strength of clays are commonly estimated from CPT data. The most common approach is to utilize bearing capacity theory and apply the bearing capacity equation to a situation of a deep circular foundation in clay, treating the corrected cone tip resistance, q_t, as the ultimate bearing strength and replacing the bearing capacity factor, N_c, with the total stress CPT cone factor, N_{kt} (Schmertmann 1975).

A variety of other approaches have also been proposed. These include site specific correlations, relationships based on soil properties (such as plasticity index or overconsolidation ratio), cavity expansion and strain path models that incorporate the rigidity of the soil (Kim et al. 2006) and relationships based on alternative cone measurements such as effective cone resistance and excess pore pressure (Varathungarajan et al, 2008). Literature indicates that the effective cone resistance relationship can be subject to small errors in measured cone resistance and the excess pore pressure relationship. It appears that the total stress approach is most commonly used and the excess pore pressure approach is often considered for soft clays is it does not rely on tip resistance values, which can be quite small and subject to measurement errors in low bearing capacity materials.

Based on bearing capacity theory, the total stress cone factor should be close to 9 for clays that are not very sensitive (Lunne et al. 1976, Kim et al. 2006). In practice, it has been found that the total stress cone factor typically ranges from 10 to 20, although it is considered best practice to develop site-specific cone factors based on strengths obtained from other methods, such as unconfined compressive strength or vane shear testing (Schmertmann 1975, Lunne et al. 1976). Multiple references indicate that a uniform total stress cone factor can be appropriate for a given material type (Eid and Stark 1998, Schmertmann 1975) but can lead to serious errors if applied uniformly to varying material types. For general soils, total stress cone factors ranging between 5 and 70 have been reported (Amar et al. 1975). For clays, total stress cone factors ranging from 7 to 26 have been reported (Kim et al. 2006). Accordingly, a key concern in estimating undrained shear strength from CPT data is the selection of a cone factor. The following section provides a discussion on the approach used to select a cone factor for the Cerro Corona Campaign 3 CPT data.

4.2 Campaign 3 Cone Factor Selection

For Campaign 3, a total stress cone factor of 10 was initially selected by the investigation contractor as a best fit value to correlate the VST values with the CPT data set. The calculated shear strength values were then normalized to undrained shear strength ratios as discussed previously in this document. A significant variability in undrained shear strength ratio values was observed (ranging from approximately 0.02 to 1.8) with many calculated values well outside of the range of typically reported range of values for clays (Varathungarajan 1998).

The applicability of the proposed total stress cone factor was then further evaluated considering total stress, effective cone resistance, and excess pore pressure methods by plotting the VST-based undrained shear strength versus the corrected cone resistance minus total vertical stress, effective cone resistance, and the net excess pore pressure, respectively. Ideally, a uniform ratio would be observed between the data (i.e. the cone factor). However, a large spread in data was observed for all three considered methodologies, indicating a large variation in the cone factor for each method. Note that a relatively more linear relationship was observed for the total stress method data and accordingly it was adopted for use in further evaluating CPT data.

For each vane shear test, the total stress cone factor was calculated based on the VST data and the data from the adjacent CPT at that depth. A wide range in total stress factors was observed, ranging from approx. 3 to 44 (considering 100 mm averaging of the VST and CPT data to account for the length of the VST and the influence of adjacent materials on CPT and VST performance). Considering literature data which indicates that cone factors are most directly applicable to a specific material type, this appears to indicate variability in the material type deposited in the TSF and is consistent with sieve analysis results for the impoundment which indicates a relatively non-homogenous deposit, with fines contents ranging from 16% to 80%.

The data was then reviewed to evaluate if a relationship exists between the material type and the total stress cone factor for the deposit. The Soil Behavior Type Index (I_c) was utilized as a metric to represent material type. The Soil Behavior Type Index is a function which includes the normalized cone tip resistance and the normalized friction ratio. It has been found useful in characterizing the consistency of fine grained soils as clayey and sandy materials exhibit differing tip resistance and skin friction behavior when tested with a cone (Robertson and Cabal, 2010).

The individually calculated total stress cone factors (based on VST and CPT results) were then plotted versus the I_c value obtained from CPT and a relationship was developed, as shown in Figure 4. A correlation is observed, with higher I_c values (i.e. more fine grained materials) typically having lower cone factors. Some engineering literature indicate what may be a similar relationship, between increasing plasticity index and decreasing total stress cone factor (Lunne and Kleven 1981, Baligh et al. 1980). However, other researchers have found opposing trends or no relationship at all (Kim et al 2010). Accordingly, it appears that the engineering literature does not currently support any general conclusions about the relationship between cone factor and material type and that such relationships should be viewed as site specific. For reference, Figure 4 also includes the originally selected cone factor of 10 is presented as a red dotted line in the figure. Note the significant variation in calculated cone factors from this value.

Note that the range of I_c values obtained from CPT for the whole deposit slightly exceed the range of I_c values used to develop the N_{kt} relationship presented in Figure 4 (as this relationship only includes I_c values adjacent to VST locations) and that the relationship contains a limited number of Ic values below 3.0 (silts and coarser grained soils). This is due to the limited VST sampling at greater depths in the deposit where coarser grained soils are thought to exist due to deposition environment. Future investigation programs should consider the non-homogeneities of the deposit and include sufficient shear strength testing (such as VST) to encompass the range of materials within the deposit.

The calculated I_c values obtained from CPT generally range between 2.3 and 4.5. This indicates that the tailings range from silty sands and clayey sands to very fine grained clays (Robertson and Cabal 2010) and is consistent with the range of soil classifications obtained from Campaign 3 laboratory testing. This indicates that the Soil Behavior Type Index may be applicable to tailings as well as naturally occurring soils. A detailed review of the data to compare I_c values to individual adjacent sample sieve analysis results was not performed.

The cone factor as a function of I_c relationship presented in Figure 4 was then applied to the full CPT data set to calculate peak undrained shear strengths and the undrained shear strength ratio was then calculated in a manner consistent with that used in Campaign 1 and 2. This data set was then used to select the undrained shear strength ratios for Campaign 3, as presented in Table 1. As seen in Figure 5, the use of the variable cone factor relationship resulted in a significant reduction in the range of calculated undrained shear strength ratios and results in values that are generally within the range reported in literature for clays (0.1 to 0.5) (Varathungarajan 1998). The calculated values are also consistent with the range of peak undrained shear strength values obtained from VST (0.1 to 0.45). This allows for a significantly higher level of confidence in the use of CPT to estimate peak undrained shear strengths at the project.

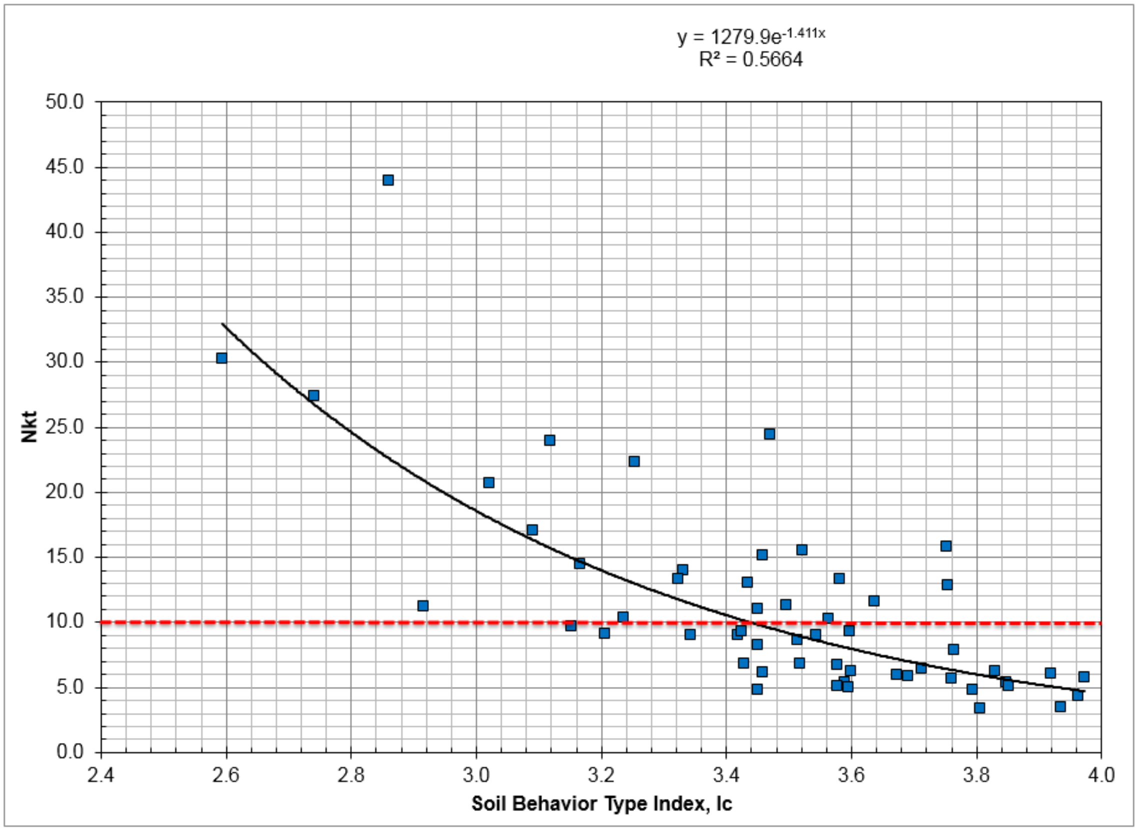

Figure 4. Total Cone Factor vs. Soil Behavior Type Index and Plotted Relationship Used for Analysis (originally assumed $N_{kt} = 10$ shown for reference)

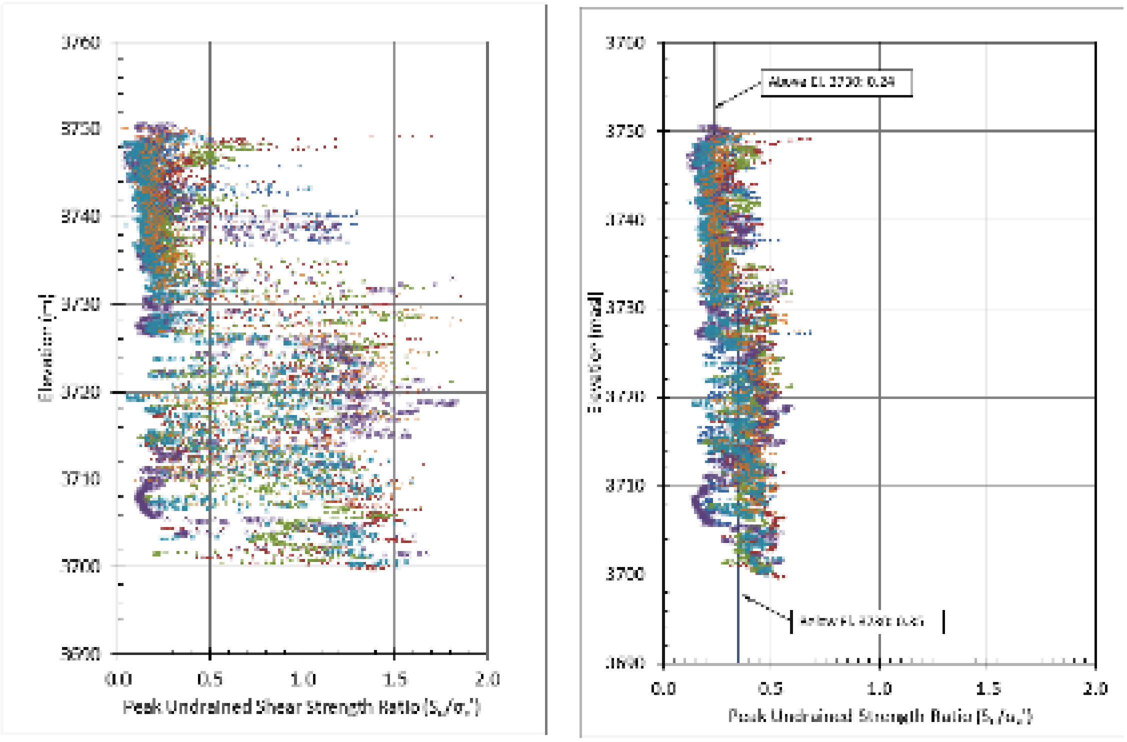

Figure 5. Calculated Peak Undrained Shear Strength Ratio Vs. Depth – Las Gordas (left – with N_{kt} = 10, right – with variable $N_{kt}(I_c)$ relationship)

5 CONCLUSIONS

The following is a summary of key conclusions from tailings investigation programs performed at the Cerro Corona Mine:

- The tailings deposition environment can impact the engineering characteristics of the resulting tailings deposit. Variations in the tailings deposition environment appear to have resulted in variations in the grain size distribution and shear strength of the deposited tailings at the Cerro Corona TSF.
- Visual observations of the supernatant pond water during operations indicate a reduction in suspended fine sediments (EFTs) within the supernatant water pond corresponding with an increase in subaerial beach lengths. This is consistent with laboratory test results which generally indicated the presence of coarser beach materials during periods of subaqueous deposition and finer beach materials during periods of subaerial deposition. This indicates that subaerial beach deposition serves to capture a portion of the fines present in the tailings stream.
- Test data from Cerro Corona generally does not indicate a significant variation in tailings gradation with distance from the deposition point at the upstream dam face. This indicates limited segregation of tailings along the length of the subaerial beaches. This may be due to the relatively short and wet beaches present at the site or it may be a function of the limited data set. Note that the test data does indicate increasingly fine material farther from the deposition point for the case of the well-drained and desiccated Las Gordas beach at elevation 3730 m.
- Testing methods that provide a direct measurement of shear strength (such as laboratory triaxial testing or in situ VST) should be performed to allow for development of a site specific cone factor for use in estimating undrained shear

strength from CPT data. Variations in the characteristics of the tailings deposit may require the use of a specific cone factor for zones within the stratum or the development of a site specific relationship such as one based on the soil behavior type index to provide a reasonable correlation between shear strength test results and CPT data. The relationship developed for Cerro Corona indicates a decreasing total stress cone factor with higher soil behavior type index values (finer materials). However engineering literature suggests that such trends may be site specific.

- The data set used in the development of the variable cone factor does not encompass the full range of Soil Behavior Type Index values measured in the deposit. This is due to limited VST at greater depths in the deposit, where coarser materials appear to be present. For development of site specific cone factors applicable to the full deposit, investigation programs should consider the non-homogeneities of the deposit and include shear strength testing (such as VST) of materials that encompass the range of materials within the deposit.
- The range of soil types indicated from the Soil Behavior Type Index are consistent with the range of soil types obtained from testing of laboratory samples. This indicates that the Soil Behavior Type Index may be applicable to tailings as well as naturally occurring soils. A detailed review of the data to compare I_c values to adjacent sample sieve analysis results was not performed.
- The use of the site-specific variable cone factor relationship resulted in a significant reduction in the range of calculated undrained shear strength ratio values. The calculated undrained shear strength ratios are within the range of values typically reported in literature for clays and are consistent with the range obtained from VST.
- The Campaign 3 data indicates that the tailings strength can be adequately characterized with a linear shear strength ratio (shear strength divided by effective vertical stress pressure). The data also indicates that the strength ratio varies slightly within different portions of the impoundment and varies with depth between zones of differing deposition environment.

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