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Geotechnical–Metallurgical Characterization of Crushed Agglomerated Ore in Shahuindo Heap Leach

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Abstract

The geotechnical design of a heap leach facility, generally considers a mine production plan, mineral processing information, leaching cycles and general information of the project site with the aim of defining physically stable heap geometry with the ability to allow stacking of ore throughout its lifetime. To meet these objectives is important to characterize both shear strength and hydraulic conductivity of the ore, even more if we have to deal with lithological variation or mineral pre-processes such as the crushing and agglomeration technique that will affect these properties.

The ore from Shahuindo open pit comes from different mineralogical alterations classified as: siltstones, sandstones, sulfides and breccias. Upon which the metallurgical characterization of each lithological unit has been done and a suitable agglomeration technique for fine ore was identified as well, in order to improve the Au / Ag leachate solution recovery. Column leach tests were conducted to determine recovery percentages of ore composed by sandstone and siltstone. In addition, tests for mixtures, of both lithologies in different proportions adding cement as a blinder, will justify adequate proportional mixing and use of the agglomeration technique to increase permeability and consequently increase the rate of diffusion velocity of cyanide solution through the pores of the ore as well as enhancing the physical stability of the heap.

The identified ore at the site presents coarse and fine particle size distributions and a wide range of values of hydraulic conductivity coefficients that makes the conventional heap leach design implicated. 77 hydraulic conductivity tests were conducted on leached, agglomerated and non-agglomerated ore samples from different lithologies or mixtures of them, 59 rigid wall permeability tests and 18 flexible

wall permeability tests, in order to characterize the leached ore permeability as a function of confinement pressure. Likewise 10 triaxial compression tests were conducted on these samples. Finally hydraulic conductivity, SWCC and shear strength, for different conditions and lithology of ore from one site were obtained; moreover liquefaction susceptibility assessments for the ore were evaluated.

Introduction

During the design of a heap leach pad is common to require a geotechnical laboratory program of the component of the heap leach design, such as the foundations materials, liner system (composed by a geomembrane over a low permeability soil), borrow materials and ore in order to define the mechanical and hydraulic properties, as well as metallurgical characterization of ore. It is usual for feasibility or even in basic engineering phases of the design to assume some properties of the ore material, this practice is common for ROM (run of mine) ore, due to the fact that there are lot of experiences in the heap leach design of ROM ore, however it should not be an excuse for avoiding a correct laboratory testing program.

In most gold mine operations, ROM ore is stacked by truck dumping with or without previous crushing process, as long as the nature of the rocks allow to obtain a high permeability ROM ore and high strength properties which allow a good recovery of gold during the leaching process and enhance stability of the heap. However, several mine operations have experienced problems associated with poor recovery due to percolations issues caused by a complex ore (Dhawan et al., 2012) as the case of Shahuindo mine where the ore comes from different mineralogical alteration classified as siltstones, sandstones, sulfides, intrusive rocks, quaternary sands and breccias.

As the key element in a successful heap leach project is a heap with a high an uniform permeability (Kappes, 2005), due to the fact that the ore from Shahuindo contains a high percent of fines and for this reason it need to be crushed and agglomerated using cement (6 kg of cement per ton of ore) with a 18% of water content in order to improve gold recovery. Agglomerated and non-agglomerated ore samples were tested, in order to characterize leached ore permeability as a function of confinement pressure, SWCC and strength according to the American Society for Testing and Materials (ASTM), Table 1 summarizes performed tests and their principal aim and use.

Table 1: Summary of laboratory testing

Geotechnical test	ASTM Standard	Number of units	Aim

Sieve analysis	D422	25	Determine the size of particles to filter design, wick drains installation
Hydrometer analysis	D422	6	Determine the size of fine particles, filter design
Atterberg limits	D4318	25	Limits for classification, basic correlations, susceptibility to liquefaction
Specific gravity	C127 y D854	10	Base for special tests
Point load test index	D5731	10	Classify the material for other uses
Consolidated–undrained triaxial compression	D4767	12	Determine the mineral resistance for stability analysis
Saturated hydraulic conductivity (rigid wall)	D2434	59	Ore characterisation for flow analysis
Saturated hydraulic conductivity (flexible wall)	D5084	18	
Soil water characteristic curve	D6836	5	

Geological Characterisation

In the open pit of the project, ores of different geological origin were identified; the ore composed of sandstone (SD) predominates for phase 1 of the project, which does not present any problem for design and operation. For the phase 2A the predominant ore corresponds to the intercalations of siltstone-sandstone (ST-SD), however, the presence of ore SD and intercalations of sandstone and siltstone (SD-ST) are considerable. It is important to note that in the SD-ST intercalations, sandstone origin ore predominates, while in the ST-SD intercalations siltstone origin ore predominates. In Table 2 ore distribution for the different phases of the project is shown, also considering the materials slightly predominant as breccias and intrusive rocks.

Table 2: Mineralogical composition of ore in percentages

Geotechnical or metallurgical test	Heap Leach 1	Heap Leach 2A	Heap Leach 2B
Sandstone (SD)	64%	29%	6%

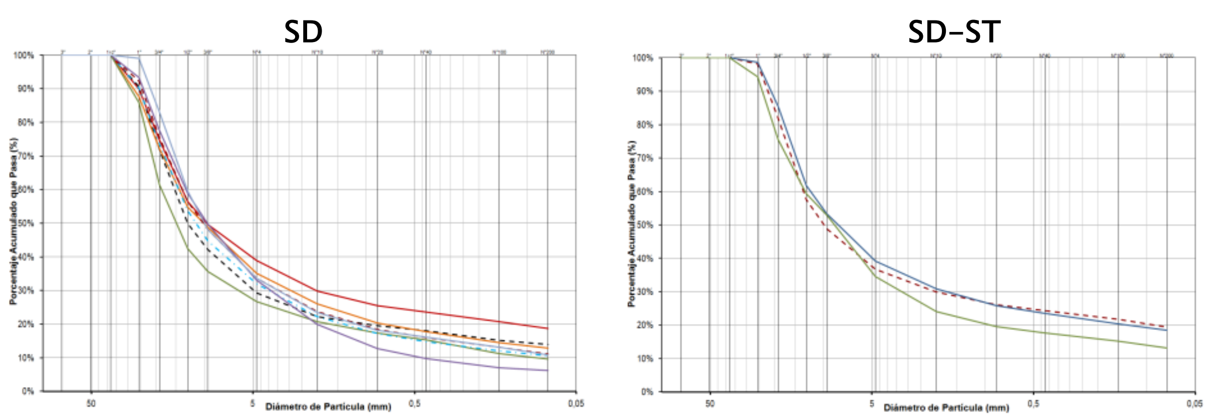
Intercalation sandstone –siltstone, Sandstone >50% (SD-ST)	17%	27%	21%
Intercalation siltstone - sandstone, Sandstone <50% (ST-SD)	19%	40%	60%
Brecias soil (BX)	–	2	7
Intrusive rock (ftp)	–	2	7

Laboratory Program

Geotechnical and metallurgical laboratory testing program was established in order to characterize resistance and hydraulic behavior of the ore, and recovery potential of the leached ore samples. To estimate ore recovery and validate a kinetic model for heap leaching, column leach tests were performed on each ore type of Shahuindo open pit. On the other hand, several saturated hydraulic conductivity tests and soil-water characteristic curves determination were conducted on the ore samples for transient unsaturated flow analysis of the pregnant leached solution within the heap, and consolidated-drained triaxial tests (CU) to estimate ore resistance in undrained conditions.

Soil classification

According to the classification reported in Table 2 a laboratory program was developed in order to identify the particle size distribution of each type of ore, Figure 1 depicts grading curves; the SD ore is mostly classified as GP, GP-GC and GP-GM according to USCS (unified soil classification system). The SD-ST ore is mostly classified as GC and GC-GM. The ST-SD ore is classified as SC, GC and to a lesser extent as CL.



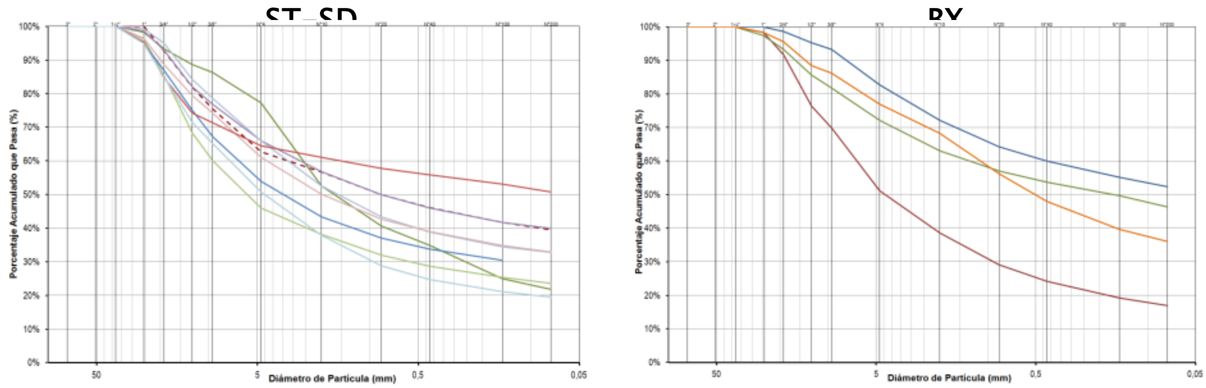


Figure 1: Sieve distribution for different materials from open pit boreholes

The average particle size distribution of the different types of ore are shown in Figure 2, the same that were used to define the index properties, filters characteristics and drainage gravel that the heap will need in both the liner system at the base of the heap and on the zone of interlifts. Moreover, due to the large amount of fines and to enhance collection of the pregnant leached solution, the heap design is likely to include a system of sub-vertical drains, the same that will be designed by considering the ore particle size distribution and principally its hydraulic conductivity.

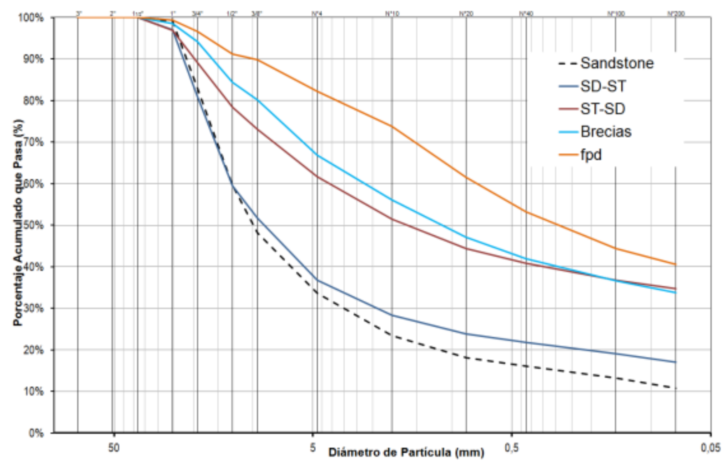


Figure 2: Average sieve distribution for each material

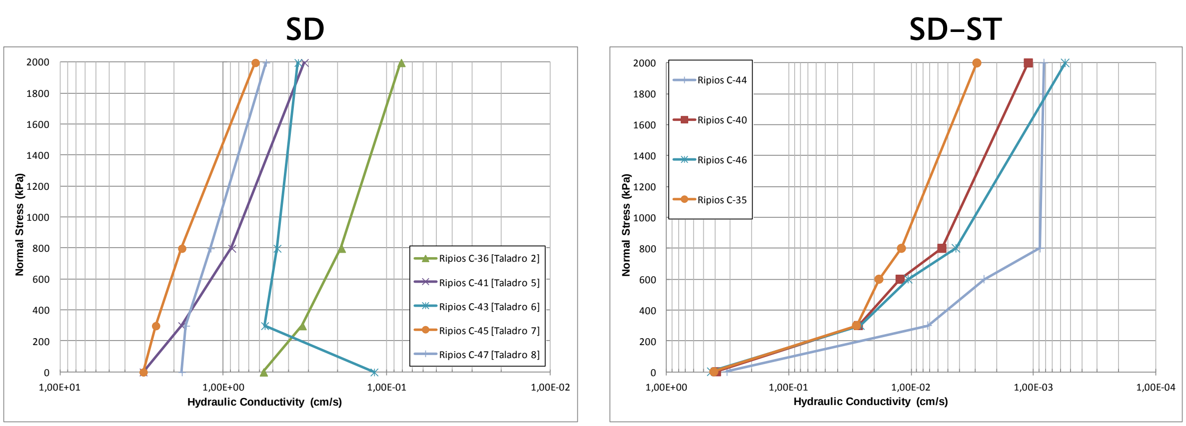
Metallurgical Tests

Since some types of ore have considerable fines content ranging from 20 to 50%, especially the ST-SD (predominant in 2A and 2B phase), and plasticity indexes between 6 and 12 and in order to improve the ore permeability and solution recovery, it was decided to crush and agglomerate the ore, for this purpose a set of metallurgical tests were performed to obtain an optimum dosage of cement of 6 kg per ton of ore, with agglomeration drums to an average moisture content of 18% for an ore with a D_{80} of 25 mm.

Saturated hydraulic conductivity

The ore types described in Table 2 were prepared to simulate the process of crushing and agglomeration, in order to obtain their properties of hydraulic conductivity, as well as grading analysis, the test program was developed by ore type and considering the agglomeration process, the same that causes higher hydraulic conductivities at lower confinement pressures; however, the effect of higher values of the agglomerated ore permeability was reduced when an increase of normal stress was considered.

In Figure 3 variation in permeability values for different normal stresses is shown, it is observed that for the SD ore, there is not important variations shown in the values of the hydraulic conductivity (K) remaining between values of 1 to 0.1 cm/s, even for normal stresses up to 2000 kPa. For SD-ST ore a variation of K from 0.5 to 1.0E-3 cm/s was obtained, this due to the sandstone material which predominates in this type of material. On the other hand, in the ST-SD ore type an important variation for the value of K was obtained, for the tests without confinement it was obtained a value of 0.5 to 0.05cm/s, because of the agglomeration, the same that loses the agglomerating effect by increasing the normal stresses in a minimum, such behavior is verified by testing at 300 kPa confinement pressure, obtaining K values lower than 1.0E-6 cm/s. The breccia material had similar behavior to ST-SD.



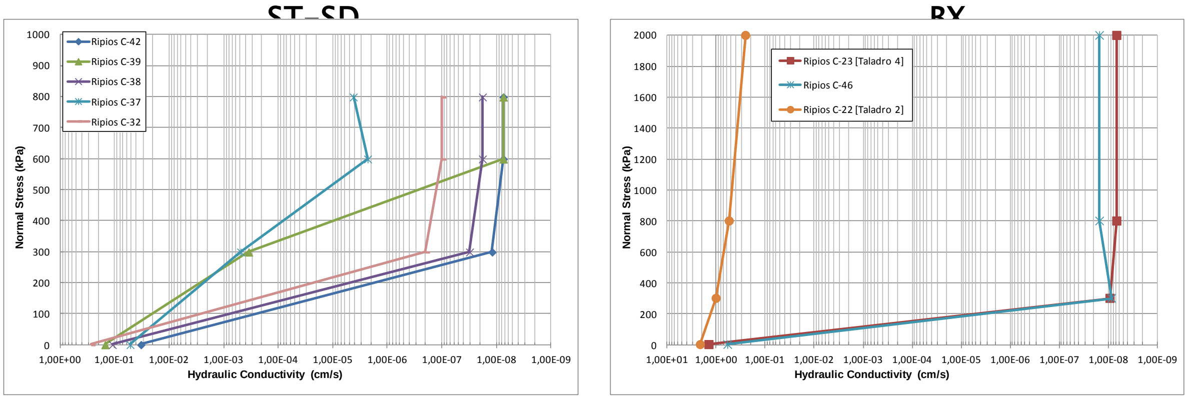


Figure 3: Hydraulic Conductivity for different materials from open pit boreholes

The average k values of the different types of ore are shown in Figure 4, the same that were used to the steady state and transient state flow analysis and for slope stability calculations.

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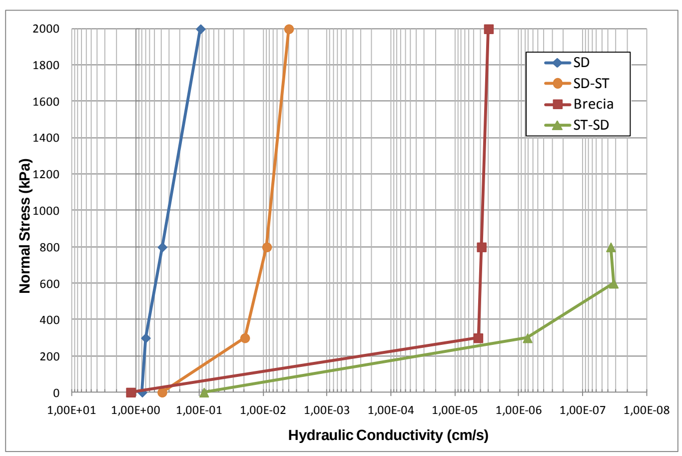

Figure 4: Average hydraulic conductivity for each material

For heap leaching operations of Shahuindo mine, the use of cement as a binder for agglomeration has been considered at first for the siltstone ore, in order to limit its fines content and enhance pregnant leached solution recovery, as a result of the metallurgical test the agglomeration technique has been established a gold recovery of 85%. Agglomerated ore provided by Shahuindo presented coarser particle size distribution (Fig. 5a), it was tested with unconfined conditions (Fig. 5a) and it was observed the agglomerated ore became finer as the confinement pressure was increased (Fig 5c).

a) b) c)

Figure 5: condition of sample ST-SD a) before first test b) after first test 0 kPa c) after second test 300 kPa

Consolidated-undrained triaxial compression

Every kind of ore was tested in order to obtain the internal friction angles in terms of effective and total stresses for stability analysis using the limit equilibrium method, Figure 6 depicts distribution results regarding friction angles obtained via triaxial tests according the ASTM4767 standard.

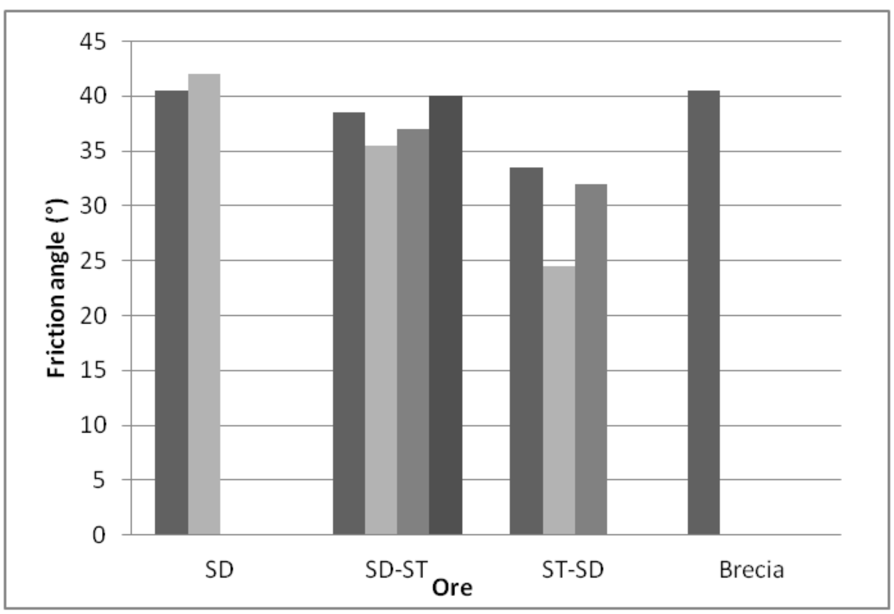

Figure 6: Internal friction angle distribution on each ore type

Liquefaction susceptibility analysis

Several criteria are available in practice to assess the liquefaction susceptibility of soils. For the present research, three of the most recent and commonly used liquefaction susceptibility criteria were used. The analyses were conducted considering Seed et al (2003), Bray and Sancio (2006) and Boulanger and Idriss (2006) recommendations.

It is well known that the key factors in susceptibility to liquefaction assessment are: plasticity index, fines content, water content to liquid limit ratio, among others. The ore from Shahuindo open pit are essentially low plasticity fine - grained soils, so it is quite probable that the agglomerated ore will undergo liquefaction and ROM ore would develop cyclic strength loss during an earthquake. These facts give rise to assess, via cyclic triaxial tests or more classically SPT or CPT, an undrained residual strength of the ore to the vertical stress ratio for post-earthquake static analyses. Figure 7 depicts the potentially liquefiable zones and details the mean Atterberg Limits of each ore analyzed. Table 3 summarizes the key factors for assessing susceptibility to liquefaction of Shahuindo ore for the different lithological types of ore from Shahuindo open pit.

Table 3: Key factors for susceptibility to liquefaction assessment of Shahuindo ore

Geotechnical or metallurgical test	USCS	L.L. (%)	Fines Content (%)	Plasticity Index (%)	Specific Gravity (mean)	w_c/L.L.	Liquefaction Susceptibility Potential
Intercalation sandstone–siltstone (SD–ST)	GC	28	13,2	12	2,66	1,35	No. Potential cyclic strength loss instead.
Intercalation siltstone–sandstone, (ST–SD)	GC	37	49,4	17	2,67	0,95	Yes.

Intrusive sand	SM	52	47,5	18	2,59		No. Potential cyclic strength loss instead.
Quaternary sand	SC	41	40,6	16	2,57		No. Potential cyclic strength loss instead.
Pad 1 intercalated ore	GC	30	24,1	12	2,64	1,07	Yes.

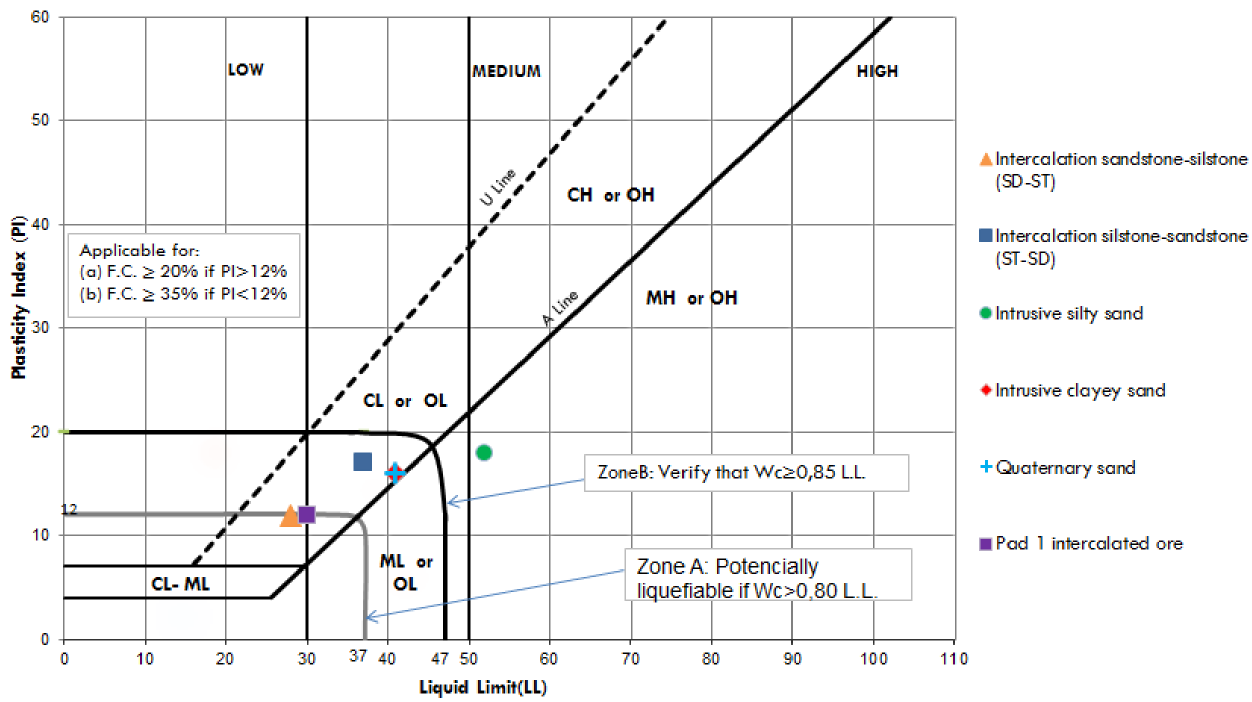

Figure 7: Assessment of "liquefiable" agglomerated and ROM ore

It is important to determine if the ore, which are potentially liquefiable, would feature whether a clay like behavior or a sand like behavior. The term "sand like" is used to define fine-grained soils where the soil skeleton is essentially supported by the coarse fraction of the soil, and can be evaluated using standard liquefaction procedures and the term "clay like" is used to define fine-grained soils where the soil skeleton is essentially supported by the fine fraction of the soil. In this case study, the ore from Shahuindo open pit is mainly composed by silty and clayey sands and gravels and is highly probable that they will undergo liquefaction during the pad operational works where a high level of pregnant leached solution is expected. Also, if liquefaction is not somehow triggered, cyclic strength loss will develop during an earthquake for the ore with fines content up to 35% following the recommendations of Boulanger and Idriss (2006) on the most appropriate testing procedures for cyclic softening evaluation of fine-grained soils. In the other hand, Bray and Sancio (2006) recommends cyclic laboratory testing for fine-grained soils besides estimation for the increased pore water pressure that would develop during an earthquake. Cyclic laboratory testing will be conducted for the ore with an important matrix of non-plastic silts (clay like behavior) and for ROM ore (sand like behavior), SPT's and CPTU's must be conducted during pad construction.

Hydraulic Conductivity and Shear Strength Discussion

- (Dhawan et al., 2012) reported that agglomeration limits the size variation and increases the permeability of an ore heap; however the effect of agglomeration can be lost for a higher normal stress, which is the case of finer ore as ST-SD ore type from Shahuindo open pit.
- Scattering of the data increases as the fines content become higher, as shown in figure 1 where material ST-SD has a wide range of fines content between 20 to 50 %, thus it is expected that hydraulic conductivity coefficients would present a wide range of values as shown in figure 4 (see green line) where average value of K varies from 0.5 cm/s for agglomerated ore in unconfined conditions to 2.0E-8 cm/s at 2000 kPa for normal stress conditions. For normal stresses higher than 200 kPa, k values were reduced considerably as a consequence of agglomeration properties loss due to the ore density increases and porosity reduction by means of normal stresses rised up, as shown in figure 3, where an after-test condition the sample (300 kPa normal stress contions) looks as a compacted material without agglomerating appearance.
- Coarse material which presents high point load indexes, such as SD ore does not show a considerable reduction of K values, as shown in figure 3, it is important to say that SD ore has not been crushed and agglomerated.
- It is possible to assume that the BX and ftp ore types features similar behavior as ST-SD ore, also these kinds of material represents only 9% of the whole heap.
- There is a trend of k values for ST-SD and BX ore types keeping their mean K values of 1,0E-8 cm/s at higher stress normal conditions.
- It is also observed that K values for SD-ST ore type were reduced in minor degree as the normal stress increased, as shown in Figure 3 where k values are within the range of 1.0 E-2 to 5.0 E-4 cm/s). (Dhawan et al., 2012) suggested a saturated hydraulic conductivity of the ore sample should be at least 1.0E-3 m/s under ultimate load will typically be reached using a typical pad configuration and permeability value (less than 1.0E-4 cm/s) will be reached using an interliner pad or on/off pad.

- SD ore type friction angles are greater than any kind of ore type, even higher than 40°. Likewise the ST-SD ore type friction angle is less than friction angles of SD-ST ore type. Figure 6 depicts friction angle values distribution for each ore type according their geological composition.

Conclusions

- The saturated hydraulic conductivity of the ore decreases, based on the ore geological nature and its fines content, and also as a function of confinement pressure within the heap.
- The saturated hydraulic conductivity of the ore decreases when normal stress increases; this effect is showed in ST-SD and BX ore with more intensity.
- For normal stresses higher than 200 kPa, saturated hydraulic conductivity of the ore is considerably reduced as soon as the agglomerating properties of the ore are missed.
- There is a big scattering for the saturated hydraulic conductivity coefficients of the ST-SD ore; additional data obtained via laboratory testing is required for better knowledge. It will be necessary to conduct a geotechnical laboratory program during the pad operational works.
- The internal friction angle of SD ore is greater than any kind of ore for normal stresses lesser to 600 kPa. For larger normal stresses, ranging from 600 kPa to 2000 kPa, there will be a testing program focused on the ST-SD material.
- The ore from Shahuindo open pit is potentially a liquefiable material, based upon its mean fines content, saturated media within the heap and plasticity index ranging between 12 to 18. Also, if liquefaction flow failure is not triggered, cyclic strength loss is expected for the ore with fines content greater than 30%.
- Cyclic laboratory testing must be conducted for “clay like” behavior ore (silty sands and clayey sands) and SPT’s or CPTU’s must be conducted for “sand like” behavior ore such as the ROM ore from Shahuindo open pit.
- Non-saturated flow analysis in steady and transient states considering low hydraulic conductivities of the ore must be conducted in order to estimate the pregnant leached solution levels within the heap. This estimated phreatic level must be used in performance-based post-earthquake static analyses.

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