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Study of the behavior of materials with fines content in heap leaching processes

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Abstract

The geotechnical design for a leach pad requires several different variables to be reviewed during the analysis of the physical stability of the structure. These variables include: 1) the material that comprises the natural foundation; 2) the potential fill material that will form the grading surface; 3) the interface shear strength between the soil liner and the geomembrane; 4) the ore that will be part of the heap; 5) the irrigation rate during the operation and 6) the placement/zoning of material within the heap leach pad.

Typically, the first three variables are controlled during the design and construction of the heap leach pad, while the last three variables are controlled by the mining company as part of their operation process. Simply, we can say that the combination of the last three variables can have a solution flow behavior along the following range: 1) free drainage, if the irrigation rate is applied at a lower enough rate compared to the ore hydraulic conductivity; and 2) pore pressure generation at areas where the irrigation rate is applied exceeding the ore hydraulic conductivity.

This paper presents an analysis of the last three variables taking into account the characteristics of two types of materials available at a mining project: 1) till material with significant fines content and medium to high plasticity; and 2) coarse ore, which corresponds to a material with a maximum size of 6” and low fines content. For the analysis, different mixtures were prepared using these materials in order to obtain the physical characteristics and hydraulic properties to develop the geotechnical analysis and material zoning/placement within the heap configuration.

Based on the zoning recommendations, the mine developed a large scale leach test in an existing pilot cell in order to evaluate the mixing process and solution flow behavior during the implementation of the leaching process. This consisted of: 1) controlling the flow and volume (input and output); 2) recording the

pore pressure readings; 3) electrical resistivity testing and 4) soils classification testing. The results of the pilot cell monitoring and testing are also presented in this document.

Introduction

The successful operation of a heap leach facility requires the participation of different parties, such as: 1) a Geotechnical Engineer, who is in charge of reviewing the physical stability of the heap, considering the ore behavior during the leaching process; 2) a Geological Engineer, who is in charge of maximizing sources of materials for the extraction of high grade metals; and 3) a Metallurgical Engineer, who is directly involved in the leaching process and review of alternatives to optimize the percentage of extraction of minerals. One of the keys aspects during the leaching process is to achieve a balance between the interests of each of the participating parties, which sometimes can be contradictory. Specifically, regarding the geotechnical design for a leach pad, the following variables should be reviewed during the analysis of the physical stability of the structure: 1) the material that comprises the natural foundation; 2) potential fill material to form the grading surface; 3) the interface shear strength between the soil liner and the geomembrane; 4) the ore that will be part of the heap; 5) the irrigation rate during the operation and 6) the placement/zoning of material within the heap leach pad.

This paper presents an example of analysis for the last three variables taking into account the characteristics of two types of materials available at a specific mining project and in coordination between the three parties. Figure 1 illustrates the steps followed in this paper.

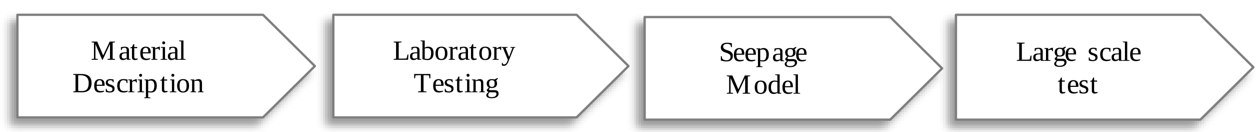


Figure 1: Steps followed in this paper

Initially, the materials that will be used to load the heap are described. The sources and types of materials were coordinated with the Geological Engineer and the Metallurgical Engineer from the mine. Then the results of laboratory testing performed for each representative sample are shown in order to characterize the geotechnical condition of the materials. After that, we present the seepage model prepared to determine the distribution of pore pressures within the body of the heap and recommend zoning alternatives for location of the materials within the heap leach pad.

Based on the zoning recommendations, the mine developed a large scale leach test in an existing pilot cell, in order to evaluate the mixing process and solution flow behavior during the leaching process. This included: 1) controlling the flow and volume (input and output); 2) recording the pore pressure readings;

3) electrical resistivity testing and 4) soils classification testing. Future additional testing will be developed by the mine and has not been included in this paper.

Material description

According to the Geology, Metallurgy and Geotechnical department of the mine, the project has two main types of materials, which will be used to load the heap leach pad. The characteristics of these materials are: 1) coarse ore (CO), which consists of gravel and cobble with 6" maximum size with low fines content and represents most of the available material; and 2) till material (TM), which has between 22 to 55% of fines content and its plasticity varies from medium to high.

The grain size bands of these materials are shown in Figure 2, in which we can observe the distribution of different sizes of particles expressed in percentages.

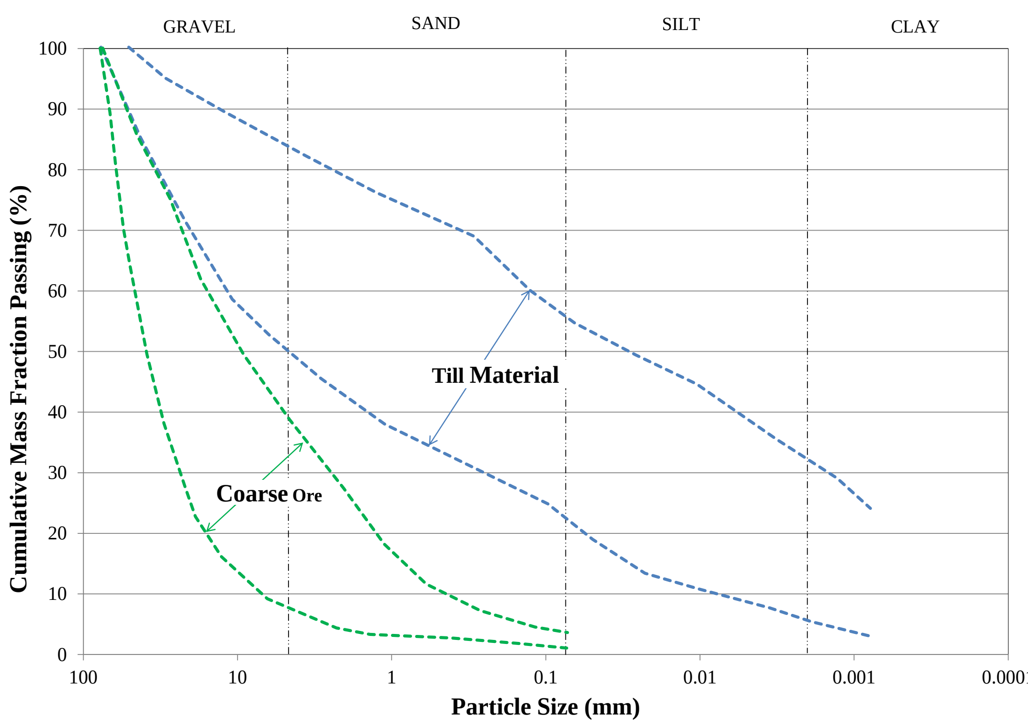


Figure 2: Grain size distribution curve of the coarse material and till material

The coarse ore (CO) consists of by 60 to 90% of gravel content and 1 to 6% of fines content, which indicate that this material will present appropriate conditions with the application of irrigation during the leaching process. This material could have a behavior as a free draining material.

Till material (TM) consist of 22 to 55% of fines content. The presence of a significant amount of fines content could reduce the overall void inside the heap leach; consequently, this material would present a low hydraulic conductivity (O'Kane Consultants Inc., 2000). During the leaching process, application of irrigation on the low hydraulic conductivity material will develop potentially saturated areas with generation of pore pressures. Therefore, this material might be a problem for physical stability of the heap leach as well as present low recovery of metals during the leaching process.

Hence, the development of a seepage model was required in order to evaluate zoning alternatives that will allow the overall fines content within the heap to be maximized without developing areas with increased pore pressures that could compromise the physical stability of heap and also allow an appropriate recovery of gold. The geotechnical characterization of the materials to be disposed within the heap was required in order to develop a seepage model. Thus, a series of laboratory testing were developed in samples of these materials, and is described in the next section.

Laboratory testing

Standard classification tests

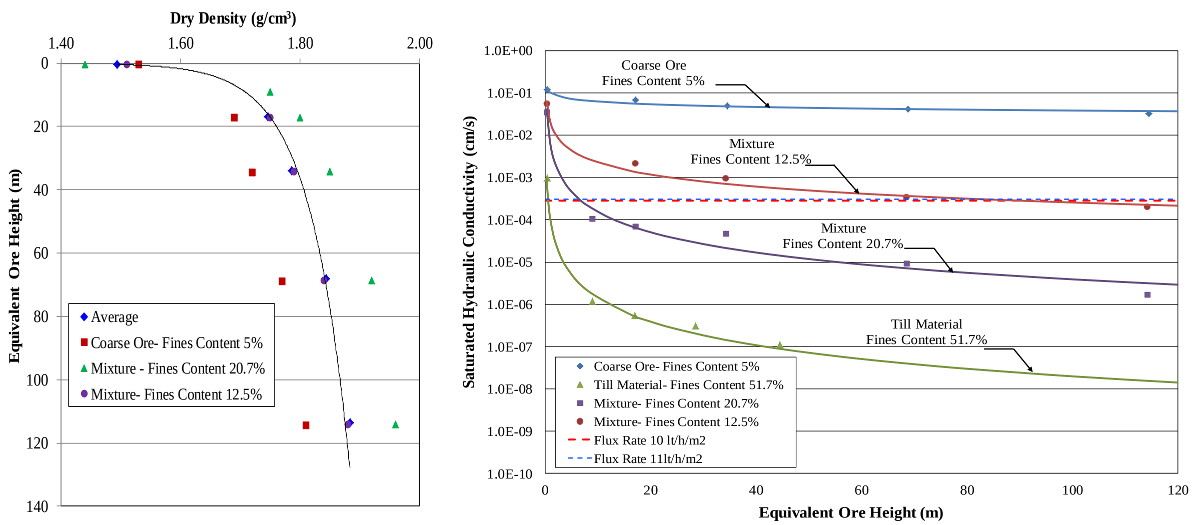
For physical characterization of coarse ore (CO) and till material (TM) standard classification tests were performed on samples provided by the mine. The results of these tests show that the coarse ore was classified as well-graded gravel with 5.3% of fines content and the till material classified as silt with 51.7% fines content.

Using these two types of materials, some mixtures were prepared in the laboratory using the following weight ratios: 6CO:1TM and 2CO:1TM. The standard classification tests show that the mixture 6CO:1TM classified as clayey gravel with 12.5% fines content and mixture 2CO:1TM classified as poorly graded gravel with clay with 20.7% fines content.

Permeability tests

Rigid wall and flexible wall permeability test were performed in order to determine the saturated hydraulic conductivity of the original materials and mixtures. When developing these tests, the application of different loads, which represent the conditions that these materials are subjected within the heap configuration, was considered. Additionally, during the development of these tests the variation of dry density for different loads of equivalent ore height was determined (see Figure 3a). Figure 3b shows the results of saturated hydraulic conductivity and its variation with different loads (expressed on the equivalent ore height) and different fines content.

As illustrated in Figure 3b, the saturated hydraulic conductivity of the coarse ore is higher than the irrigation rates of 10 and 11 L/h/m^2 (which will be applied in the leaching process) for all loads of equivalent ore height, indicating that this material will has a behavior of “free draining” material during the leaching process (O’Kane Consultants Inc., 2000). In the case of the mixture of materials with 12.5% of fines content, the behavior as “free draining” material can be observed until a load of equivalent ore height of 86.0 m; for higher loads could be generated pore pressure within this material during the leaching process (O 'Kane Consultants Inc., 2000). In the case of till material with 51.7% of fines content and mixture with 20.7% of fines content, the saturated hydraulic conductivity is lower than irrigation rates, even for low loads of equivalent ore height (about 0.5 to 6.5 m), this condition could generate that areas with generation of pore pressures can be created within the body of heap during the leaching process, which will affect physical stability of the heap and will decrease the recovery of high-grade solution. For that reason the use of the mixture that exceed 20% of fines content is discarded. Agreement with this preliminary analysis, based in the saturated hydraulic conductivity tests, should develop a seepage analysis in order to limit the fines content within the configuration of the leach pad.



(a) **(b)**

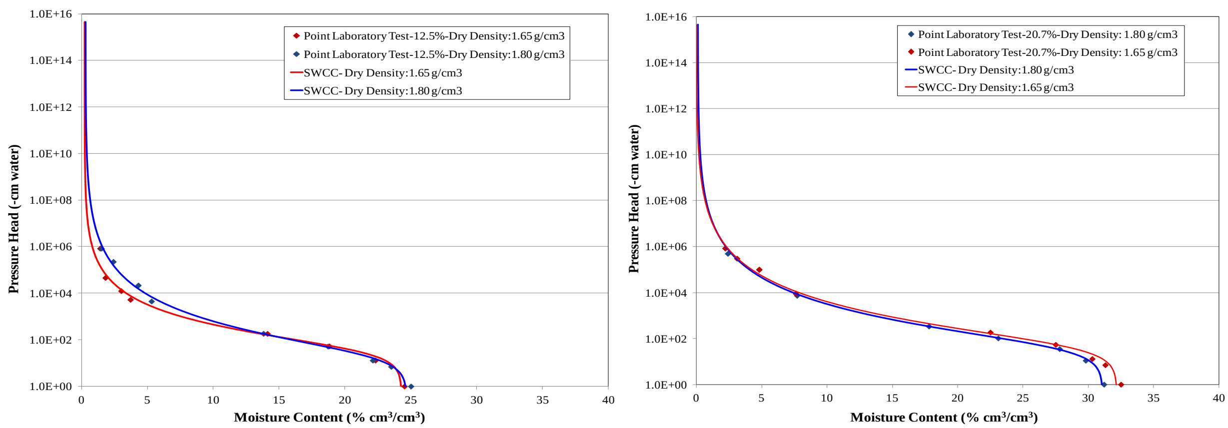
Figure 3: (a) Variation of dry density vs equivalent ore height
(b) Variation of saturated hydraulic conductivity vs equivalent ore height

Soil-water characteristic curve

Soil-water Characteristic Curve (SWCC) tests were carried out on materials to determine the hydraulic parameters under unsaturated conditions, according with the numerical model proposed by Van Genuchten (1980). The samples tested corresponded to the mixtures with fines content between 12.5% and 20.7%. These samples were remolded to dry densities of 1.65 and 1.80 g/cm^3 in order to represent different loads of ore height based on the variations shown in Figure 3a.

Figure 4 shows the soil-water characteristic curve (SWCC) obtained in the mixtures, and Table 1 summarizes the hydraulic parameters for unsaturated conditions in these materials.

The results of the laboratory testing described in this section were used to develop the seepage model, which is described in next section.



(a) **(b)**

Figure 4: Characteristic curve for remolded samples using dry densities of 1.65 y 1.80 g/cm³ (a) mixture of materials with 12.5% of fines content, (b) mixture of materials with 20.7% of fines content

Table 1: Hydraulic parameters under unsaturated conditions for the developed mixtures

Mixture proportion (Coarse ore: Till material)	Fines content (%)	Density (g/cm³)	α (1/cm)	n	Θ_r (% vol)	Θ_s (% vol)
6:1	12.5	1.65	0.0258	1.3668	0.23	24.29
6:1	12.5	1.80	0.0461	1.2753	0.29	24.71
2:1	20.7	1.65	0.0196	1.2668	0.00	32.20
2:1	20.7	1.80	0.0233	1.2661	0.10	31.09

Seepage model

The configuration of the heap used to develop the seepage analysis is shown in Figure 5. The overall slope was 2.5H: 1V with benches of 8.0 m high and 12.0 m wide. The maximum height of the heap is 120.0 m. In the heap, coarse ore was already loaded between elevations 4,380 and 4,396 m; from that elevation, coarse ore and till material were evaluated for placement.

In order to optimize the maximum fines content within the heap configuration, the materials considered for heap loading were designated as follows: 1) material with 5% fines content, which represents the coarse ore, was named as "type A"; 2) material with 14% fines content, which represents a mixture of materials, was named "type B"; and 3) material with 16% fines content, which represents a mixture of materials, was named "type C". Other mixtures were also evaluated as part of the alternative analysis, but they are not presented in this paper, as they were not selected for the final evaluation.

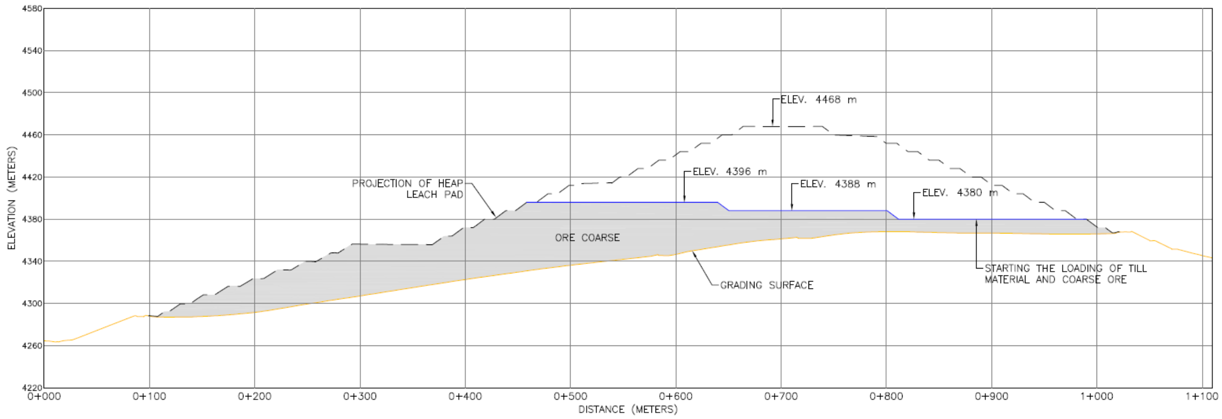


Figure 5: Heap leach configurations

Hydraulic parameters for unsaturated conditions

For the study of the hydraulic parameters in unsaturated conditions initially were reviewed results SWCC tests for the mixture of materials with 12.5% and 20.7% of fines content, which at the same time varies with the dry density. The parameters obtained in SWCC tests correspond to the parameters according to the mathematical model of Van Genuchten (1980), the variation of these parameters according to SWCC tests is described below:

- Parameter α: according to laboratory results it has been noted that the value of this parameter has a tendency to be higher when the fines content decreases, which agrees with that described by Lu and Likos (2004). When the material is denser, it has been seen that the value of this parameter increases slightly.
- Parameter n: according to laboratory results it has been noted that this parameter tends to be higher when the fines content of material decreases, which agrees with that described by Lu and Likos (2004). When the material is denser, the value of this parameter tends to be lower.
- Parameter θs: according to laboratory results it has been noted that the value for this parameter decrease as the fines content in the material decreases. When the material is denser this parameter has no significant variation.
- Parameter θr: according to laboratory results it has been noted that the value for this parameter tend to be near to zero in all cases (for different fines content and dry density values).

Additionally the trend of variation for the parameters mentioned above, for different fines content and different dry densities, was analyzed using this database of the computer program RETC (Van Genuchten et al., 1991). Also, other databases and some criteria for the estimation of soil water characteristic curves found in references such as Leij et al. (1996), Carsel and Parrish (1988) and Schaap et al. (2001), Shao and Horton (1998) and Yang and You (2013) were revised. Based on the literature review and the results of

SWCC tests for mixture of materials with 12.5% and 20.7% of fines content and different dry densities, were obtained the parameters according to model of Van Genuchten (1980) for the materials type A, type B and type C using an interpolation process.

Subsequently, the hydraulic conductivity for unsaturated conditions was built based on the Van Genuchten parameters and the saturated hydraulic conductivity, while considering that these parameters will vary with the load applied of ore. Figure 6 shows an example of the variation of the hydraulic conductivity curves.

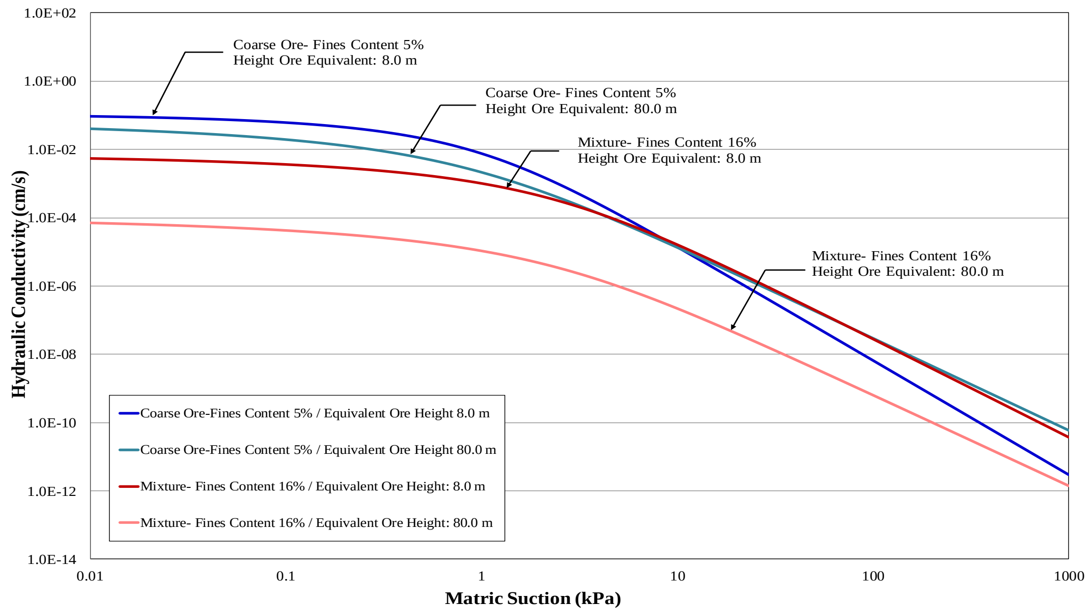


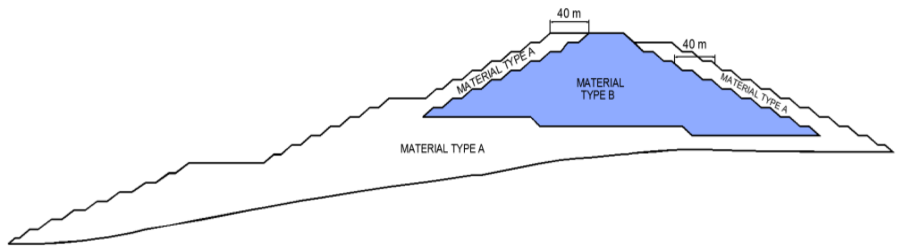
Figure 6: Variation of hydraulic conductivity curve for materials with different fines content and different loads of ore

The flow conditions applied on the heap were distributed according to the mine operation plan, which considered the following distribution: 1) an irrigation rate of 11 L/h/m^2 applied on the upper surface of the heap, 2) an irrigation rate of 10 L/h/m^2 applied on the slopes and benches for the last four layers, 3) a flow rate of 400 mm/year, which represents the average annual rainfall, applied on the faces of slopes and benches.

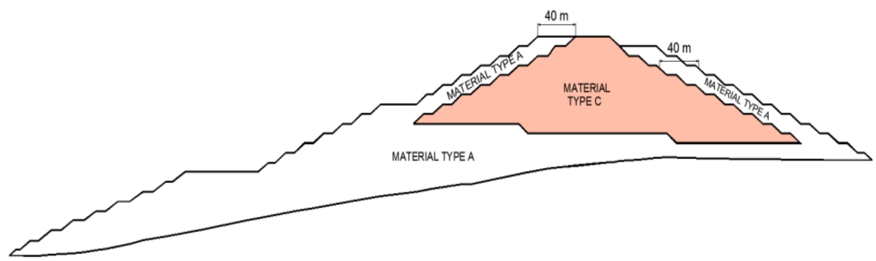
Zoning alternatives analyzed

Three zoning alternatives were defined for the materials within the heap configuration, which were analyzed using the seepage model that was described previously. Such zoning alternatives are presented in Figure 7 and their characteristics are summarized in Table 2.

As illustrated in Figure 7, all the alternatives considered a minimum distance of 40m from the mixture of materials (types B and C), intending to place coarse ore (type A) in order to avoid potential saturated areas that could be generated during the leaching process, and compromise the stability of the heap.



(a)



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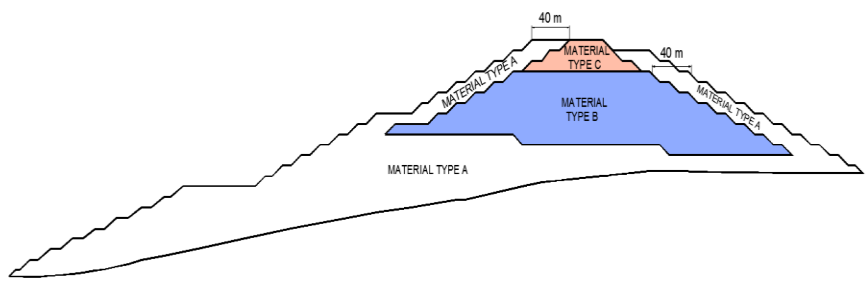

(c)

Figure 7: Zoning alternatives for the materials within heap configuration

Table 2: Description of zoning alternatives proposed

Alternative	Zoning of materials within heap configuration
Alternative 1	Extremes: material type A in a width of 40 m from the edges of the slopes Internal: material type B
Alternative 2	Extremes: material type A in a width of 40 m from the edges of the slopes Internal: material type C
Alternative 3	Extremes: material type A in a width of 40 m from the edges of the slopes Internal: material type B in the last 3 lifts and material type C underneath

Results and interpretation

Seepage analyses performed in the zoning alternatives, show that pore pressure areas were developed as shown in Figure 8. The results obtained in each zoning alternative are described below.

- Alternative 1, formation of saturated areas are produced from a depth of four lifts, which generate pore pressures that reach values of 60 kPa as maximum; consequently, a reduction of approximately 10% in the safety factor of the physical stability of the heap is produced.
- Alternative 2, formation of saturated areas are produced from a depth of one lift, which generate pore pressures that reach values of 180 kPa as maximum; consequently, a reduction of approximately 25% in the safety factor of the physical stability of the heap is produced.
- Alternative 3, formations of saturated areas are produced from a depth of four lifts, which generate pore pressures that reach values of 60 kPa as maximum; consequently, a reduction of approximately 10% in the safety factor of the physical stability of the heap is produced.

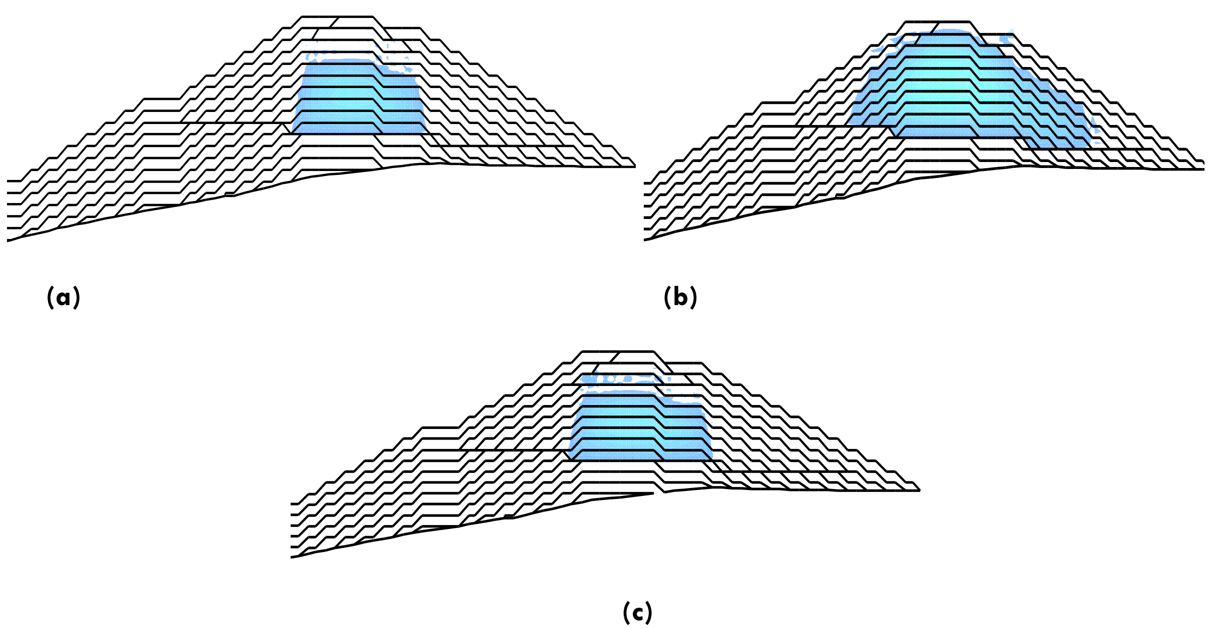

Figure 8: Saturated areas generated (a) Alternative 1, with pore pressure of 60 kPa as maximum; (b) Alternative 2, with pore pressure of 180 kPa as maximum; (c) Alternative 3, with pore pressure of 60 kPa as maximum.

As shown in Figure 8, there are some lifts located in type B and C areas that do not present areas with pore pressure generation, because in lifts near the surface the materials have hydraulic conductivities that allow adequate drainage with the application of the selected irrigation rate; however, with depth, a decrease in hydraulic conductivity is produced (tendency which is presented in Figure 3), with the generation of pore pressures within the body of the heap configuration.

For areas with coarse ore (type A), as expected, the behavior generated with the application of the selected irrigation rate was as a free draining material due to high hydraulic conductivity that this material presents.

The results of the seepage analysis indicate that zoning alternatives 1 and 3 appear to be viable for the loading of the coarse ore and till material within the heap configuration. Furthermore, based on the results of the permeability testing it was required to limit the maximum fines content for the till material to be used in the mixture to avoid the formation of "blocks with low permeability" that might lead to the generation of areas where non-adequate contact exists between the solution and the till material (which could produce a reduction in the recovery of gold). Because of the importance of a good mixing process and in order to test the effectiveness of a mixing process using the existing crushing system rather than the direct discharge with trucks, the mine decided to conduct a large scale test in an existing pilot cell. In the following section we present the results obtained as part of this work.

Large-scale test

Initially, it was planned to perform a test in the pilot cell using only the till material (in order to evaluate the maximization of fines contents); however, based on the results indicated in the previous section, at this stage, the mine determined that for the first test, the mixing process would be evaluated using the existing crushing system and aiming to obtain a material whose fines content did not exceed 14%, in accordance with the characteristics of alternative 1 reviewed in the previous section. Also, in order to review the geotechnical behavior of the stockpiled material in the pilot cell, inspection records and control tests during the development of the leaching test were also incorporated.

Adaptation of the pilot cell

The existing pilot cell was adapted for testing while considering the following aspects: 1) a lining system, consisting of a smooth HDPE geomembrane 2.0 mm, 2) a collection system, which would consist of pipes HDPE perforated of 100 mm arranged in a "herringbone", and 3) a protection system, comprising 300 mm overliner material whose granulometric characteristics met the appropriate functions of a filter material and drainage layer. The material staked in the pilot cell was 8.0 m height.

Under the considerations described above, modifications to the pilot cell were made (see Figure 9a). The material to be used for the test was then prepared carrying out mixtures between the coarse ore and till material using an average proportion by weight of 2.7 to 1.0 respectively in order to not exceed the fines content of 14%. The mixing process began with the entry of materials in the proportions indicated in a primary crusher of rotary type (see Figure 9b); then passing through the apron feeder, conveyor belts and ore bin. At this point, the mixed material was transported to the pilot cell trough giant fleet.

During the loading of the material, control laboratory testing of sieve analysis were performed, determining that the average fines content in this material varied between 10% and 15%. Furthermore, the till material used for the testing had a fine content up to 30%. In Figure 10, the final configuration of the pilot cell is shown.

(a) **(b)**

Figure 9: (a) Overliner material in the base of the pilot cell, (b) Mixing zone of the materials

Figure 10: Final configuration of pilot cell

Monitoring during leaching test and inspection records

After completion of the material loading, the mine proceeded to start the irrigation phase of the test over 65 days. During this time, daily inspection records were completed, recording also the input flow and output flow, which were measured by flowmeters installed in the pilot cell. The variation of the input and output flow is presented in Figure 11.

The leaching test began with a wetting stage of the stockpiled material, for which an irrigation rate of 5 L/h/m^2 was applied on the flat area (platform) of the pilot cell. After three days of starting irrigation, the first reading of outflow was recorded. The average rate of irrigation was then increased to 11 L/h/m^2 and monitoring of the input and output flows was modified to a frequency interval of 2 h. Five days after the irrigation rate was increased, similar values of input and output flow were recorded, achieving stabilization in the flow through the stockpiled material; this can be interpreted as the time when the saturation of the flow transit zone turned almost homogeneous.

After seven days of flow stabilization in the stockpiled material, the application of irrigation in the slopes zone of the pilot cell was incorporated, reaching a new equilibrium in the values of input and output flow after seven days, which was maintained until the end of the leaching test. During the period of application of the irrigation on the stockpiled material in the pilot cell, there were some days when there were variations in the flows recorded, which were produced due to some blockage in irrigation pipes which were caused by weather effects and the normal operation process.

As part of the monitoring during the leaching tests, readings of piezometric level (pore pressure), were recorded. Recorded readings indicated that pore pressures did not occur during the irrigation period. This can be interpreted as the solution infiltrated into the body of the heap (due the application rate irrigation) drained normally through it, which caused a partial wetting of the material, but did not generate a load of pore pressure within the heap body.

Additionally, during the development of the leaching test, the mine metallurgy department performed tests in order to estimate the percentage gold recovery obtained in the leaching test, obtaining 69.9%, a value that was higher than their originally expected value for the mixture.

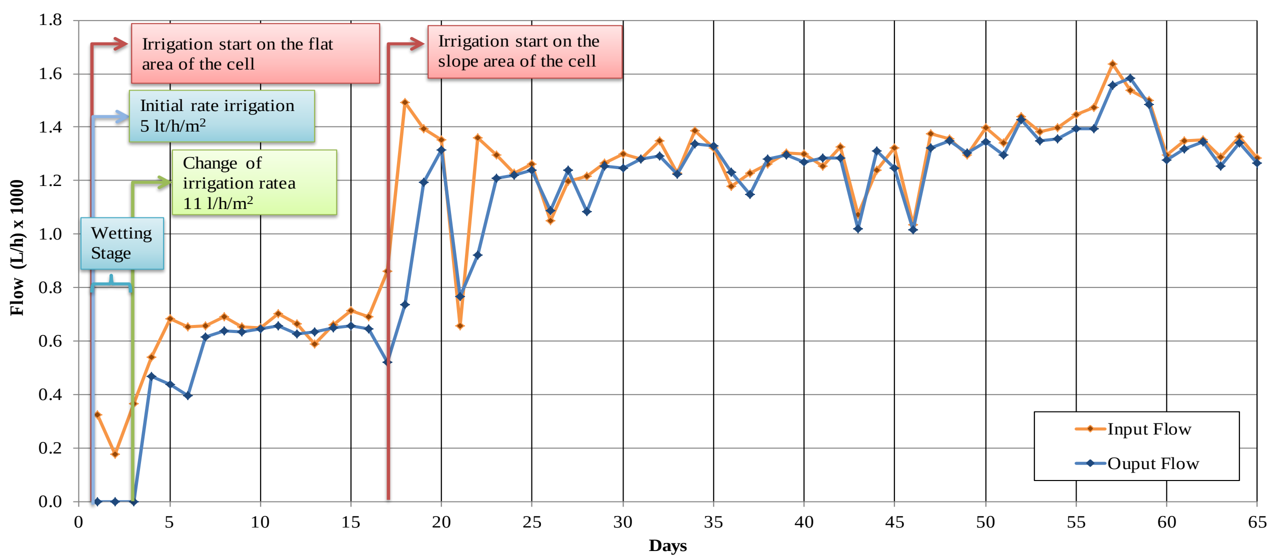

Figure 11: Variation of input flow and output flow during the development of leach testing

Monitoring post-leaching test

After the end of the leaching test, some excavations were conducted in the stockpiled material of the pilot cell, in order to review the wet profile within the heap. Additionally, samples of this material were extracted, to perform laboratory testing such as particle size analysis and moisture content.

Profiles exposed for excavations, showed a homogeneous distribution of moisture within the body of the stockpiled material, having obtained moisture contents in these materials around 10%. Furthermore, saturation areas or areas with preferential flows paths within the body of the stockpile were not detected (see Figure 12).

The test results for particle size analysis show that the average fines content of the stockpiled material within the pilot cell was between 10% and 15% (more closely to 10%). This indicates that the process used for mixing and loading the material resulted in a decrease of the overall fines content with regards to the original fines content for the till material before the mixing process.

It is noteworthy that prior to the development of the excavations, electrical resistivity testing was performed on the stockpiled material, simulating additional irrigation. These profiles are illustrated in Figure 13. The results indicate that within the body of the stack there were 3 distinctive zones with variation in the electrical resistivity: 1) low resistivity zone (55-132 Ω.m) at the top of the cell, 2) intermediate to high resistivity zone (141-591 Ω.m) in the middle part of the cell and 3) high resistivity zone (≥ 801 Ω.m). These zones were generated mainly by: 1) surface compaction due to the transit of trucks and tractors that were used in the loading of material, 2) the normal segregation process which occurred during the discharge of material at the pilot cell, resulting in the content of gravels being greater in the lower part and less at the top, 3) the effects of the geomembrane material installed at the base of the pilot cell, and 4) moisture generated during the infiltration of the solution into the material of the cell.

Figure 12: Excavations performed after completion of the leaching test, a homogeneous moisture distribution along the profile of excavations were observed

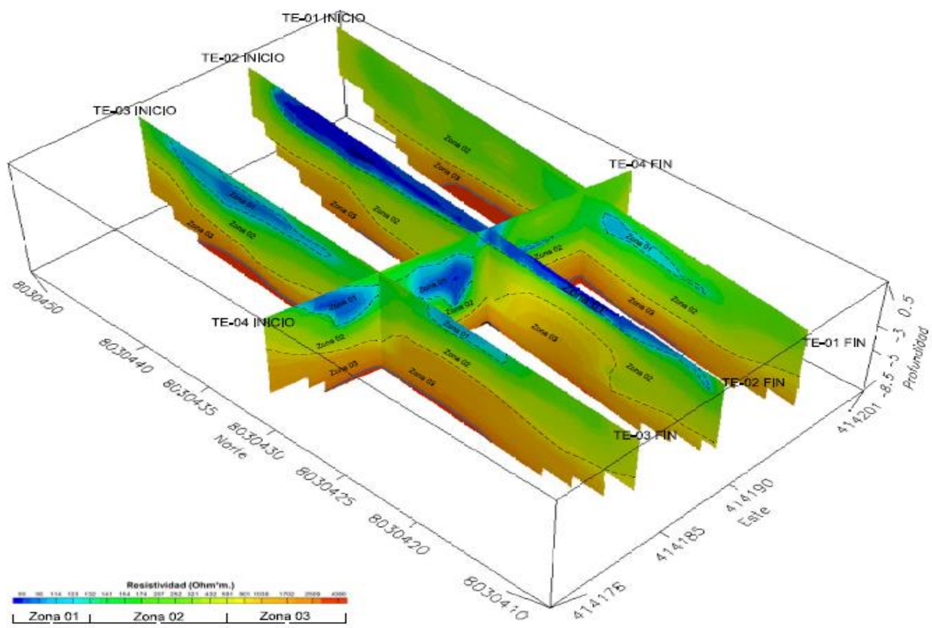

Figure 13: Electrical resistivity distribution within the stockpiled material in the pilot cell

According to control records made after the end of the leaching test, it was verified that this material had a behavior as free draining material (for 8 m load). Additionally, in the body of the stockpiled material, after the cut (see Figure 12), an homogeneous moisture distribution was observed, confirming that the low resistivity value obtained on the test was produced mainly due to the compaction of the materials near the surface and not by the effect of increased moisture content or generation of saturated areas.

Conclusions

There is an influence on the geotechnical behavior of materials produced during the solution application, due to the fines content (or more precisely, related to the granulometric composition of the material. According to saturated hydraulic conductivity or permeability tests, materials with more than 20% of fines content could cause pore pressure generation problem, because for low loads the saturated hydraulic conductivity is less than irrigation rate; for that reason this type of material (20% of fines content) was not considered between the zoning alternatives.

Additionally, in this paper the seepage analysis for the proposed alternatives illustrated that the presence of materials with significant fines content produced saturated areas with the generation of pore pressure within of the heap configuration, due to the low hydraulic conductivity of these materials.

The zoning of materials allowed adequate control of seepage considering the global fines content of materials that will be included in the heap. However, the method to be used for the construction of the heap should be duly reviewed and planned in order to verify that this method or procedure avoids placing materials that could include "blocks or concentration of low permeability material" due to a poor mixture, as this effect could generate an inadequate interaction between the percolated solution and the material, resulting in a reduction in the metal percentage recovery. For the example analyzed in this work, this effect was verified with a large scale test, where the mine used a mixing process which allowed homogenization of the material that was placed in the pilot cell and reduction of global fines content. This process allowed the stockpiled material in the pilot cell to have behavior as free draining material and also allowed the use of the existing till material.

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