

Hydraulic performance of permanent heap leach with intermediate drainage system

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Abstract

When the hydraulic properties of the ore that constitute a permanent heap leach do not allow proper percolation of solutions through its full height, intermediate drainage systems between different ore layers must be considered.

These drainage systems commonly comprise an impervious liner deployed below a layer of drainage and collection pipes. Under this configuration, each layer is hydraulically isolated, thereby preventing the solution to flow through ore layers that have gone through a process of densification and permeability reduction caused by overload of higher levels. One downside of this system is that generates a series of weak planes in the contact interface between the impervious liner and the ore, generating several potential block failures. An alternative configuration has been considered in some operations that may decrease this adverse effect and reduces the costs associated to the impervious liner, consisting on the compaction of the surface of certain layers, and leachate collection pipes on each compacted layer. The reduction of permeability on the subgrade of each layer aims to isolate the solution outflow of a set of lifts, similar to the condition with geosynthetic inter-lift liner. However, depending on the densification degree and the geotechnical properties of the compacted ore, part of the applied solution may not be captured by the drain pipes due to infiltration into the lower layers of the heap leach, resulting in different saturation degrees in each of them, with negative consequences in terms of recovery and slopes stability.

Through numerical models, hydraulic behavior is analyzed on heap leach systems composed by intermediate drainage systems without impermeable liner. The resulting phreatic level of each layer and the vertical infiltration flow is evaluated in relation to different initial conditions regarding to irrigation rates and saturated ore properties for different geometrical configurations. Regarding the results of this analysis, the authors discuss about the implications of the maximum irrigation rate and a maximum number of layers for a configuration comprised of an intermediate compacted layer, complemented with a collection piping system.

Introduction

Inter-lift liners have been used on copper heap leach pads mainly in South America starting in the mid 1990's (Breitenbach, 2005) with the primary objectives of reducing acid consumption (Smith, 1996) as well as increasing recovery kinetics.

The inter-lift liner system can also mitigate the flow blockage effect of permeability loss which is caused by self-weight induced densification and by the fine particles transport, forcing the solutions to flow only through the ore between liners.

In order to reduce operational costs, inter-lift liners are generally thinner than base liners, since its breakage should not cause major risks in terms of environmental or operational issues, unlike the case of the base liner. The materials that are commonly used as inter-lift liner are LLDPE and PVC (Smith, 1996). Figure 1 shows a schematic of a heap leach system with inter-lift liner.

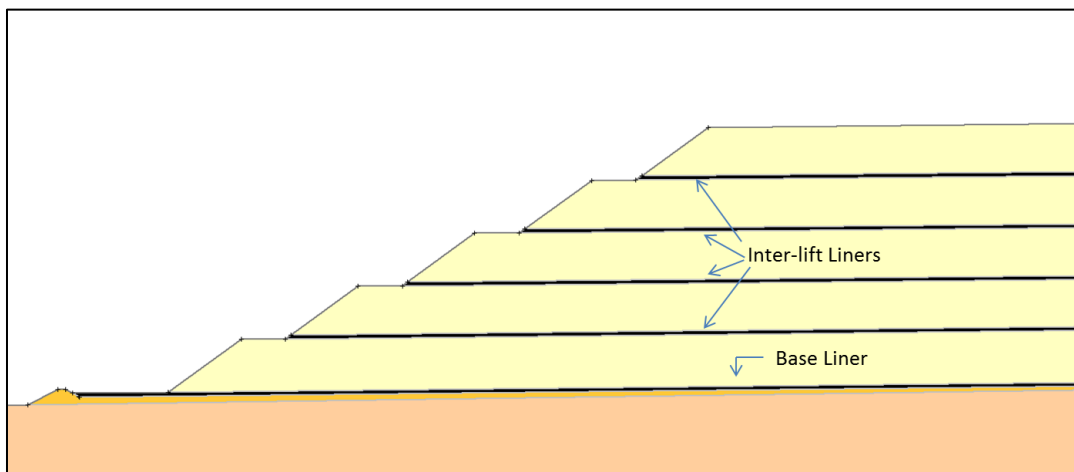


Figure 1: Schematic of a Heap leach with inter-lift liner system

With the aim to reduce the operational costs associated to the inter-lift liner, there are experiences in Chile where inter-lift liners have been partially eliminated, maintaining intermediate drainage systems. These systems are comprised by drainage pipes installed on each layer over the compacted prepared surface of the previous layer (leached ore). As an indirect positive effect, this system reduces the instability condition generated by the numerous intermediate liners, since they produce a series of weak interfaces favorable to slope block failure, which is caused by the low strength properties of the interface between the overliner or underliner material and the liner. In fact, a heap using inter-lift liners will be less stable than a conventional heap, if all other factors are equal (Smith, 1996).

The drainage system without inter-lift liner but with a compacted leached ore layer instead, aims to achieve a similar barrier effect that the geosynthetic liner system would provide, through decreasing permeability at the base due to the material compaction. However, this procedure does not provide

absolute impermeability, which means that a certain percentage of the irrigation flow will still be infiltrated to the inferior layers. This solution flow can develop water table build-up in the lower layers, which must be checked and controlled in order to achieve adequate metallurgical behavior and a proper stability condition.

The infiltrated flow on each layer and the resulting water table depends on the design conditions of each layer and its corresponding drainage system, irrigation rate and the geotechnical properties of the ore and the intermediate compacted leached-ore layer. Through numerical models, the hydraulic behavior of a heap leach is analyzed, considering drainage systems without inter-liner but with a compacted leached ore layer on each level.

Hydraulic performance analysis

Methodology

The analysis methodology was focused on determining the water-table height and the amount of flow that is infiltrated from each layer into deeper layers, depending on the solution application rate and the permeability coefficients of the ore and the compacted layer. From this data, and the relationship between the variables, an assessment of the hydraulic behavior of a heap leach conformed by intermediate drainage systems with compacted layers instead of a geosynthetic liner is carried out.

In order to determine the behavior of the flows under these conditions, two-dimensional numerical models were developed, based on the finite element method. The models were developed considering a saturated flow condition in order to represent the irrigating operation stage, assuming that on this stage the ore in the system will reach a condition close to saturation on the surface level and on the lower levels. The initial stage of impregnation that is characterized by a non-saturated flow condition has not been incorporated on the analysis, since the results shown on this paper reach the critical period during the irrigation stage, after the impregnation stage.

Typically, the range of leach cycle durations for copper-oxide heap-leach process may go from 100 to 200 days. On the other hand, results of cribs tests and experience on full-scale operations, indicate that the impregnation stage (which is not considered on the analyzed models), typically range from 10 to 15 days, which is a small period of time compared to the total time considered on the analysis.

A representative 150-days leach irrigation cycle has been considered for the analysis, and during this period, the solution is applied only on the active top surface of each heap model. This consideration implies that each of the lower layers have already completed their own 150-days leach cycle. Therefore, all models have been developed through a transitory analysis limited to the time frame of the upper-layer leach cycle.

Different models were established, modifying on each one, the number of layers, the geotechnical properties of the materials involved, and the irrigation rate. On each model, the resulting water table height and the infiltration flow rate for each layer are determined after a 150-days period of solution application.

Analysis model

The general model used for the flow analysis corresponds to a permanent heap section composed by several layers, each one of them with an intermediate drainage system configured by a compacted material base and three drain pipes, which represent the behavior of the total extension of the heap leach. At the base of the first level an impervious liner was provided. The model used is shown schematically on Figure 2.

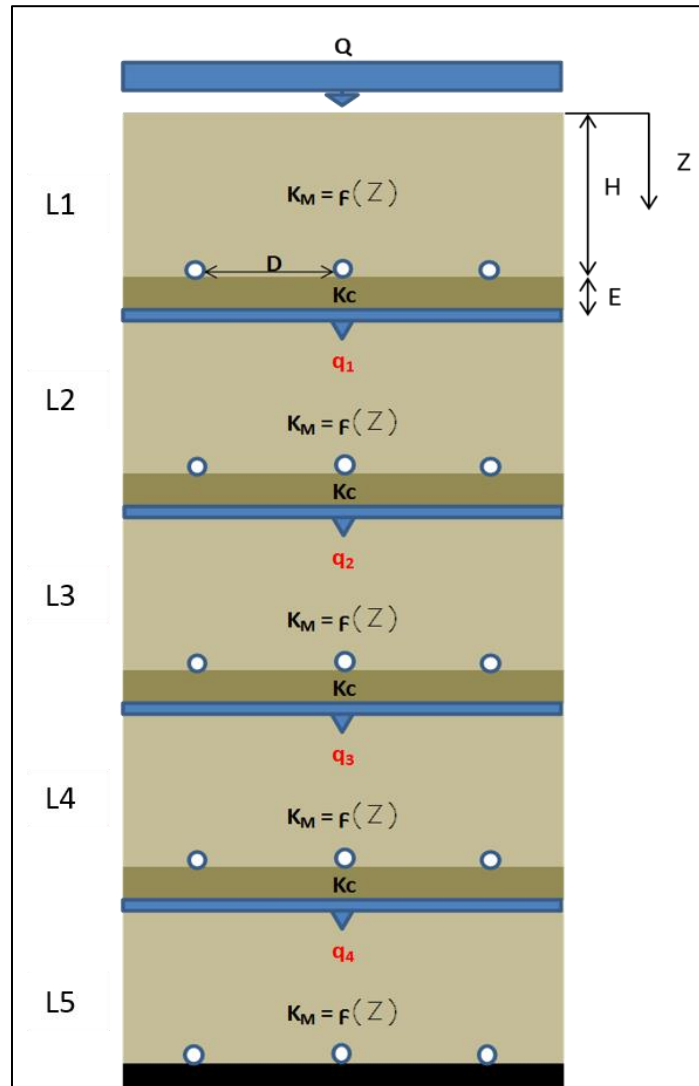


Figure 2: Analysis model scheme

The different analysis models have been defined upon the combination of a few parameters set as variables. A set of parameters were defined as constant throughout all models. These parameters correspond to geometrical conditions and geotechnical properties characteristic of the heap leach type define for this study. Table 1 indicates the adopted values for the parameters set as constant, and Table 2 indicates the variable parameters.

Table 1: Constant parameters

Parameter	Unit	Symbol	Values	Observation
Distance between drainage pipes	m	D	4	Typical distance varies between 3 and 6 m
Compacted layer thickness	m	E	0,3	Typical value for compaction effectiveness in depth
Layer height	m	H	8	Typical lift heights vary between 4 and 8 m

Table 2: Variable parameters

Parameter	Unit	Symbol	Values
Ore permeability	cm/s	K_{M1}	$0,0748e^{-0,050 \times Z}$
		K_{M2}	$0,1581e^{-0,144 \times Z}$
		K_{M3}	$0,0018e^{-0,072 \times Z}$
Compacted layer permeability	cm/s	K_{C1}	$5,00 \times 10^{-05}$
		K_{C2}	$5,00 \times 10^{-06}$
		K_{C3}	$5,00 \times 10^{-07}$
Irrigation Rate	L/h/m ²	Q_1	8
		Q_2	12
		Q_3	15

Saturated ore permeability is expressed in terms of the depth (Z), to represent the density increase (and decreased permeability) that is produced by the ore overload itself. The functions were defined on the basis of records of several consolidation tests performed on representative copper ore samples with permeability measures for different loading conditions. Three functions were defined representing three different ore materials (M1, M2 and M3) with different hydro-mechanical behaviors, in order to assess this condition. For modelling purposes, the permeability as function of depth was discretized per layer, assuming a uniform layer permeability equivalent to the maximum depth of each level. Figure 3 shows the function of the saturated permeability coefficient in relation to the depth for the three materials

considered. The red markers represent the permeability value assigned to each layer, according to the maximum depth of each, for the three considered functions.

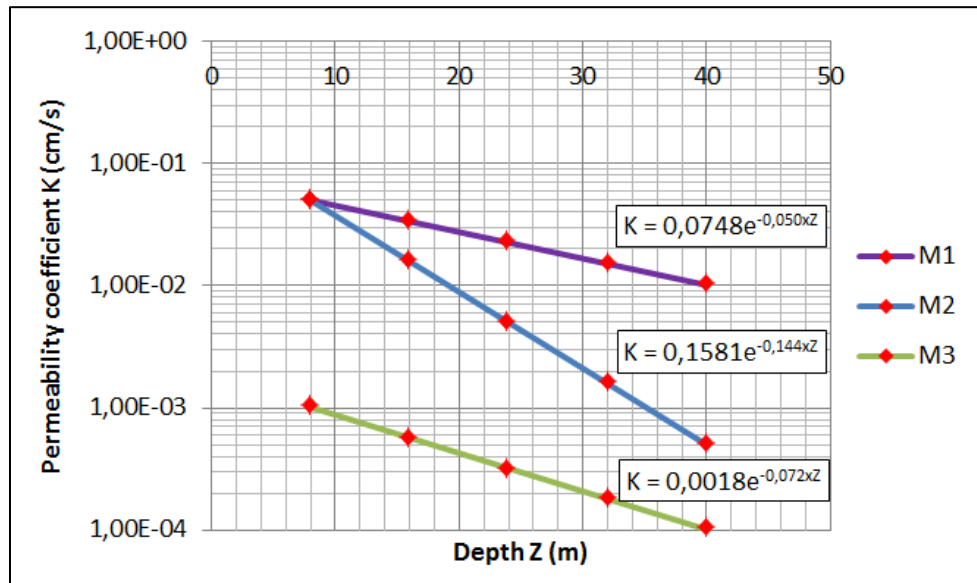


Figure 3: Saturated permeability coefficient v/s depth

As boundary condition, a unit vertical flow has been considered in the upper limit of the model corresponding to the irrigation rate as defined in Table 2.

The lower limit of the model was defined under the zero flux condition representing the impervious liner laid on the base. Drain pipes placed on the base liner and each compacted levels were modeled as a review boundary condition, which only allows flow out of the model when a point on the vicinity reaches a pressure equal to or greater than zero.

Furthermore, the side edges of the model are assumed to have null boundary condition, i.e., there is no lateral influence on the result. This condition is based on the hypothesis that horizontal dimensions of the heap leach are considerably larger than the vertical dimensions, and the section modeled is representative of a center portion and the lateral boundaries are located at the middle of two drain pipes, generating a symmetry axis at each boundary respect to the flow behavior, as shown on Figure 4.

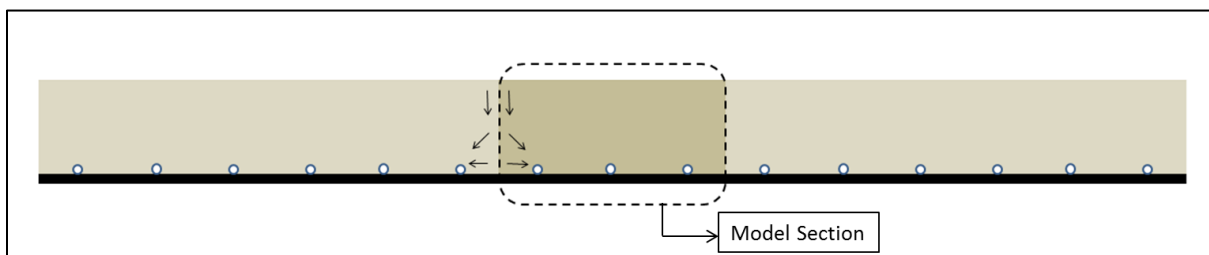


Figure 4: Lateral boundary condition scheme

Results

The results of each model were analyzed in terms of the resulting water table height and the infiltrated flow on each layer. The phreatic level is measured through a virtual piezometer located at the center of two contiguous drain pipes, which according to the hydraulic theoretical behavior, corresponds to the point where the maximum phreatic level height should be developed for each layer, as shown on Figure 5. Based on these results, and in relation to the parameters set as variables, the hydraulic behavior of the heap leach has been evaluated. Some of the results that demonstrate the hydraulic behavior are exposed below.

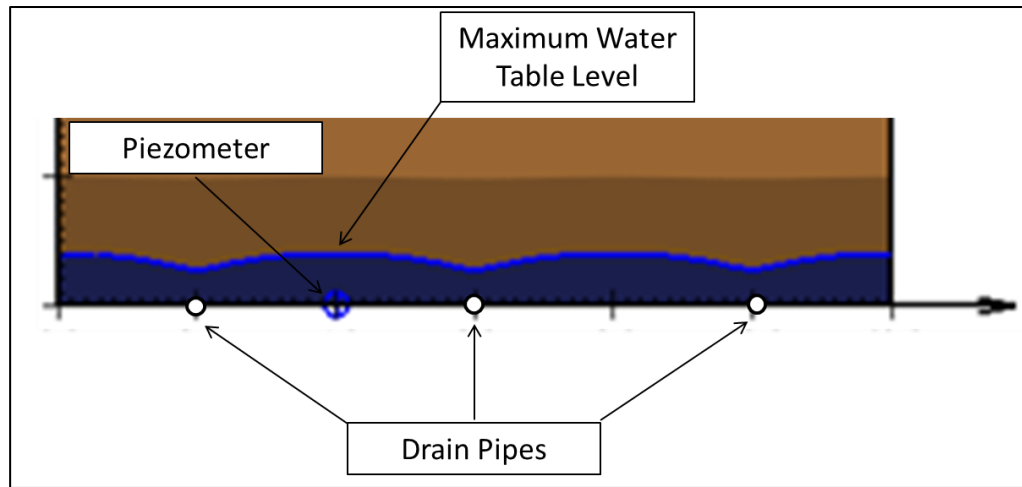


Figure 5: Maximum phreatic level measurement

A first evaluation on the water table height generated at the base of the heap leach (over the impermeable liner), stands out the importance of the number of stacked layers without impervious liner and the permeability value reached by the inter-lift compacted layer. Figure 6 shows the resulting water table height on the first lift, for a heap leach configured from one to five layers, for the same material (M2) and at the same irrigation rate ($Q_1 = 8 \text{ L/h/m}^2$). For each case, three different permeability values assigned to the compacted leached ore layer are represented. Figure 7 shows the model schematic representation of the results expressed on Figure 6.

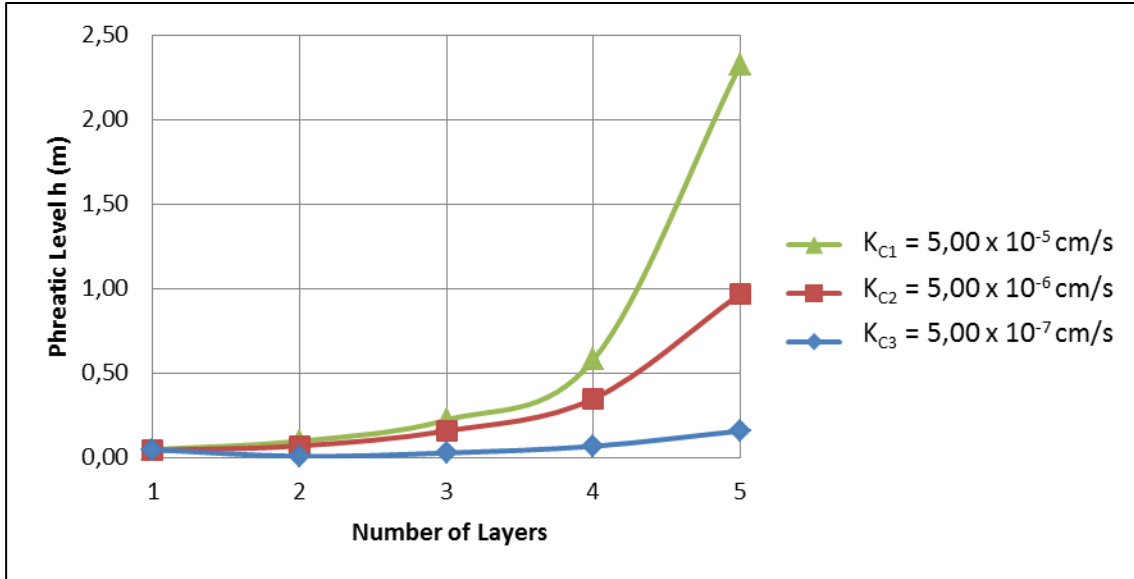


Figure 6: water table height over the base liner v/s number of layers, for different compacted layer permeability values, for M2 material and Q_1 irrigation rate

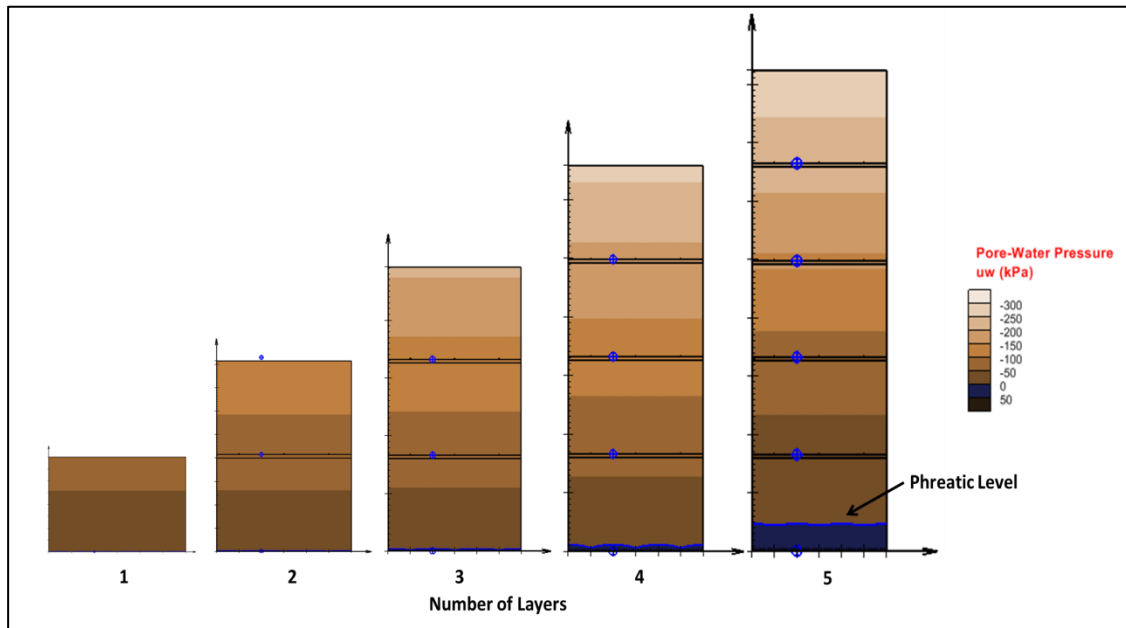


Figure 7: Pore-Water pressure related to number of layers, for $K_{C1} = 5,00 \times 10^{-5}$ cm/s

Can be observed that the higher the number of layers are stacked without intermediate liners, the higher the water table builds up in the first lift (or at the base) of the heap. Moreover, the water table will be higher as inter-lift compacted layers with higher permeability are considered. Conversely, as the permeability value of this compacted layer decreases, the behavior approaches to that of an impermeable geomembrane, and therefore the resulting water table at the base is closer to zero. From the graph it can

also be observed that the permeability of the compacted layer is more relevant, as to the resulting water table height, at higher number of layers stacked without impervious liner.

The foregoing results are all for the same ore type respect to the permeability value assigned to each layer. When analyzing the same plots, i.e., the water table height versus the number of stacked layer, but this time varying the permeability coefficient of ore and keeping the compacted layer permeability fixed, the curves displayed on the graph of Figure 8 are obtained. This graphic considers a $5,00 \times 10^{-6}$ cm/s permeability for the compacted layer (K_{C2}) and an irrigation rate of 8 L/h/m^2 (Q_1)

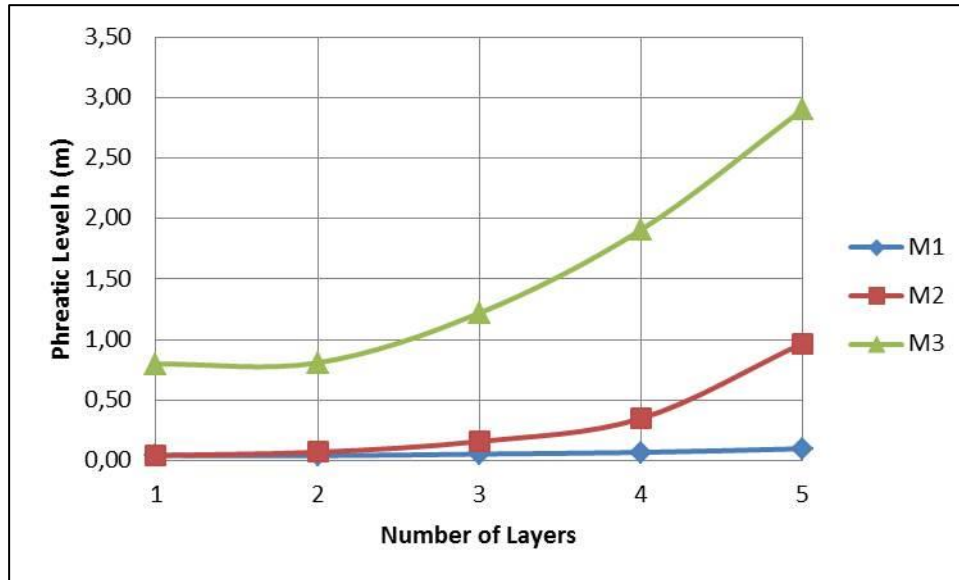


Figure 8: Water table height over the base liner v/s layers number, for different ore permeability's, for C2 compacted layer and Q1 irrigation rate

The chart above shows that the lower the permeability of the ore is, the higher the water table will build up. This will be accentuated by the increasing number of stacked layers. In the case of M1 ore sample, corresponding to the highest permeability material, water level near to zero is observed even for the maximum number of levels considered. This represents a mineral ore with the hydraulic capacity to be leached in a conventional permanent heap leach with no need for inter-lift liner, which is consistent with sandy gravel ores. Moreover, it is noted that M1 and M2 ore samples have similar behavior at low number of stacked layers, however differ when the number of layers increase. This is related to the hydraulic characteristics of the materials in relation to the permeability characteristics (permeability v/s overload function). For M1 and M2, the permeability value is similar to low overload levels, however in the case of M2, permeability decreases further with increasing load, resulting in increased height of the water table.

Another important aspect of analysis is the evaluation of infiltration that occurs at each level to lower levels, which determines the percentage of solution that is captured by the collection system of each

level. This analysis also allows evaluating the efficiency of the inter-lift compacted layer in terms of the imperviousness degree and hydraulic independence of each level.

Figure 9 shows the percentage of solution that is captured at each layer in the case of a heap leach consisting of 5 8-meter lifts, with collection system and inter-lift compacted layer, for the three different ore materials M1, M2 and M3.

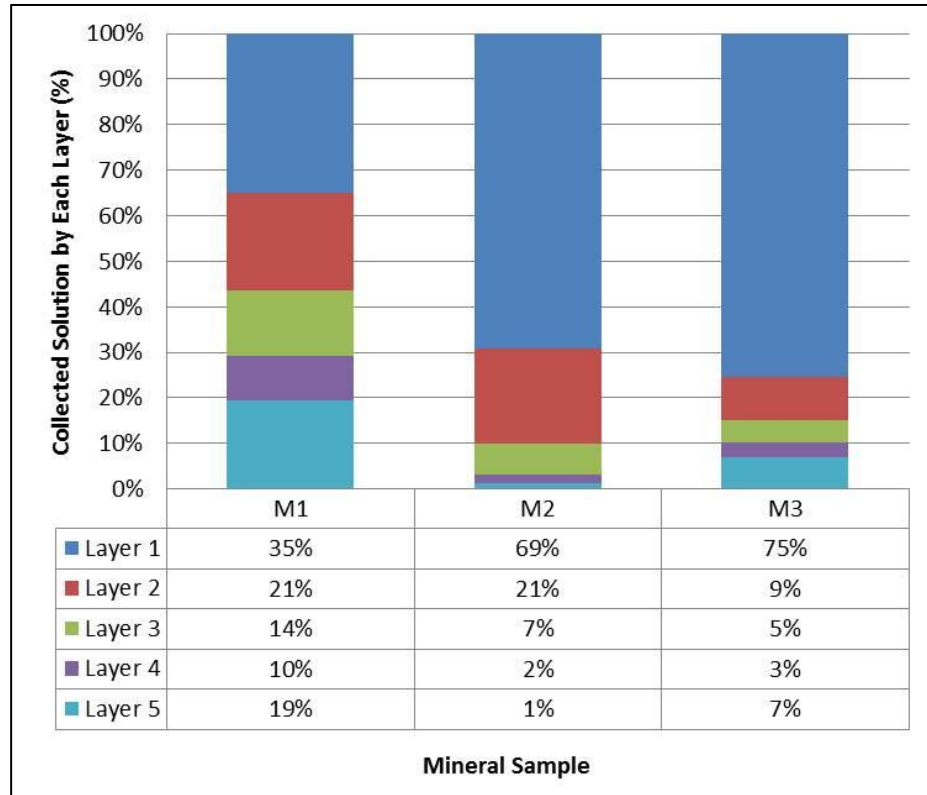


Figure 9: Percentage of solution captured by each level, for the different ore types.

This graph demonstrates that in all three cases there is some degree of percolation of solution to lower levels, due to the difficulty of reaching an adequate impermeability by compacting the superficial leached ore. The higher the permeability of the ore, the higher the percentage of infiltration that occurs at each level is. This is evident when comparing the corresponding graphs to the M1 and M3 samples, since the permeability characteristics functions have similar slopes, with lower permeability value in the case of M3. When evaluating the infiltration for M2, a different trend is observed respect to M1 and M3 showing the influence of the permeability versus depth function on the behavior in terms of percolation to lower levels.

Furthermore, can be noted that while decreasing the permeability of the ore, is possible that certain water table levels on the surface of each ore lift could be generated. This also depends on the permeability

of the inter-lift compacted layer and its potential to allow infiltration of solution to lower levels. Figure 10 shows the result of a 5-layer model, in which a certain water level is generated within each of the lifts.

Figure 10 shows the most critical case in terms of ore permeability among all of those studied, corresponding to M3 ore sample and an inter-lift compacted layer permeability equal to $5,00 \times 10^{-6}$ cm/s. This case shows that the water table build-up may reach up to 0.5 m over the compacted surface of intermediate lifts.

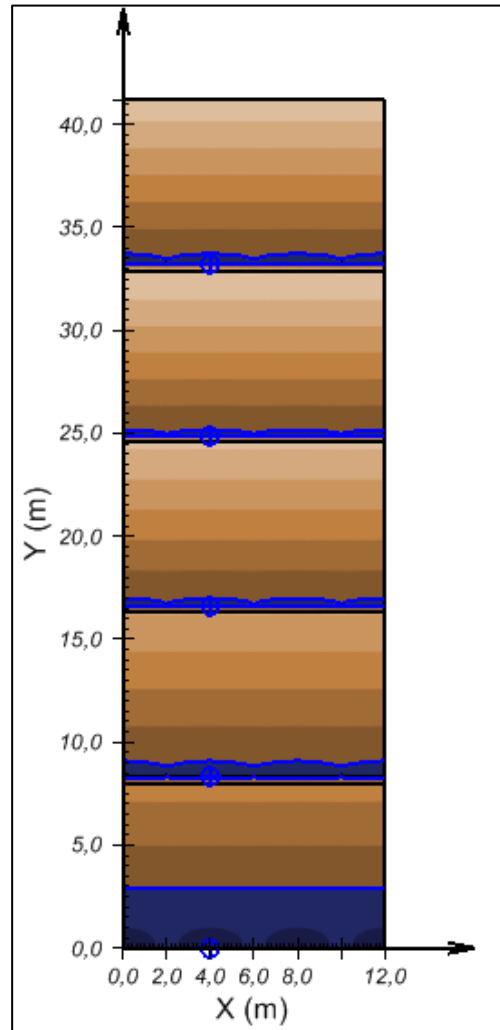


Figure 10: Result of 5-layer model, with water table formation in all layers.

Regarding the irrigation, in general terms, an increase on the application rate causes an increase on the resulting water table at each level, however, it will depend both on the hydraulic characteristics of the ore and the compacted layer and the number of layers stacked. For this reason, the critical irrigation rate will be defined by the maximum water table considered on the project-specific geotechnical design criteria, and subject to the hydraulic conditions of the materials and the geometric conditions of the heap leach.

Conclusion

The use of inter-liners is a common practice in permanent heaps when the ore does not provide an adequate hydraulic capacity to infiltrate solutions throughout its full height. The superficial compaction of the older leached ore layers, plus a proper drainage system at the base of each level is feasible to implement as an alternative to replace the liner installation, and therefore obtain potential savings on operational costs. However, the hydraulic behavior of this system is complex and depends largely on the hydraulic properties of the ore at a loose as-stacked condition, after further overloads of upper lifts and also at a highly compacted condition with operating moisture conditions after leaching and draining.

A clear trend of the hydraulic behavior of the heap, in terms of the resulting water-table height and the infiltration degree, has been determined regarding the hydraulic properties of the materials and configuration of the number of layers. The results show that the number of layers stacked without geomembrane is an important aspect to take into account on the design; higher water-table levels are expected at the base of the heap when increasing the number of stacked layers.

The permeability of inter-lift compacted layers are also an important factor, given that the higher their permeability is, the greater the flow of solution infiltrated into the lower levels can be expected, and therefore, higher water table build-up may be generated at the base. Conversely, the higher level of imperviousness is able to achieve through compaction, the higher hydraulic independence of each layer is obtained. In this sense, it becomes very important the level of compaction achieved during the surface preparation for each new lift stacking, and the permeability value associated to this compaction. Proctor compaction tests and permeability tests prepared at the specified compaction percentage are very important to determine the hydraulic properties of this layer. For mines that count with actual data from pilot heaps or commercial operations, field compaction tests would provide valuable data such as level of compaction, number of roller passes, actual operating moisture conditions after leaching, draining and repose stages, etc.

Moreover, the ore permeability is critical on the expected water-table height. As expected, the lower ore permeability is, the greater the resulting water table; however, a multilayer system as set forth on this work, a more profound knowledge of the hydraulic behavior of the ore in relation to overloading or density becomes critical. For small amount of stacked layers (one or two layers), two materials may have the same behavior, nevertheless, if more layers are considered with the proposed inter-lift system, the water table will vary on each layer, depending on the permeability losses related to higher densification.

Taking into account the influence of the different variables on the result, the recommended maximum irrigation rate should be defined upon these critical variables and on the criteria defined for the maximum expected water table, which must be considered in the slope stability analyses of the heap leach.

The relationship between permeability and number of layers, also defines the percentage of solution captured by each layer. This should be analyzed from the point of view of the process solution recovery plan, because, as mentioned before, the intermediate compacted layer does not generate absolute impermeability and therefore, part of the flow passes through to lower layers. This is higher while more permeable is the compacted leached ore layer and ore.

It is important to mention that the phreatic level, the infiltration rate, and other hydraulic outputs resulting from this analysis can be controlled by modifying design elements that have been considered constant on the present study, such as the drain-pipes spacing, ore layer height, and compacted layer thickness among others.

Since this drainage system means greater difficulty on determining the hydraulic behavior of the heap leach system, the application of numerical models is recommended in order to analyze the possible designs. It is recommended that these analyses are developed using parameters obtained from laboratory tests, such as saturated permeability, consolidation, Proctor, plus general characterization test, and complemented by hydrodynamic column test (HCT), in order to adjust the numerical models and refine the geotechnical characterization of materials on the unsaturated condition. Also, it is equally important, verification of the results provided by the numerical models, taking data from operating heaps with these drainage systems through monitoring instruments or in situ investigation.

Finally, the decision to switch from a classic geosynthetic inter-lift liner to an intermediate drainage systems with compacted material layer, has to take into consideration an economic analysis, in terms of Capex and Opex, including critical aspects such as acid consumption, modification of the expected copper recovery, the solution inventory within the heap, geomembrane costs relative to compaction costs, etc.

Acknowledgements

The authors would like to thank Andrés Olea (Ausenco Chile) for his support in terms of review and valuable technical data related to the study, and to Murray Fredlund, for facilitating the software Soilvision®, module SVFlux®, which was utilized to develop the numerical analyses for the different models hereby developed.

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