Flow analysis and dynamic slope stability in a copper ore heap leach

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ABSTRACT
This paper presents a numerical analysis for the unsaturated flow throughout a copper ore heap leach as well as static and dynamic slope stability analyses since the structure is planned to be built in a highly seismic region in the South of Peru. The heap will be constructed with non-treated copper ore (run of mine) on an impermeable pad specially devised to avoid the possibility of ground contamination by the flow of the acid solution. The numerical results obtained in the stability analyses indicate that the heap leach presents satisfactory safety factors even when considering earthquakes of magnitude 7.5 with maximum acceleration of 0.30g. It has been also observed that the phreatic line formed by the lixiviation solution does not reach the layers devised to protect the drainage pipes of the lixiviation system.

RÉSUMÉ

Cet article présente une analyse numérique de l'écoulement non saturé d'une solution acide à travers une pile de mineraux de cuivre soumise a un procédé de lixiviation. Cette structure sera construite dans un région de forte activité sismique au sud du Perou et, en consequence, evaluations de la stabilité des pentes, sous chargements statique et dynamique, doivet être effectués. La pile de mineraux de cuivre non traités sera située sur une base impermeable spécialement conçue pour éviter la possibilité de contamination du sol de fondation par la solution acide. Les résultats numériques obtenus dans les analyses de stabilité indiquent que la pile présente des facteurs de sécurité satisfaisants même lorsque on considére séismes de magnitude 7.5 avec l'accélération maximale de 0.30g. Il a été aussi remarqué que la ligne phreatic formée par la solution de lixiviation n'atteint pas les couches conçues pour protéger le système de drainage du procédé de lixiviation.

1 INTRODUCTION

Currently precious metal heap leaching technology has largely developed into an efficient method of treating copper ore. It has proven to be both an efficient way to extract precious metals from small, shallow deposits, as well as an attractive way to treat large, low grade and disseminated deposits. Heap leaching has several advantages compared to other conventional system to extraction ores. In general, these advantages include simplicity, lower capital and operating costs, shorter start-up times.

Irrespective of the specifics of any particular project a heap leach operation consists of the following components, which will be just mentioned in this paper: mine/ore source, ore preparation, heap and pad, solution application/collection system, pregnant solution containment, metal recovery circuit and barren solution containment. A schematic illustration of a heap leach system is given on Figure 1.

Numerous variations exist on the heap construction methods, involving reusable pad, expanding pad, and valley leach. In addition, various combinations of certain aspects of each method may be valid for a project, as may be the use of more than one constructive method for a project specific evaluation.

The engineer may face great challenges when carrying out geotechnical analysis of ore heap leach installations, given the considerable heights that these structures can reach nowadays and because some of them are situated in geographical locations subject to high seismic activities, such as the copper ore heap leach studied in this paper which will be constructed in the South of Peru (Figure 2). This non-treated structure (run of mine ore) will spread over an area of 2000m x 4000m and will reach an estimated height of 127.5m.

The numerical analyses, based on the finite element method, consider the infiltration process of the acid solution throughout the entire structure. Slope stability studies are carried out in order to evaluate both the static and pseudo-static safety factors and additional dynamic analyses are also undertaken to predict the occurrence of excessive displacements that could eventually compromise the serviceability of the slopes of the heap leach.

2 INFILTRATION ANALYSIS

2.1 Geotechnical Parameters

The non-treated copper ore can be classified as sandy gravel to gravelly sand. The fines content (percent by weight finer than 0.074 mm) often ranges between 15 to 35% and it may be characterized as low plasticity silt. The heap leach will be analyzed as a structure formed by six successive layers of 21m thick and two additional 0.75m layers for drain protection (Figure 3). The slopes have an inclination of 37°measured with respect to the horizontal and the base of the heap an inclination of 4.5% (Figure 8).

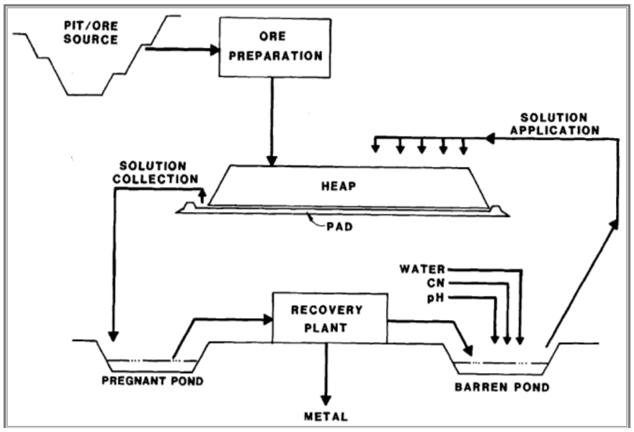


Figure 1 - Scheme of a heap leach process (Van Zyl, Hutchison & Kiel, 1988).

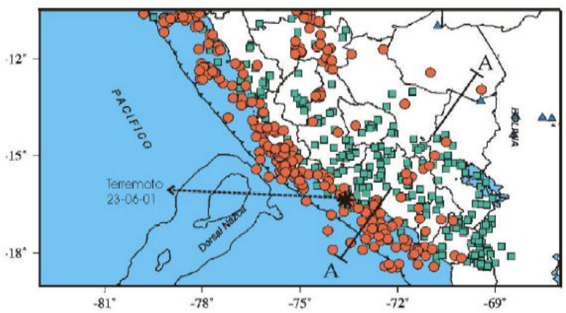


Figure 2 - Seismic activity in the South of Peru showing earthquakes with magnitude M > 5 (Instituto Geofísico del Perú).

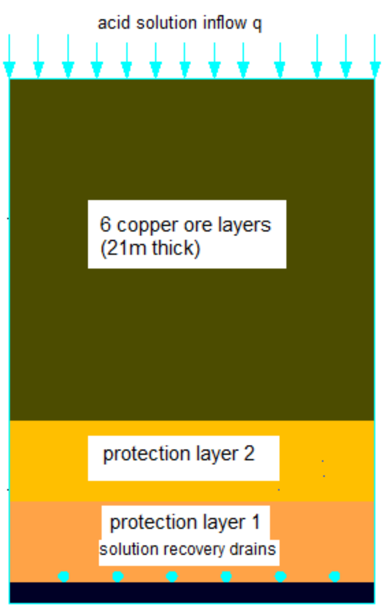


Figure 3 - Copper ore and protection layers for the acid solution recovery.

An important point to be considered herein refers to the phreatic level. Good leaching systems require that the phreatic level should be kept below the drainage protection layers, so that the ore material do not be saturated in order to maintain an appropriate system performance.

Laboratory tests were carried out to determine the saturated coefficient of permeability using 12" samples in a rigid wall permeameter. The samples were subject to stress levels corresponding to the construction of each one of the 6 layers of 21m thick. The unit weights were also measured as shown in Table 1.

Suction characteristic curves were also obtained in laboratory tests through the pressure plate technique. As a result, those curves showed subparallel forms but with different starting points given the several values of porosity and volumetric water content exhibited at each construction stage (Figure 4). The corresponding curves for the protection layers were also determined (not shown).

According to the Van Genuchten (1980) model the suction characteristic curves can be described by the following general equation

$$\theta_\psi = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left(\frac{\psi}{a}\right)^n\right]^m} \qquad [1]$$

where a, n and m are parameters to be adjusted from the experimental results through a least squares method , θ_ψ represents the volumetric water content at matric suction ψ, θ_r the residual volumetric water content and θ_s the saturated volumetric water content

Thus, the hydraulic conductivity function can be expressed as

$$k_\psi = k_s \frac{\left[1 - (a\psi)^{n-1}\left[1 + (a\psi)^n\right]^{-m}\right]^2}{\left[1 + (a\psi)^n\right]^{\frac{m}{2}}} \qquad [2]$$

where k_ψ is the unsaturated coefficient of permeability k_ψ and k_s the saturated coefficient of permeability. Just two of the parameters must be determined since m = 1 – 1/n with the restriction n > 1.

The parameters for the Van Genuchten model (1980) are listed in Table 2.

Additionally, infiltration laboratory tests were executed to determine the minimum acid solution flow for a leaching cycle of 265 days of continuous irrigation, resulting q = 8 $\ell/h/m^2$ as the flow rate value.

2.2 Assessment of Drain Spacing

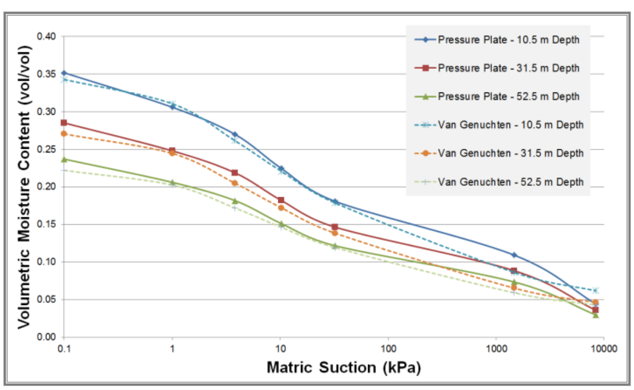
In order to approximately determine the position of the phreatic line, since the occurrence of high saturation levels can potentially decrease the efficiency of the leaching system as well as affect the stability of the pile slopes, a first analysis was carried out using the Dupuit theory for unconfined flow considering a 1D vertical inflow rate with $h_1 = h_2 = 0$ (Figure 5). Three different drain spacing were considered (L = 3m, 6m and 9m) admitting the cases of normal average value (L = 3m) and the assumption when one (L = 6m) or two (L = 9m) drains fail due to the great stresses from the 127m high pile. Also, two saturated coefficients of permeability were used, namely k = 2.53 x 10^{-2} cm/s, corresponding to the measured value for the protection layers, and k = 2.53 x 10^{-3} cm/s, under the hypothesis of a permeability decrease due to fines migration from crashing of upper copper ore material.

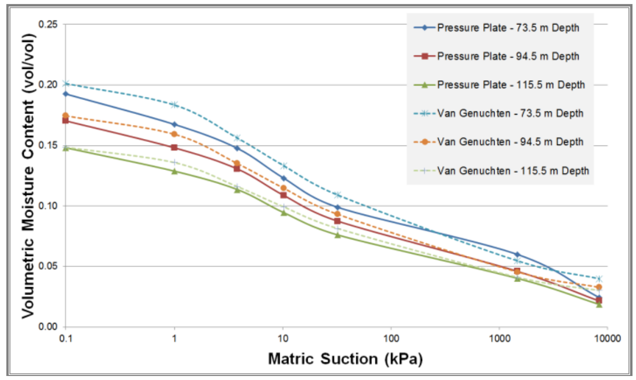
$$h^2 = \frac{q}{4k} L^2 \qquad [3]$$

The position of the phreatic line was also investigated through 2D unsaturated steady flow analyses using the computational finite element program PlaxFlow (Figure 6). Table 3 show the predicted values of the maximum height h_{max} which, except for the situation L = 9m and k = 2.53×10^{-3} cm/s, are not quite different from those computed by the simpler Dupuit solution (equation 3) considering saturated flow only.

Table 1 - Ore properties at the several construction layers (Mendoza, 2005).

Depth	Dry Unit Weight (kN/m^3)	Porosity	Specific Gravity Gs	Saturated Permeability k (cm/s)
Layer nº 1	15.66	0.3462	2.70	3.47E-01
Layer nº 2	17.44	0.2731	2.70	1.78E-01
Layer nº 3	18.68	0.2241	2.70	9.14E-02
Layer nº 4	19.13	0.2031	2.70	5.32E-02
Layer nº 5	19.93	0.1761	2.70	3.53E-02
Layer nº 6	20.55	0.1499	2.70	2.20E-02
Protection Layer nº 2	19.21	0.2095	2.72	2.53E-02
Protection Layer nº 1	17.88	0.2645	2.72	2.53E-02





Figures 4a) and 4b) –Suction characteristic curves for the ore copper layers.

Table 2 - Parameters of the Van Genuchten model (Mendoza, 2005).

Layer	θs (%)	θr (%)	a (kPa^{-1})	n	m
Layer nº 1	34.62	0	1.030	1.195	0.160
Layer nº 2	27.31	0	1.043	1.194	0.165
Layer nº 3	22.41	0	1.072	1.188	0.155
Layer nº 4	20.31	0	1.066	1.178	0.154
Layer nº 5	17.61	0	1.118	1.185	0.159
Layer nº 6	14.99	0	1.091	1.180	0.152
Protection Layer nº 2	20.95	0	2.507	1.189	0.160
Protection Layer nº 1	26.45	0	1.688	1.200	0.167

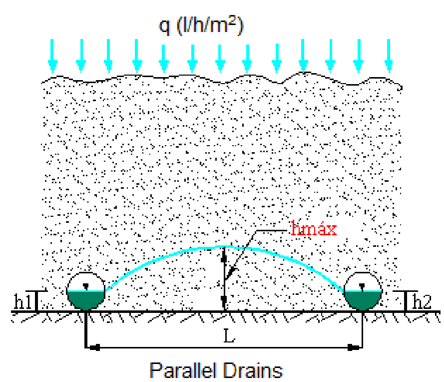


Figure 5 – Phreatic line determined by Dupuit theory of unconfined flow.

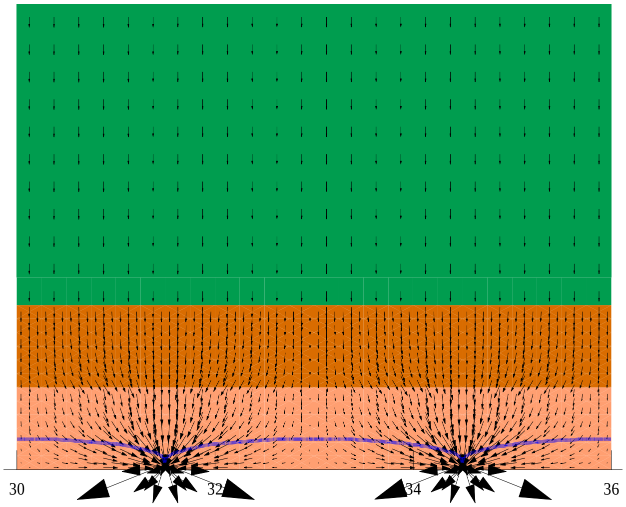


Figure 6 – Illustrative results from a finite element analysis of the unsaturated flow problem, showing the two protection layers, the phreatic line and two drains.

Table 3 - Maximum height h_{max} reached by the phreatic line at mid-distance between drains.

Dupuit Solution				
L (m)	k1 (cm/s)	h1 (m)	k2 (cm/s)	h2 (m)
3	2.53x10-2	0.14	$2.53x10^{-3}$	0.44
6	2.53x10-2	0.28	$2.53x10^{-3}$	0.89
9	2.53x10-2	0.42	$2.53x10^{-3}$	1.33
FEM Analysis				
L (m)	k1 (cm/s)	h1 (m)	k2 (cm/s)	h2 (m)
3	2.53x10-2	0.13	$2.53x10^{-3}$	0.42
6	2.53x10-2	0.26	$2.53x10^{-3}$	0.8
9	2.53x10-2	0.39	$2.53x10^{-3}$	0.99

3 SLOPE STABILITY ANALYSIS

3.1 Geotechnical Parameters

The slope stability studies were carried out using a limit equilibrium approach (slice method) and the finite element method, considering the Mohr-Coulomb constitutive model (with cohesion c = 0) to describe the strength behavior of the ore copper. A conservative approach was adopted herein, by reducing the friction angle ϕ (in this study the secant friction angle), gradually from top to bottom of the pile (Table 4) following a suggestion presented by Leps (1970) – Figure 7 – for granular materials submitted to high normal stresses. Ore degradation caused by mineral dissolution and bacterial action in the leaching process is always a concern in heap leach systems but in the present analysis these long-term degradation effects are not being considered.

Table 4 - Geotechnical ore properties at the several construction layers (Mendoza, 2005).

Material	Depth (m)	Wet unit weight (kN/m^3)	Friction angle ϕ (°)	Young modulus (MPa)
Layer nº 1	0-21	20.30	37	96.20
Layer nº 2	21-42	21.50	37	168.25
Layer nº 3	42-63	22.27	36	219.68
Layer nº 4	63-84	22.69	36	262.21
Layer nº 5	84-105	23.08	35	299.37
Layer nº 6	105-126	23.52	35	332.96
Protection Layer nº 2	126-126.75	22.69	34	349;22
Protection Layer nº 1	126.75 -127.5	21.78	34	350.76

3.2 Static Stability Analysis

The safety factor was determined in the finite element analysis using the c and ϕ reduction technique, in which the strength parameters are gradually decreased until the failure of the slope occurs. The factor of reduction is actually the sought factor of safety.

The porepressure distribution throughout the pile was already computed in the previous infiltration analysis and taken into account in the stability analysis.

Figure 9 shows the displacement field at the moment of rupture, corresponding to a factor of safety FS_{static} = 1.60 and two potential surfaces of rupture: one formed by 2 planes and the other composed by a plane, near the slope toe, followed by an arc of circle.

In the limit equilibrium analysis (Spencer method of slices) the same factor of safety FS_{static} = 1.60 was computed for both surfaces.

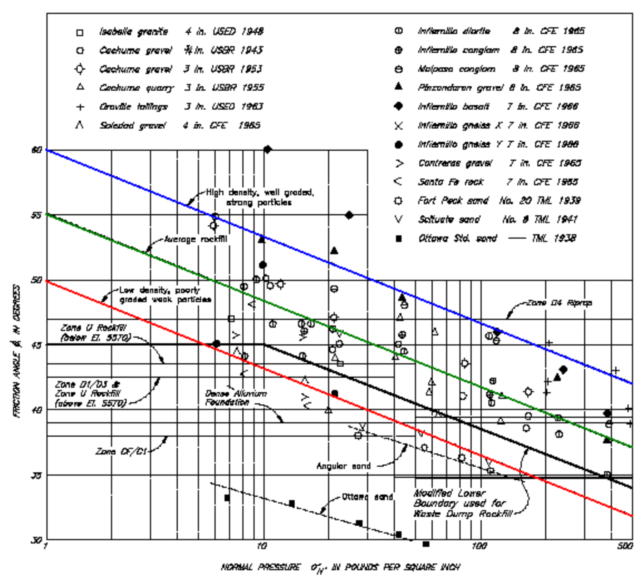


Figure 7 - Decrease of the friction angle with increase of the normal vertical stress (Leps, 1970).

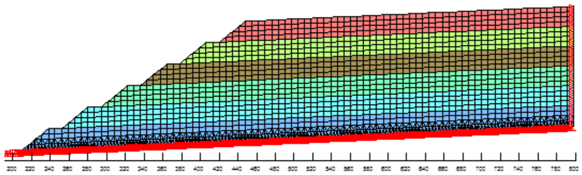


Figure 8 – Discretization of the pile cross section by finite elements. The rock foundation has an inclination of 4.5%.

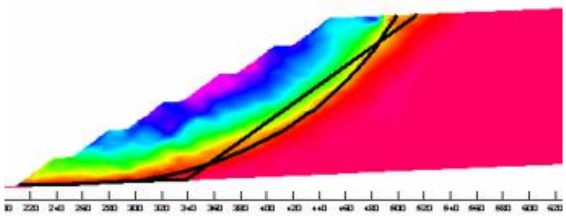


Figure 9 – Displacement field and two potential rupture surfaces from finite element analysis (FS_{static} = 1.60).

3.3 Pseudo-Static Stability Analysis

The various solutions for limit equilibrium analysis under static conditions, which can be considered familiar to geotechnical engineers, can be extended to a dynamic context by applying a horizontal force to the centroid of each slice, representing the inertia force generated by the propagation of seismic waves across the geostructure. The modulus of this pseudo-static force is obtained multiplying the weight of the unstable mass by the horizontal seismic coefficient k_h. The choice of k_h represents the most important aspect, and the most difficult one, in the use of pseudo-static methods. A common mistake is using the maximum expected horizontal acceleration as the seismic coefficient, which produces very conservative results, since the maximum acceleration acts in a single instant of the whole time history of the seismic event. Several suggestions were made in the literature, comparing the results of pseudo-static analyses with field experience and values obtained by other methods where the deformability properties of the materials are taken into account, such as in the finite element method. In this study the recommendation given by Hynes-Griffin and Franklin (1984) was adopted and the horizontal seismic coefficient was made equal to 0.5PHA /g, where g is the acceleration of gravity and PHA stands for Peak Horizontal Acceleration (0.30g at the heap construction site). Results from pseudo-static analyses with k_h = 0.15 yielded FS = 1.15 (curved surface) and FS = 1.18 (plane surface).

3.4 Dynamic Stability Analysis

Based on average elastic properties of granular (rockfill) materials the Poisson ratio for all layers was fixed as ν = 0.3 and the maximum shear modulus G_{max} was calculated according to equation [4], proposed by Seed and Idriss (1970) where k_2 = 100 (typically ranges between 80 and 180) and σ'_m is the effective normal octaedric stress which varies depending on the depth of the layer.

$$G_{máx} = 218.82 k_2 \left(\sigma'_m\right)^{0.5} \quad (\text{kPa}) \qquad [4]$$

The equivalent linear model was adopted as the constitutive law for the dynamic response of the copper ore. In this model the shear modulus (G) and the damping ratio ζ are continuously updated depending on the amplitude of the cyclic shear strain. Several linear analysis are carried out by the finite element program until the predicted shear strains are compatible with the adopted shear modulus and damping ratio (Figure 10).

The seismic activity in Peru is mainly due to the subduction movement of the Nazca plate under the South American plate at a relative speed from 8 to 10 cm / year. As a result, the South of Peru, region of the copper ore heap leach, presents high seismic activity as seen in Figure 2, where the circles represent superficial earthquakes, the squares the seismic events with intermediate epicentral distances (100km) and the triangles the deep earthquakes.

From regional seismic hazard maps (Castillo & Alva, 1993), earthquakes with local magnitude 7.5 on the Richter scale can be expected to occur in this region, with PHA equal to 0.30g. In this investigation, the seismic records of the Lima earthquake (1974) was used, but previously normalized to this maximum expected horizontal acceleration (0.30g), as indicated in Figure 11.

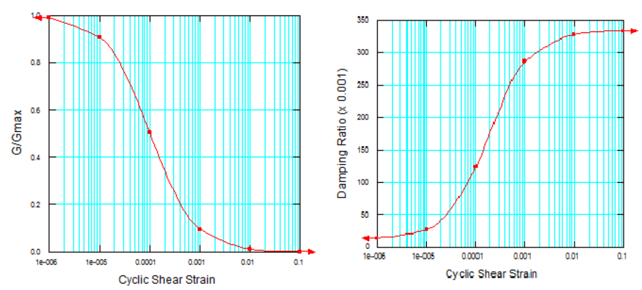


Figure 10 – Shear modulus decrease (left) and damping ratio (increase) as a function of the cyclic shear strain in the linear equivalent model.

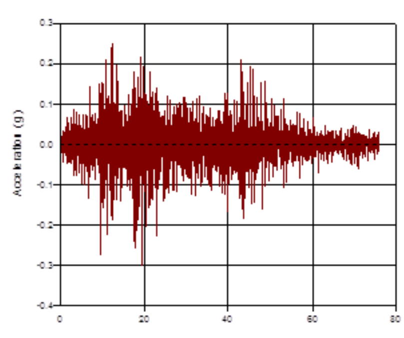


Figure 11 – Acceleration time history of the 1974 Lima earthquake normalized to a peak value of 0.30g.

An important aspect of dynamic finite element analysis is a careful choice of element size, especially in cases where high-frequency effects are important. Kuhlemeyer and Lysmer (1973) found that the element size in the direction of wave propagation has great influence on the results of dynamic analysis, with large elements proved to be incapable of transmitting movements at high frequencies. Those authors proposed a rule of thumb that the maximum size h_{max} of the finite element should not be larger than 1/8 of the shorter wavelength for an efficient transmission frequency.

$$h_{max} = \frac{1}{8}\frac{v_s}{f_{máx}} \qquad [5]$$

where v_s is the propagation velocity of S waves and f_{max} the maximum frequency of interest (cutoff frequency). In this particular problem, the cutoff frequency was established at 10Hz and the finite elements have a maximum size of 7m (Figure 8).

The variation of the factor of safety along the earthquake duration (76 s) can be seen in Figure 12, where FS varies on the interval [1,00, 3.90]. In order to estimate the occurrence of permanent displacement that could affect the serviceability of the structure, the Newmark method (1965) could have been applied, but it was observed (Figure 13) that the yield acceleration, corresponding to FS = 1.00, was not reached during the event. The dynamic response was essentially elastic.

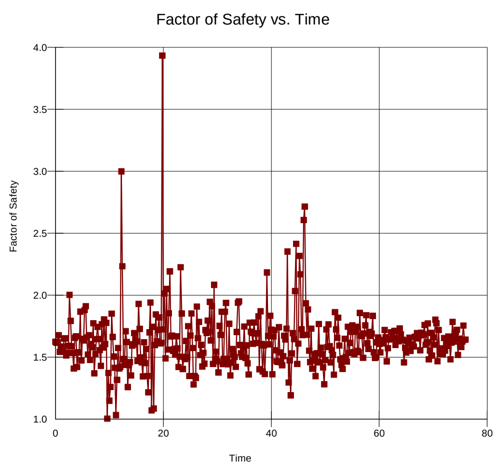


Figure 12 – Variation of the factor of safety during the earthquake.

3.5 Post Earthquake Stability Analysis

Finite element analyses were carried out considering the same discretization (Figure 8) but the porepressure distribution corresponding to the end of the earthquake. Additionally, since several authors (Seed and Harder 1990; Marcuson et al., 1996; Finn, 1998) admit a loss of material strength of approximately 20% to 25% when compared to those values determined before the earthquake, in this study the cooper ore in all layers had its shear strength decreased by 25%.

Results are shown in Figure 14, where the potential failure surface is slightly different from the one determined in the static analysis (Figure 9) as well as the corresponding factors of safety, with FS_{static} = 1.60 and FS_{post} = 1.20. The same values were found when using a limit equilibrium approach (Spencer method of slices).

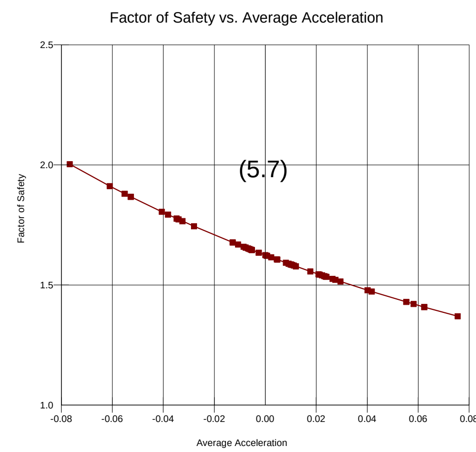


Figure 13 – Variation of the factor of safety with the average acceleration. Yield acceleration corresponds to FS = 1.00.

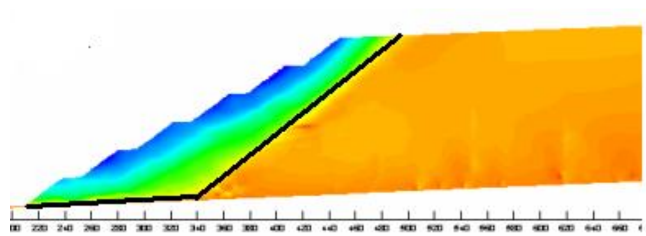


Figure 14 – Displacement field and the potential rupture surface from finite element analysis (FS_{post} = 1.20).

4 CONCLUSION

One of the most important geotechnical aspects in the design of leach heaps is the assessment of the position of the phreatic line above the liner. The saturated zone should not be greater than the thickness of the protection layers. This condition is reinforced for those installations operating bio-leaching processes where the aeration pipes, which accelerate the mineral leaching in presence of oxygen, are mounted near the bases of the ore piles. Clearly these lines should be protected from the acid solution of the saturated zones.

Another fundamental design topic refers to stability of slopes, because the height of these structures has reached considerable values in South America and also because many of them are located in areas of high seismic activity, such as in Peru and Chile. From the analysis performed in this work, the factors of safety calculated by fast and simple limit equilibrium method have the same accuracy as those determined from more complex and time consuming approaches such as the finite element method. The main advantage of using finite elements is the possibility to fully simulate the failure mechanism, without requiring the prior definition of potential failure surfaces.

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