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Stability Analysis and Stabilization of Miduk Heap Leaching Structure, Iran

Mehdi Amini *

School of Mining, College of Engineering, University of Tehran, Tehran, Iran

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Abstract

To construct copper heap leaching structures, a stepped heap of ore is placed over an isolated sloping surface and then washed with sulphuric acid. The isolated bed of such a heap consists of some natural and geosynthetic layers. Shear strength parameters between these layers are low, so they form the possible sliding surfaces of the heaps. Economic and environmental considerations call for studying such slides. In this study, firstly, results of the laboratory tests carried on the materials of the heap leaching structures bed are presented. Then, the instability mechanisms of such structures are investigated and proper approaches are summarized for their stabilization. Finally, stability of the Miduk copper heap is evaluated as a case history, and appropriate approaches and their effects are discussed for its stabilization.

Keywords: heap leaching structures, Miduk copper mine, shear strength parameters, stability analysis, stabilization.

1. Introduction

To construct heap leaching structures, a vast area, about several hundred thousand square meters, is selected. The area is, then, roughly leveled (both longitudinally and transversely) in such a way that the final bed surface takes the form of one or more valleys with a common exit and a mild slope of about 5% to 15%. The final bed is spread with one or more layers of compacted composite soil and natural or geosynthetic clay layers (GCL); the main isolated bed layer, namely the geomembrane, is placed over them. To protect the geomembrane liner, a 20 to 30cm thick soil layer, consisting mostly of sand (known as cushion), covers it. The heap drainage system, consisting of some perforated polyethylene pipes and a gravelly layer, is laid over the cushion. Finally, some ore layers of 5 to 10 meter steps are put over the gravelly layer. A suitable solvent (sulphuric acid for copper oxide ore) is dropped over the ore steps that penetrate under its own weight. On its way through, it passes the ore and solves the target element.

The pregnant leach solution (PLS) is guided out of the heap by the drainage system gravitationally. The PLS is sent to the solvent extraction-electro winning (SX-EW) plant and, after the target element it is extracted, is transferred back over the heap for a rewashing process [1, 2]. Each step is washed for a few months and the next one is then placed over it. The final heap is generally between 50 to 100 meters high, having an overall slope of 30% to 40% and a bed inclination of 5% to 10% (Figure 1). It will, therefore, have a sliding potential under static and dynamic conditions [3, 4, 5, 6]. Instability and sliding of such heaps are of utmost importance, both economically and environmentally, which require special considerations.

In 1977 and 1999, Breitenbach carried out noticeable case studies of the heap leaching structures instabilities in Americas and Australia, the most notable of which being the one in Summitville, southern Colorado [7, 8]. He studied the effect of increase in the heap height on density and other shear strength parameters of ore heaps in 2004 [9]. Kariminasab and Nabizadeh (2001) and Kariminasab, Hojat and Mollaeifard (2007) studied the stability of Sarcheshmeh copper mine heap leaching structures, and presented suitable criteria for their site selection [10,11].

Evidently, research into the issue is sparse and only a few studies have targeted slide phenomena, effect of lateral pressure on the heap stability, appropriate approaches for stabilization of the heaps and the rate of effect of each one. In this paper, stability analyses of such structures are studied and proper methods for their stabilizations are offered.

*Corresponding author: Email: mamini@ut.ac.ir

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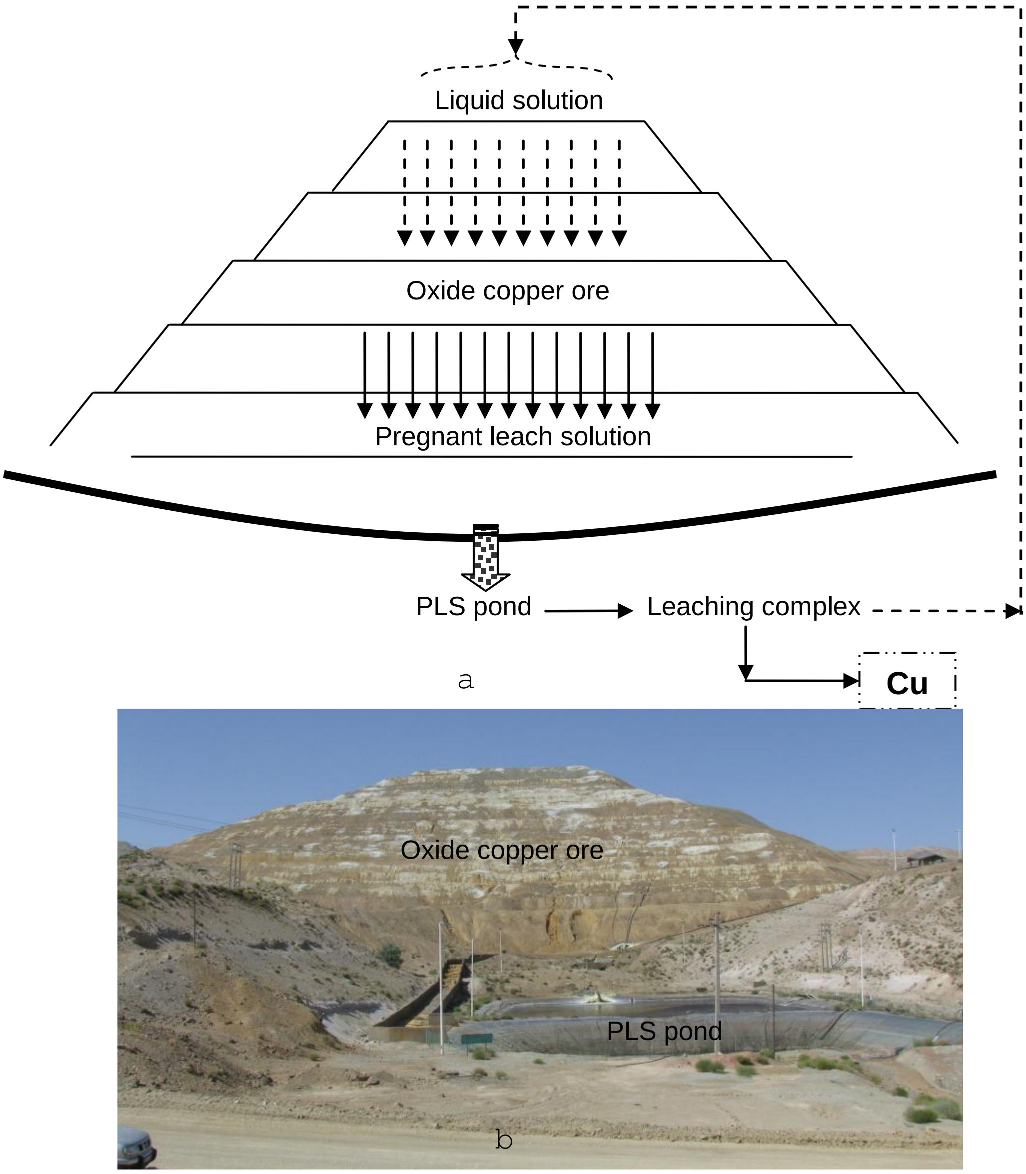

Figure 1. Heap leaching structure: a) schematic view; b) "Sarcheshmeh" copper heap leaching structure 1

2. Stability analysis of heap leaching structures

As mentioned earlier, in heap leaching structures, a huge volume of ore is placed over an inclined bed. This bed consists of some natural and synthetic layers. Although heap leaching structures might look like soil slopes at a first glance, there are major differences between the two as follows (Figure 2):

1. Contact surfaces of isolated layers of the heap bed have relatively low shear strength parameters, hence slide potentials.
2. Geometry and topography of the slide surface are quite distinct and there is no need for geotechnical investigations for its determination.
3. The critical slide planes are the contact surfaces of the isolated layers of the heap bed, that is, these surfaces are made before the establishment of the ore heap and, therefore, these are visible and changeable.
4. Since ore heaps are generally established in one valley (or more adjacent valleys with a common exit), lateral pressures on the heap are usually high and, therefore, they should be modeled three-dimensionally.
5. The leaching heap is continuously washed by chemical fluids; therefore, it is mostly polluted and can cause serious problems for the environment.
6. The stable part of the structure lies beneath the isolated bed; so, one cannot use anchors or bolts for the structure stabilization, because, to fix the anchors, one has to bore holes into the isolated bed and place them in the stable part.
7. The isolated surfaces on the slopes of each valley can be considered as two surfaces meeting at the bottom of the valley. The

Figure 2. Isolated layers of Sarcheshmeh copper heap leaching structure 2

contact line of the two planes has a longitudinal slope, so the sliding block generally moves in a wedge form.

8. Ore heaps have definite fixed compositions and gradations. They are, therefore, homogeneous and their physical and geotechnical parameters can be used more precisely.

It is obvious, then, that instability mechanism of heap leaching structures depends largely on shear strength parameters between the isolated layers of the bed. Much research and many laboratory tests have been carried out to determine the parameters between GCL-geo membrane, compacted cushion–geomembrane, geomembrane-geotextile [12,13,14]. Table 1 shows the outcomes of some of the researches. It must be noted that these parameters (especially the shear strength parameters between geosynthetic and natural materials) depend also on the type of the material used. It is, therefore, suggested that for each heap new laboratory tests be carried out with the used materials in the same project.

In this research, based on the materials used in Miduk heap leaching structure, new direct shear tests were performed on the materials of the heap bed. The results of these tests are presented in the next section.

Table 1. Shear strength parameters of the bed layers of heap leaching structures

Slide surfaces	GM[1]-CCL[2]		GM-CSL[3]		GM-GT[4]		GM-GCL[5]		Internal parameters of GCL		Ref.
Shear strength parameters	ϕ $(^0)$	c (kPa)	ϕ $(^0)$	c (kPa)	ϕ $(^0)$	c (kPa)	ϕ $(^0)$	c (kPa)	ϕ $(^0)$	c (kPa)	
1	20	0	22	0	16	0	16	0	6	0	[11]
2	--	---	19-31	3-7	--	--	--	--	--	--	[7]
3	9.5	0	--	--	--	---	6.5	---			[9]
4	---	----	----	----	----	-----	5	---	4-5	150-165	[10]

1. Geomembrane, 2. Compacted clay layer, 3. Compacted cushion layer, 4.Geotextile 5-Geosynthetic clay layer

2.1. Laboratory test results

The main objective of these laboratory tests was to find appropriate shear strength parameters of the Miduk heap leaching structure bed layers. The parameters are essential for the design, stability analysis and the stabilization of the heap. In Miduk project, the geomembrane layer is in direct contact with the upper geotextile of GCL (NWN270GT)[1] and the non-compacted cushion. Also, the lower geotextile of GCL (WN270GT)[2] is in direct contract with the compacted fine composite soil. Therefore, the surfaces having sliding potential are those between geotextile–geomembrane, geotextile–compacted fine composite soil layers and the internal sliding of the GCL. The properties and pictures of the materials are presented in Table 2 and Figure 3.

In this study, laboratory tests were carried out in a direct shear machine with a 30×30cm shear box at the above mentioned boundaries. To do the tests, geosynthetic materials were glued on a piece of wood of the same size but of half the height of the shear box. This piece was then placed at the upper portion of the box. To find the shear strength parameters between geosynthetic materials (GCL– geomembrane), the lower portion of the shear box was prepared like the upper one and the shear tests were done. To find the shear strength parameters between geosynthetic and natural materials (GCL– compacted fine composite soil), the bottom portion of the shear box was filled with soil and compacted with optimum density and water content. Also, to find the GCL internal shear strength parameters, the lower portion of the shear box was filled with a piece of gagged metal plate to create a slide surface between the two layers of geotextile and inside the clay layer. The tests results are shown in Figure 4 and Table 3.

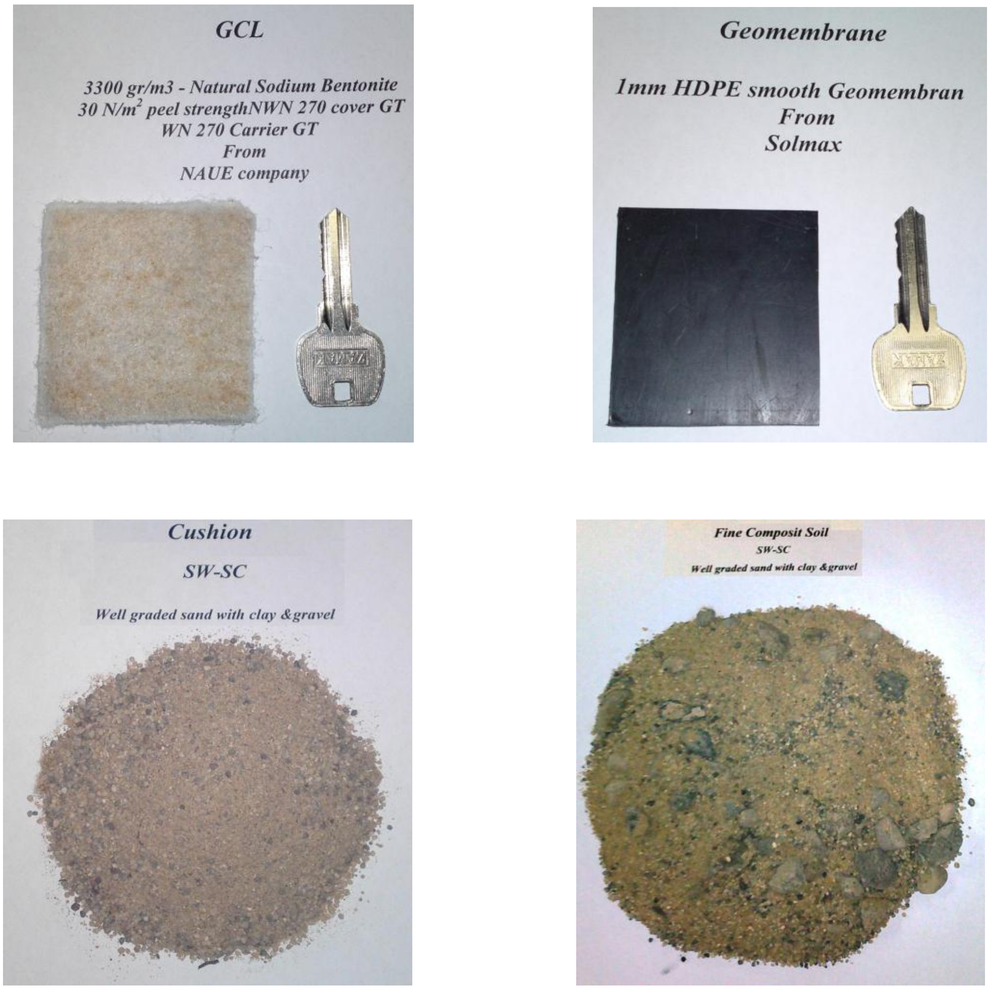

Figure 3. Photos of the materials used in these laboratory tests.

1. Non-woven needle punched- 270 gr/m^2 geotextile
2.Woven needle punched- 270 gr/m^2 geotextile

Table 2. Properties of materials used in these laboratory tests

Materials	Properties
Geomembrane	1mm HDPE smooth Geomembrane from Solmax
GCL	3300 gr/m^3 – Natural Sodium Bentonite – 30 N/m^2 peel strength – NWN 270 cover GT –WN 270 Carrier GT from NAUE company
Compacted cushion	$\gamma_{dry} = 2.01\ gr/cm^3,\ \omega\% = 8\%,\ C_c = 1.5$ $C_u = 7,\ SW - SC,\ Well\ graded\ sand\ with\ clay\ and\ gravel$
Compacted fine composite soil	$\gamma_{dry} = 2.01\ gr/cm^3,\ \omega\% = 8\%,\ C_c = 2$ $C_u = 8.3\quad SW - SC,\ Well\ graded\ sand\ with\ clay\ and\ gravel$

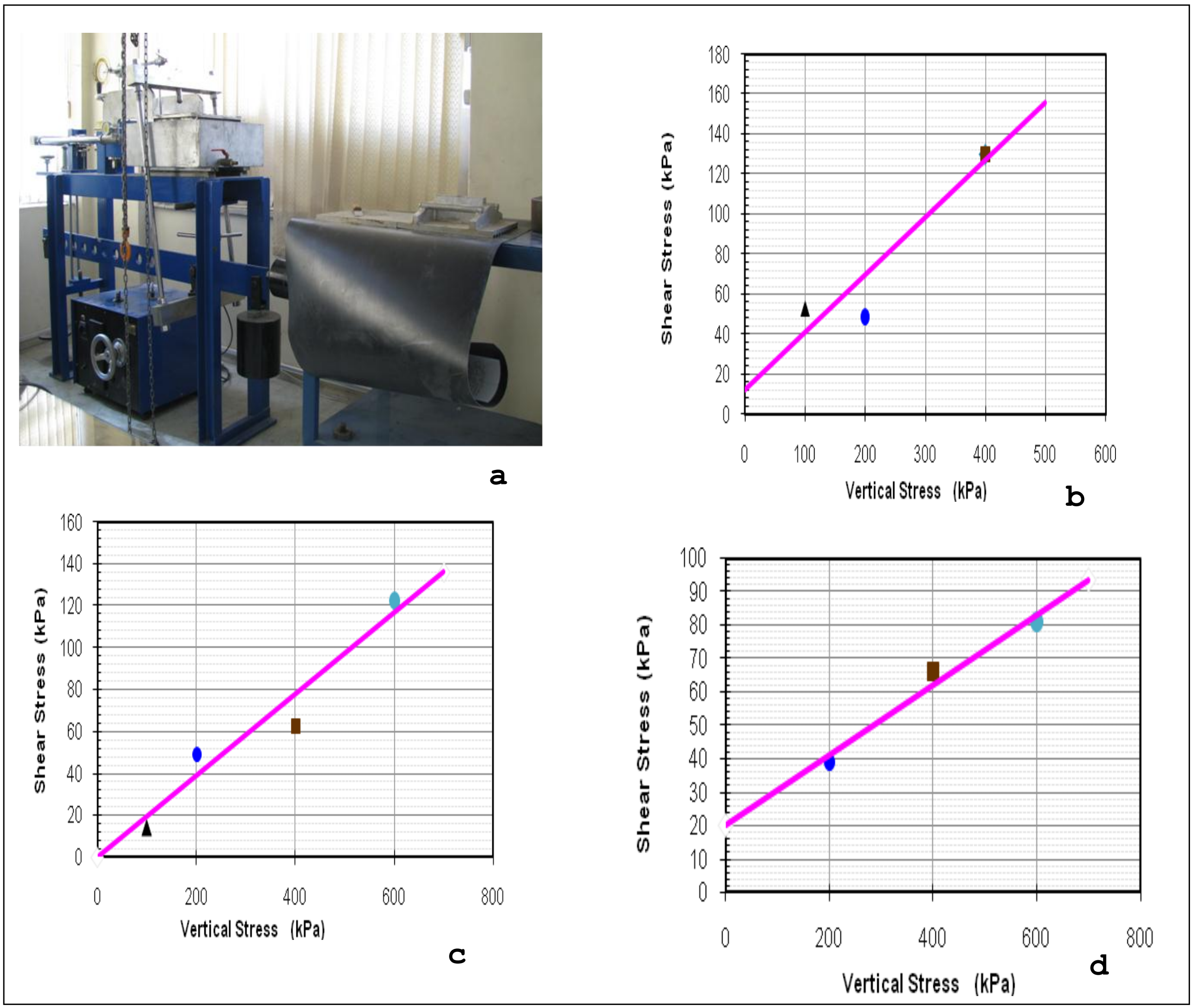

Figure 4. Direct shear tests results of the heap beds materials a) Direct shear test machine for determining shear strength parameters between geosynthetic-soil and geosynthetic-geosynthetic materials, b) Between compacted fine composite soil and GCL, c) Between GCL– GM, d) Internal slide in GCL

Table 3. Shear strength parameters of the heap bed layers used in this research

Contact surface	GCL-CFCSL[1]		GM-GCL		Internal parameters of GCL		Remarks
Shear strength parameters	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)	ϕ (°)	c (kPa)	
Values	16	12	11	0	6	20	The parameters are for residual resistance

1. Compacted fine composite soil layer

Although the contact surfaces of the isolated bed layers of heap leaching structures often form the most critical slide surfaces, there is also possibility of circular failure in ore heaps. In such failures, shear strength parameters of the ore are of utmost importance. It has to be noted that the parameters of the ore heap change with respect to time because it is under chemical reactions with the solvent. In copper leaching structures, the solvent used is sulphuric acid that can change the strength of ore grains by dissolving some of the constituent minerals. Therefore, to analyze possible circular failures in heap leaching structures, use has to be made of long term shear strength parameters of the ore. In-situ laboratory tests on acid washed specimens are usually costly and time consuming because of safety provisions. This is why there have been no specific tests carried out on such materials to find how much the acid can affect the shear strength parameters of the ore heaps. But, personal experiences of the authors and observations of some copper leaching structures show that acid dissolutions cause a reduction in frictional strength and an increase in cohesive strength of the ore heaps. Considering visual description, particle size distribution, in-situ density, "Atterberg" limits and engineering judgment, the following long and short term shear strength parameters are proposed for ore heaps.

2.2. Instability mechanisms of heap leaching structures

As mentioned earlier, heap leaching structures beds are often one or more V shaped valleys, which are filled with ore after they are isolated. Different possible instabilities in such structures may thus be explained as follows:

a) Circular slide in the ore heap: This instability is similar to usual circular slides in soil and fractured rock slopes. To analyze it, use can be made of known limit equilibrium methods (Bishop, Spencer, Fellenius, …). As stated before, overall slopes of the ore heaps are often 18^0 to 25^0 and their shear strength parameters are according to Table 4. Using these parameters and limit equilibrium methods, heap leaching structures safety factors against circular slides have been calculated and shown in Figure 5. X and Y axes in this figure show the heap height and the related factor of safety respectively. It can be seen that the safety factor of ordinary heap leaching structures against circular slides under static and dynamic conditions are more than the allowable limits (1.5 for static and 1.2 for dynamic conditions). Circular slides, then, are not considered as serious threats for heap leaching structures.

b) Multi-planar slides on the heap bed: To form a heap bed, the topography of the natural ground is changed by soil and rock

Table 4. Suggested long and short term shear strength parameters for ore heap

	Assumed and checked by back analysis				Measured and check by back analysis					
Parameter	c (kPa)		$\phi(^\circ)$		γ_{dry} (kN/m^3)	$\omega\%$	Soil classification		Soil description	
Time	LT [1]	ST [2]	LT	ST			LT	ST	LT	ST
Values	100	20	22	30	17.5	13%	GM	GP	Silty gravel with some sand	Poorly graded silty gravel

1. Long term
2. Short term

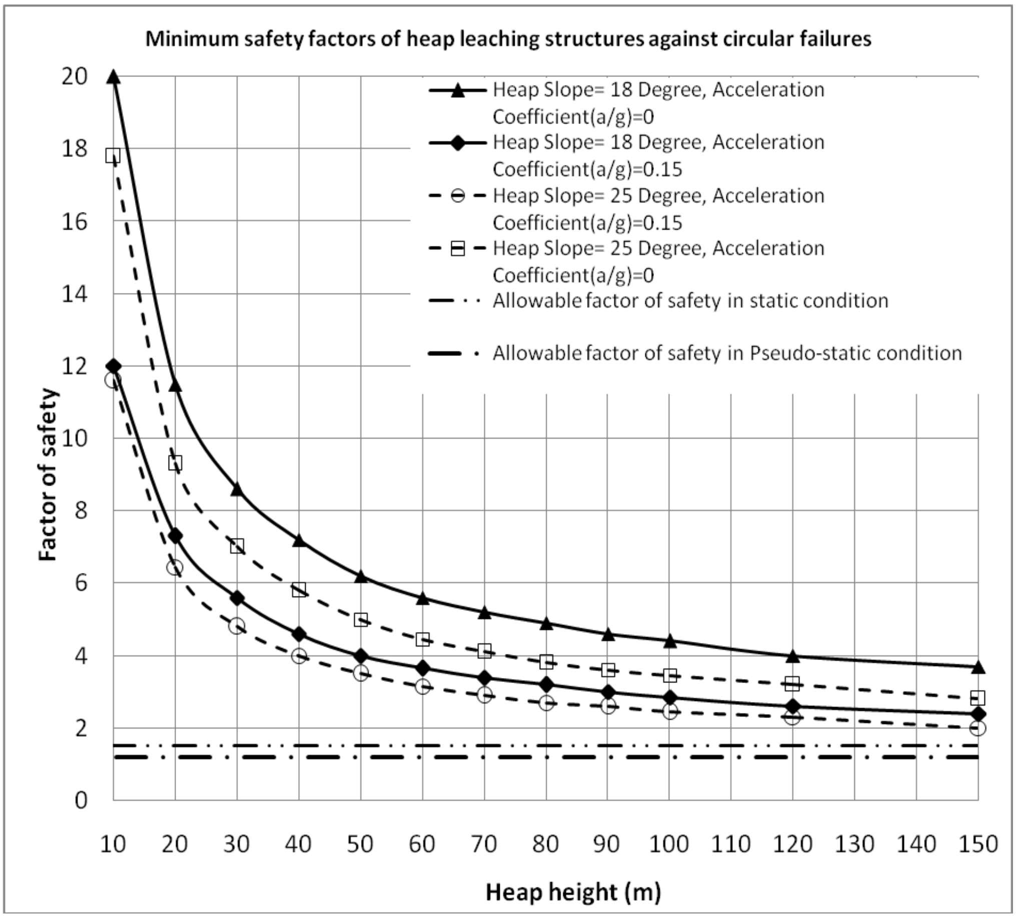

Figure 5. Heap leaching structures safety factors against circular slide in ore heap

excavations. Considering the original topography, these excavations can reduce or increase the bed slope. If the heap bed slope is less than 2%, the acid cannot drain gravitationally; and, if the slope is more than 10%, placing protective layers of geomembrane liner and gravelly drainage system over it will not be practical. To drain and guide the PLS from the ore heap to the ponds, the heap bed is selected in one of more valleys having a common exit. In such conditions, in addition to gravelly drainage at the bottom of each valley, use is also made of perforated polyethylene pipes. The acid, after dissolving the copper (i.e. PLS) and reaching the isolated bed, moves towards the bottom of the valley along the transverse slopes gravitationally. At the bottom of the valley, the PLS enters the polyethylene pipes and leaves the heap along the longitudinal slope. Ore heap transverse slide is almost impossible because the ore is placed at the bottom of the valley; therefore, there are no specific restrictions on the choice of transverse slopes as long as the stability is concerned. It has to be kept in mind that when natural materials (clay, cushion and gravel) are used at the heap bed, their placing on transverse slopes which are more than 10%, will be difficult. But, if geosynthetic materials (GCL, geotoxtile and geodrain) are used, there will not be any specific restrictions on transverse slopes. Under such conditions, transverse slopes can be chosen up to 50%. In all cases, ore heaps are mostly placed in a V shaped valley whose longitudinal slope is less than 10%. The bed slope, of course, usually varies between 2% to 12% at different parts according to the original topography of the site. As shown in Tables 2 and 3, shear strength parameters between isolated bed layers are relatively low; therefore, heap slide between isolated bed layers boundaries is probable. Under these conditions and considering the bed topography, slide may occur in a multi-planar form. To analyze the failure, use can be made of usual soil trench and slope stability analysis methods (analytical or numerical approaches).

c) Multi-planar slides in the ore heap and the isolated bed: This is the most common type

Int J Min & Geo-Eng (IJMGE), Vol. 47, No. 1, Jun. 2013, pp. 1-12

of instability in heap leaching structures. In this type, one part of the slide is in the ore heap and the other parts on the surface of the isolated bed. Such slides can be analyzed the same way as multi-planar slides on the heap bed, with the exception that for some parts of the slide, use has to be made of shear strength parameters of the ore heap.

3. Case study, Miduk heap leaching structure

Miduk heap leaching structure, with an approximate area of 270000 square meters, has been constructed near Miduk copper mine, Kerman. The objective of the hydrometallurgical plant is a yearly production of 5000 tons of cathodic copper, from low grade oxide and sulphuric copper ores of the mine. Because of the mountainous nature of Miduk region, there was no location with a suitable slope (2-10%) near the ore dumps, so the heap site was unwillingly chosen in two neighboring valleys with an average longitudinal slope of 35% and transverse slope of 45%. To construct the heap bedding, use was made of compacted composite soil, GCL, geomembrane liner, uncompacted cushion, gravelly drainage and filter layers. Figure 6 shows the heap bedding layers. Borrow resource of clay was far from the site, so GCL was used instead. As was pointed out in previous sections, if the heap bedding slope is more than 2%, the heap will need stability analysis and, probably, stabilization.

To increase the stability of the heap, the slope of the heap foundation was reduced, as far as possible, by approximately one million m^3 of earth cut and fill. The slope thus obtained was 19%. Figure 7 shows the topography of the heap bed after the earth work. The analyses carried out on this heap showed that the most critical section for the investigation of the heap stability, is sections A-A. Therefore, the stability analysis results of only this section has been presented in this paper. Figure 8 shows the analysis results of the section found by limit equilibrium methods in static condition. As it can be seen, the minimum safety factor for this heap is below the allowable limit (1.5), so it needs stabilization. The slide critical surface that has a safety factor of 0.88, occurs when the heap construction has been finished. The figure shows the safety factor of other slide surfaces at different stages of the heap utilization. It may be observed that the safety factor of the heap slide, before step 8, is above the allowable limit (1.5).Therefore, under ordinary static conditions, the possibility of its slide is quite low.

With an increase in the heap height, the safety factor decreases and reaches the critical limit of 1 after step 20 has been loaded. It can be concluded that heap slide is possible after the loading of step 8 up to the end of utilization of step 20 (probability of the unexpected happenings like earthquake has not been taken into account).

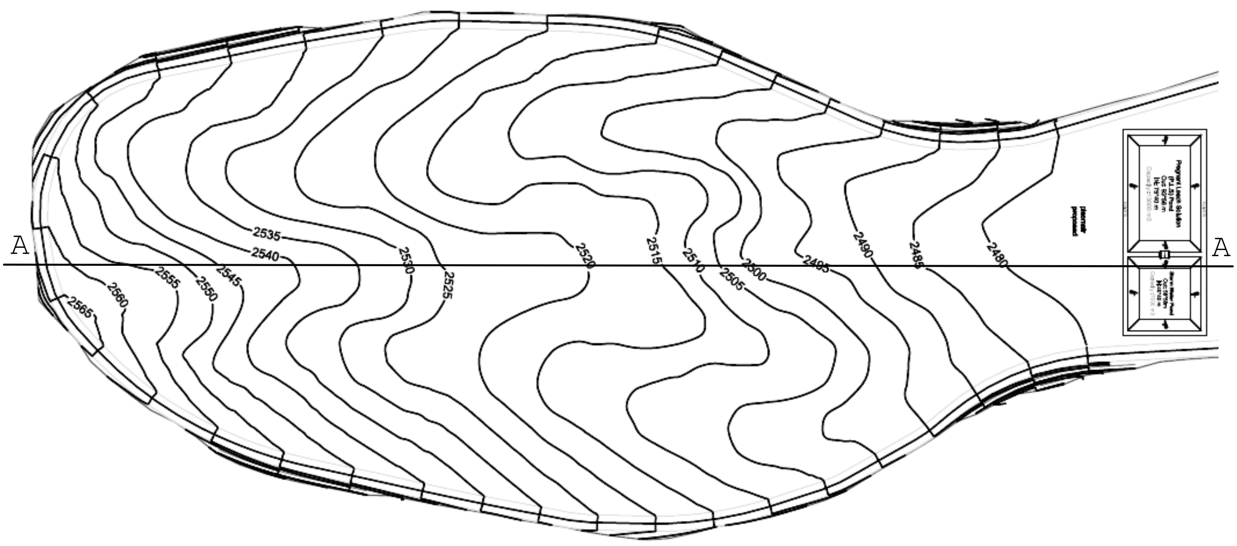

Figure 7. Miduk heap foundation topography after earthwork

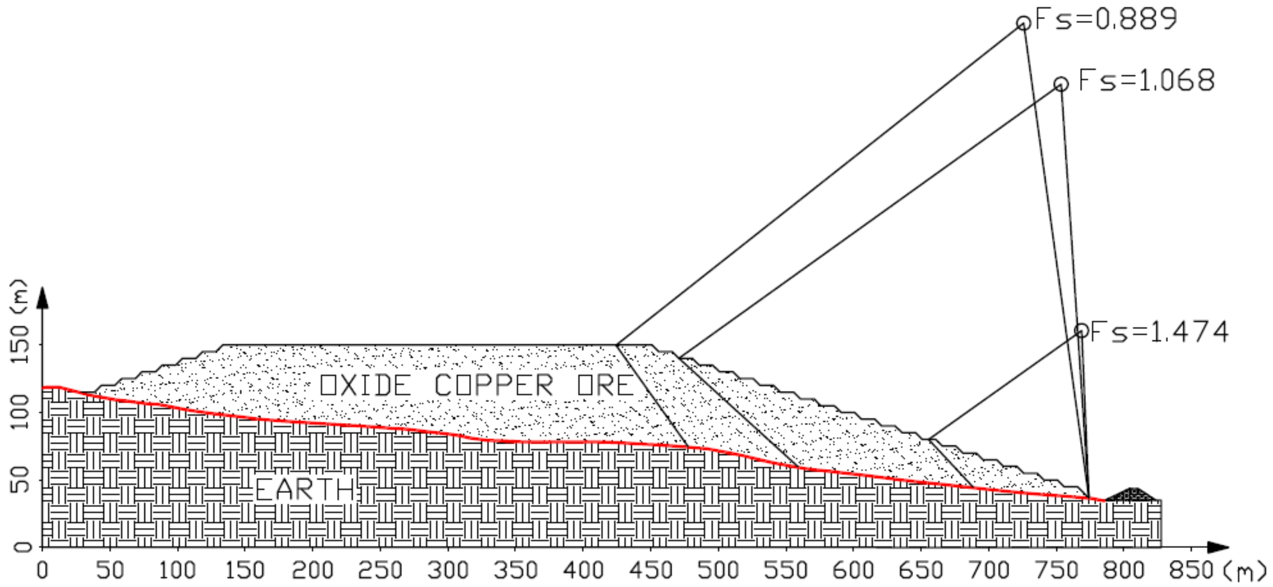

Figure 8. Stability analysis of Miduk heap after earthwork in A-A section

More slope reduction of the heap foundation is not economical due to topographical problems that cause enormous increase in the volume of earthwork. So, the following simultaneous approaches were suggested to increase the stability of the heap (Figure 9):

1. Construction of toe berm at the heap toe.
2. Construction of some internal berms inside the heap.
3. Stairing of GCL placement at the first 100 to 200 meters of the heap bedding.
4. Construction of three 40- meter safety berms in the ore heap at places where the slope of heap foundation increases.

To determine the effects of the above approaches on the improvement of the stability of Miduk heap leaching structure, section A-A was reanalyzed under new conditions. The results under static and dynamic conditions are shown in Figure 10. It can be observed that, by using these methods, the minimum safety factor of the heap slide has exceeded the allowable limit (1.25 for static and 1.2 for dynamic conditions) which guarantees the structure stability.

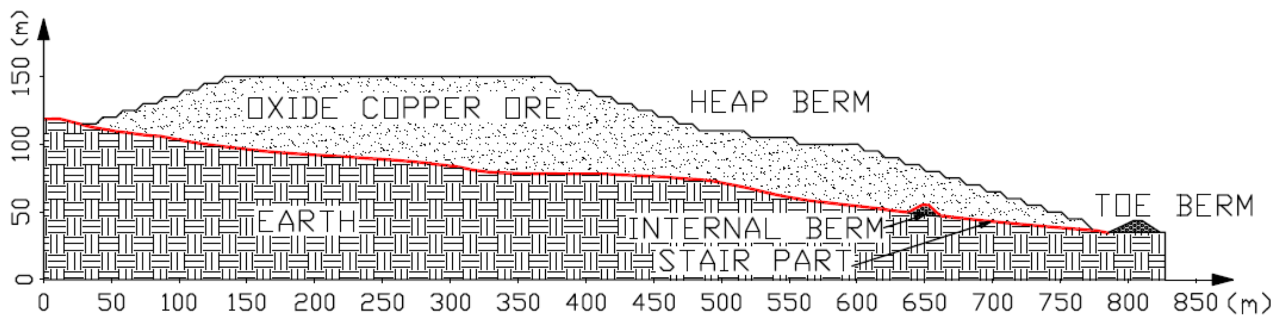

Figure 9. Miduk heap model after stabilization at A-A section

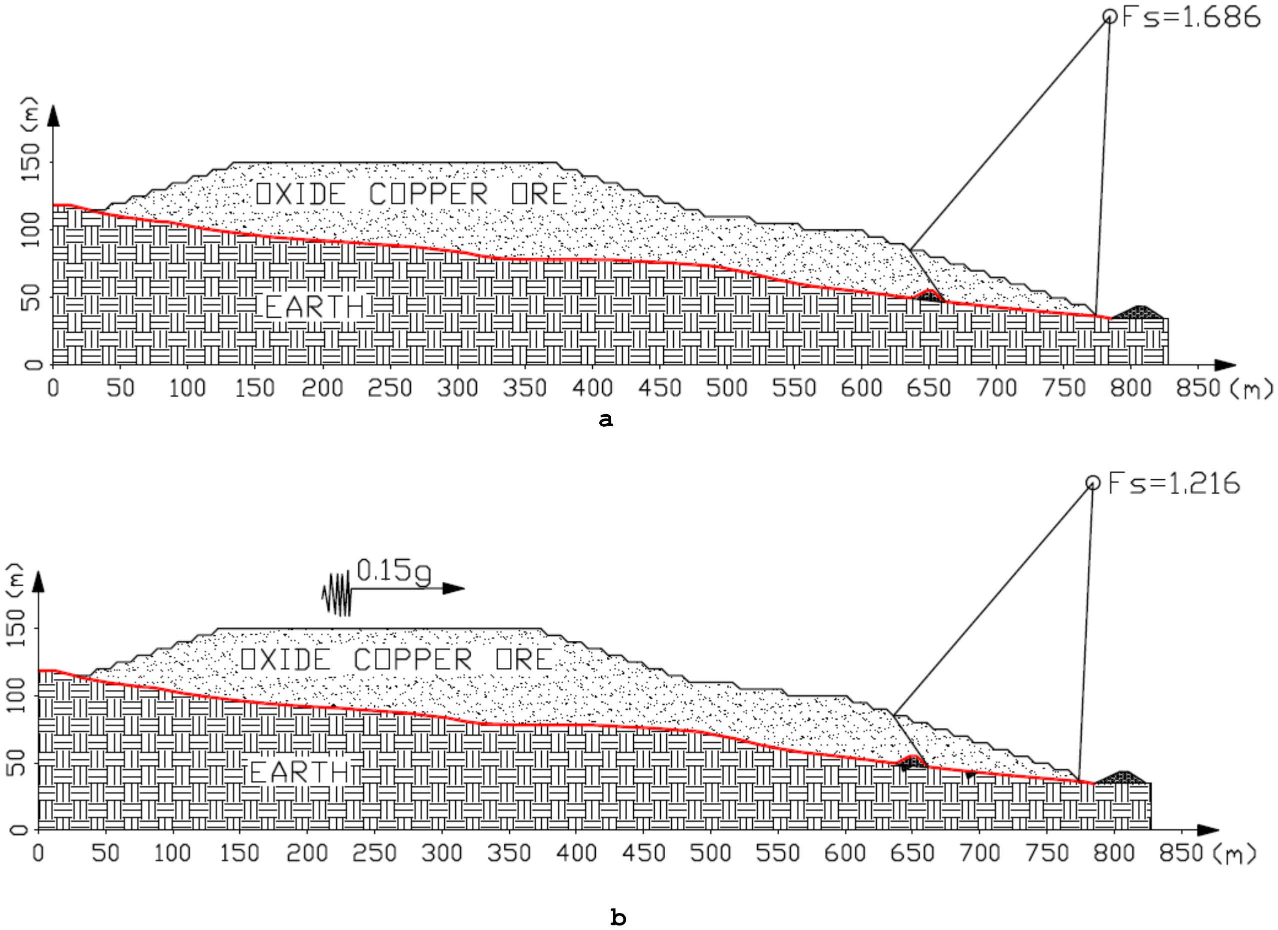

Figure 10. Stability analysis for Miduk heap after stabilization at section A-A
a) static b) dynamic

5. Conclusions

In this paper, possible instabilities in heap leaching structures were studied. Investigations showed that the structures are mostly stable against circular failures in the ore heap. The most critical slide surfaces in such structures are the internal slides in the GCL layer and the boundary of GCL-GM. For their stability analysis, use may be made of the common methods used for soil slopes. If the safety factor of the heap leaching structure against multi-planar slides (in the bed isolated surfaces) is less than the allowable limit, it can be improved by slope reduction of heap foundation, toe berms, internal berms, internal trenches, safety berms, stairing the heap bed and using textured liners. Stability analysis of Miduk heap leaching structure showed that the safety factor of the heap can reach the allowable limits with a reduction in the foundation slope, construction of some internal berms, stairing some portion of the foundation and constructing some safety berms in the ore heap.

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