Proceedings of Heap Leach Solutions, 2015
September 14-16, 2015, Reno, Nevada, USA
Published by InfoMine, © 2015 InfoMine, ISBN: 978-0-9917905-8-6

Impact of shallow and deep injection well leach solutions with respect to ore heap slope stability

Allan J. Breitenbach, P.E., M.Sc., Principal Geotechnical Engineer, Ausenco, USA
Amanda L. Dolezal, P.E., M.Sc., Project Geotechnical Engineer, Ausenco, USA

Abstract

Barren solution injection wells are a recent technology used in the heap leach processing to extract additional minerals from the ore, particularly in older deeper lifts of ore in mature heap fills. Injection wells are typically installed along linear exterior slope access benches or along the top crest surface, which can contribute to shallow and deep open cracks in the loose ore heap fills from injection well hydraulic loading. These conditions in turn contribute to lower post-peak ore and liner interface strengths, if any slippage does occur along the planar base pad liner surface or at shallower depths within the heap fill itself.

Several large geomembrane lined gold and copper ore heaps in both North and South America have had crack movements or slope failures in recent times, which were directly related to barren solution injection well activity. Ore lifts are placed on the heap in controlled loose lifts and leached at low surface irrigation rates in the range of 5 to 10 liters/hour/square meter (L/hr/m^2), which typically do not result in saturated ore material issues for most heap leach fills. However, shallow or deep injection of process solutions into the pile via injection wells several months to years after initial fully drained leaching of these ore lifts changes the short term and long term geotechnical and hydrological characteristics of the heap fill. As an example, the ore permeability may change at depth and laterally from rapid injection hydraulic loads. This causes both additional vertical settlement as well as lateral hydraulic compression movement in the loose fill by gravity or pump injection pressures. This is evidenced by the downhole buckling deformation that can be observed in the walls of PVC well pipes.

If the induced total weight from the injection well is a significant change in load stress above any deeper saturated loose heap fill zones, then there is a potential risk that static liquefaction may occur. In other words, any significant and rapid hydraulic loading on loose placed and saturated fill zones can cause excess pore pressures to temporarily develop and approach zero fill strengths. If the zones of saturation related to the injection well activities migrate toward the exterior slope of the heap in more pervious

preferential pathways, then heap slope instability may occur either in a static saturation condition or dynamic earthquake related liquefaction condition.

This paper discusses the potential instability of lined copper and gold ore heaps from solution injection well activity. The results of slope stability analyses will be evaluated and presented for several selected case scenarios of solution injection, well-related saturation conditions within an idealized ore heap section. The focus and stability analyses for this paper can also be applicable to solid waste landfills.

Introduction

The wetted heap leaching of copper ore dump piles began as early as the 1600s at the Rio Tinto mine in Spain. The practice of adding acidic water ponds on the top of heap dump surfaces for leaching of low grade run-of-mine (ROM) ore in single or multiple lifts continued into the 1980s, before switching to the current practice of thinner controlled ROM or crushed ore lift placement and leaching under fully drained conditions. This was achieved by using surface sprinklers and/or drip emitters for irrigation at low leach solution application rates. The leach solution application rates can vary with initial higher applied rates to wet conditions and start ore leaching, followed by slower non-saturated rates for best metallurgical ore recovery in the longer leach cycles. Typical non-saturation leach cycle rates range from about 5 L/hr/m^2 for acidic solution irrigation on copper heap fills to 10 L/hr/m^2 for alkaline solution irrigation on gold and silver heap fills. An example of excessive solution application flow causing surface ponding is shown in Figure 1.

Figure 1: Photo of excess sprinkler and drip emitter solution application causing surface ponding

The change from top surface solution ponds and related saturation zones in massive ore heap lift dumps to more efficient placement of thinner ore heap lifts for leaching under fully drained conditions in modern metallurgical leach designs has significantly improved the stability of heap slopes and lowered the risk of slope failures.

However, the recent development of solution injection wells in the last 10 years as a short term saturation technique for the economic releaching of deeper ore lifts in mature heap fills has introduced several geotechnical and hydrological concerns for both short term and long term slope stability. This technical study focuses on the potential impact of solution injection wells on heap slope stability by including examples of past heap slope failures related to saturation conditions, as well as the first known solid waste landfill slope failure due to excessive deep injection well leachate solution pumping into the interior of the landfill. Then an ideal heap study section will be analyzed and evaluated for several selected injection well case scenarios that may impact heap slope stability.

Leach dump and landfill saturation slope failures

Leach dump failures have occurred in the past from ponding water adjacent to the loose dump fill slopes with the most notable leach dump failure occurring at the Metcalf copper mine in Morenci, Arizona in the early 1960s (Witkind, 1961; Breitenbach past correspondence). The Metcalf leach dump was being constructed with ROM low grade copper ore placed by ore trains along the perimeter in high single lift angle-of-repose loose dump slopes. The leach ponds at the top surface apparently caused a massive slope failure from excessive leach wetting that destroyed the ore train and killed several mine workers on the train.

The Codelco Chuquicamata copper mine in Northern Chile is an example of a modern geomembrane lined heap leach pad with an overly wetted heap slope failure occurring in 1998 (Breitenbach, 1998). The first lift of crushed copper ore was placed in the interior by a large conveyor at up to 20 m in loose lift thickness and ROM low grade ore was stockpiled by truck dumping along the perimeter for exterior heap fill containment. The heap fill did not include a base drain fill layer above the geomembrane liner surface that is typical practice in modern heap leach pad designs. Relatively high rate leach application wetting was reported to be started in the interior with several days passing with no observed solution return from the base of the lined pad. Wetting application rates were then increased to "slug" the ore with excess solution, resulting in inadvertent saturation of the crushed ore and the build-up of more than 10 m of vertical hydraulic head against the loose exterior ROM containment piles. This in turn caused about a 100 m perimeter length of ore heap slope failure to occur as a rapid debris-like outflow of heap fill materials with no apparent pad liner damage and no injuries or loss of life. An example of a heap slope failure due to a likely combination of seismic earthquake shaking, piping and ore heap saturation conditions in the exterior slope is shown in Figure 2.

Figure 2: Photo of leach pad slope failure in South America caused by a combination of seismic activity, piping and saturated loose ore heap fill conditions in the downhill exterior slope

A new concept of temporary or short term injection well saturation in lined loose or compacted solid waste landfills and mature controlled loose lift copper and gold heap leach fills at depth started in the 1990s for various purposes. Solid waste landfills are included in this discussion as the first lined fill facility to use injection wells and subsequently were the first to experience a massive slope failure related to well injection activity. The injection of landfill leachate liquid solutions into large municipal landfills was a quick and easy way to dispose of the leachate solution collected at the bottom of the landfills. The injection well liquid wetted and consolidated the organic matter in the landfill materials and accelerated matter decomposition and generation of methane gas as a renewable energy resource. This in turn also created additional landfill storage capacity.

The 1997 Bogota municipal solid waste landfill slope failure in Colombia is an example of excessive injection well pumping rates deep in the interior at a single location causing rapid exterior slope debris flow failure (Blight and Fourie, 2004). The compacted and non-compacted lifts of municipal waste fills are typically about 30 to 40% less dense (Breitenbach and Thiel, 2005) than granular loose heap leach fills to where some lateral and upward heave displacement movements can more easily occur from any excess hydraulic injection well pumping pressures. This may have caused inadvertent hydro-fracturing and development of lateral water paths toward the exterior slope. The 800,000 m^3 mixture of municipal solid waste fill and leachate liquid slide debris flowed for several kilometers downhill into a river with some property damage. The landfill slide failure limits are shown in Figure 3.

Figure 3: Photo of landfill slope failure in South America caused by excessive deep interior injection well pumping activity into light-weight lift compacted solid waste fill materials

Deep injection wells in mature copper and gold heap fills allow releaching of barren solution into the lower heap lifts for economic recovery of any partial or non-leached ore zones. Other metallurgical reasons include increasing the alkalinity level in the deeper gold and silver heap lifts to improve on pregnant solution ore recovery, as the heap is allowed to return to fully drained conditions and water balance conditions over time. Thus, the leach wetting concept for ore heaps changed from top surface controlled sprinkler and drip emitter low flow irrigation wetting of heap ore fills to supplemental surface irrigation and/or internal wetting of high fill piles at various injection well depths toward the end of mature heap operations.

Several lined copper and gold heap leach fills with injection well activity starting in the late 1990s to present day have experienced large interior crack movements or exterior slope failures at mines in the USA and in South America. Detailed information on the exact cause of these heap slope failures are unknown or remain confidential as studies continue. Ore heap materials and leach solutions were reported mostly contained within lined pad limits with no injuries or loss of life.

The lessons learned from these past wetted loose fill slope failures is that the causes of failure may be complex for different fill materials and types of loose lift construction placement on lined or unlined foundation topography grades. However, the primary failure mechanism is excessive wetting or saturation conditions due to top surface ponding, excessive irrigation “slugging” of liquid solutions, or downhole injection wells creating shallow to deep saturation zones developing near the exterior slopes or along steep interior pad grades in the interior.

Modern day injection well activity also introduces the potential for shallow and deep slope instability from more distant wetted zone locations in the interior due to any excessive downhole pore pressures or increased self-weight settlements from rapid hydraulic loading conditions around each well location. Injection well-related surface cracks can extend deep into the loose fills due to "hydro-fracturing" (hydraulic vertical and/or lateral compression pressures in loose or light weight fills), in addition to self-weight differential settlement movements above steep foundation valley wall locations.

Idealized study section

General

Some potential injection fill saturation scenarios will be analyzed for discussion with the use of an idealized study section and simplified modeling assumptions for illustration purposes to show the relative impact of injection well activity on the stability of loose heap fills. The study section will assume a simplified two dimensional wedge failure condition along the pad liner surface for determining static factors of safety (FOS). Seismic earthquake FOS conditions for short and long term saturated heap fills are an additional concern in high seismic regions, but have not been included in this study. A prudent injection well operational practice would be to control the degree and time of saturation for minimizing the impact to heap slope stability and allow the heap to quickly return to fully drained stable heap fill and water balance conditions. The idealized study section assumed geometry and peak shear strength parameters for this study are shown in Figure 4.

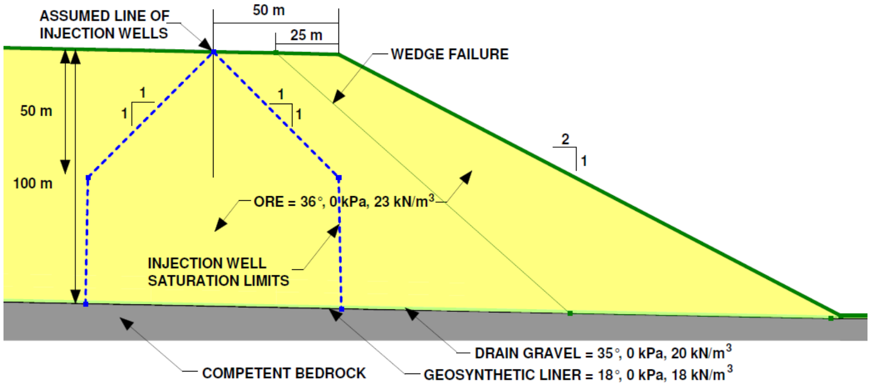

Figure 4: Idealized study section

Section geometry and phreatic surfaces

The idealized study section for this injection well study will assume a simplified 100 m heap height at a 2 horizontal to 1 vertical overall exterior slope (includes benches between angle-of-repose lift slopes), a 2% planar geomembrane liner surface grade to the downhill toe, and overall fully drained loose ore leaching conditions outside of the injection well-related saturation zones with 0.5 m of average depth phreatic water level above the pad liner surface.

The injection well saturation zone limits are assumed to extend from the ground surface at a 1 horizontal to 1 vertical downward hydraulic free water level slope to the 50 m injection well depth for steady-state gravity flow, and then near vertical to the pad drain system, as typical of gravity drainage in a moderate permeability ore placed in level lifts at more than three times the horizontal permeability compared to the vertical permeability. The influence of some surface compaction reduction in vertical permeability as each ore lift is placed by trucks or conveyor traffic, as well as potential hookups at the well head to pressurized pipelines to deliver solution flows to the injection well locations were a consideration in this simplified phreatic model with non-saturated zones not shown extending further away from the saturated zone limits over time.

The foundation is assumed competent and stable beneath the heap fill and liner system to where the assumed wedge analyses failure plane for this study will extend from the top of the heap down to the liner surface as the most critical slide surface for illustration purposes. It is important to note that steeper interior lined pad grades or the location of the injection wells on exterior bench slopes will reduce the FOS.

Section strengths

The study section material strength parameters assume an effective stress (zero excess pore pressure) peak strength condition, which includes 36 degrees friction and no cohesion for the ore heap fill and 18 degrees friction and no cohesion for the geomembrane liner interface contact with the ore fill or foundation surface (Cases 1 to 4). A post-peak shear strength of 26 degrees in the ore fill and 16.5 degrees for the liner contact with no cohesion will be assumed for any shallow or deep heap slide movements for illustrating the effects of any potential loss in peak strength conditions (Case 5).

Stability analyses for Cases 1 to 5

General

The study section case scenarios selected for evaluating the impact of injections wells on slope stability include the following:

- Case 1 scenario evaluates the relative location of the injection well on the top heap surface relative to the edge of the exterior slope under simulated steady-state gravity flow;
- Case 2 scenario evaluates the change in vertical open surface cracks for the Case 1 injection well located at 50 m away from the exterior slope, and with the failure wedge adjusted to initiate at the bottom of the selected open crack depth downward to the relatively flat 2% pad grade;

- Case 3 scenario evaluates Case 2 further for a change in the base pad liner grades from 2% to 4 and 6% in overall steepness with the injection well located 50 m away from the exterior slope and with the selected surface crack extending vertically down to the 20 m depth;
- Case 4 scenario evaluates pressurizing (increasing hydraulic pressures above gravity flow conditions) for the Case 1 injection well located 50 m away from the exterior slope by doubling the lateral extent of the saturation zone limits for illustration purposes; and
- Case 5 scenario evaluates a selected Case 1 injection well located 25 m away from the exterior slope and subjected to post-failure movement in the heap with effective stress peak strength conditions before slide movement (Case 1) reduced down to selected weaker ore post-peak strength conditions (Case 5).

Case 1 scenario

Case 1 assumes the 50 m deep injection well is located at an interior distance of 50 m, 25 m, 20 m, 15 m, 10 m, 5 m and 0 m away from the exterior slope as a saturated homogeneous fill zone, as shown in Figures 5 through 11, respectively. The saturation zone represents a horizontal permeability at least three times greater than the vertical permeability of about 1×10^{-3} cm/sec in steady-state gravity flow through multiple ore lifts. The bottom of the saturation extends to the base drain system that is assumed to be relatively free draining beyond the saturation zone limits. Non-saturated zones are not shown for this analyses and would be increasing in lateral distance over extended injection well and drain down time.

The wedge failure plane selected for study comparison purposes is assumed to be a simplified straight line from the heap top surface down to the pad liner surface. Injection well locations at 25 to 50 m away from the exterior slope with the saturation zone located further in the interior from the selected slide plane have fully drained exterior slope static factors of safety (FOS) = 1.301, as shown in Figures 5 and 6. Note that the slide failure plane for the lowest FOS values can change in location as well as be modified to a near vertical failure plane at the heap top surface which changes to a curved failure surface with depth. The results from varying the injection well distance away from the top edge of the exterior slope for the selected failure plane are shown in Figures 5 to 11 and are summarized in Figure 12.

The Case 1 trials show that as the injection well location and its subsurface saturation zone approaches the edge of the exterior slope, the static FOS values decrease. As the line of injection wells are moved further into the heap interior, the FOS values increase. It can be concluded from these simplified Case 1analyses and assumed conditions that any injection well locations on the exterior bench slopes or any changes to steeper lined pad grades in the interior would show lower FOS values.

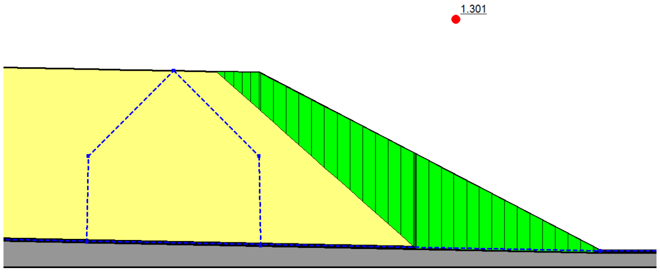

Figure 5: Injection well located 50 m away from exterior slope, FOS = 1.301

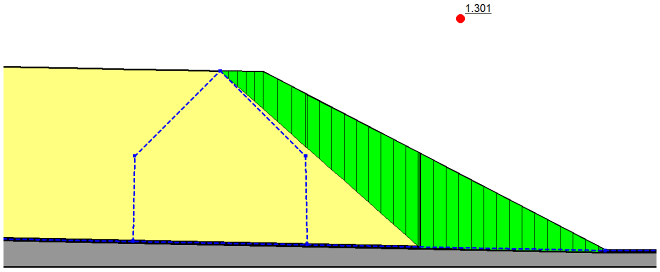

Figure 6: Injection well located 25 m away from exterior slope, FOS = 1.301

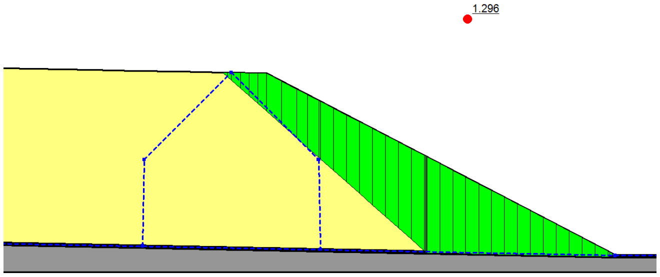

Figure 7: Injection well located 20 m away from exterior slope, FOS = 1.296

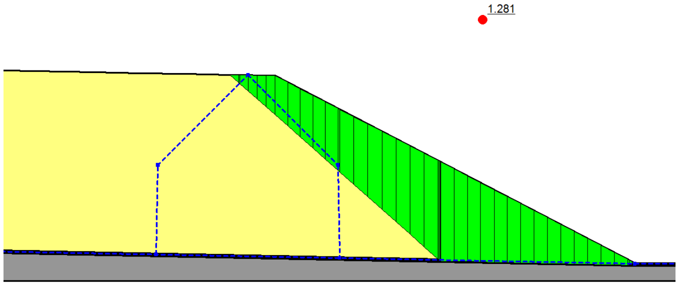

Figure 8: Injection well located 15 m away from exterior slope, FOS = 1.281

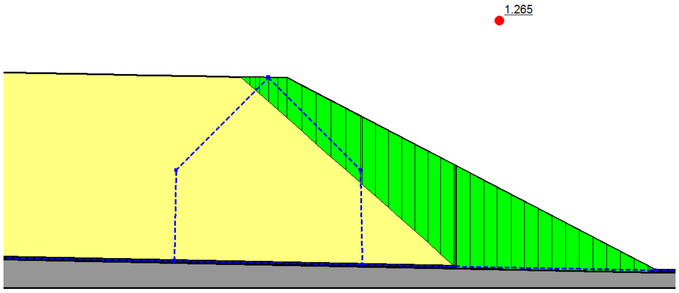

Figure 9: Injection well located 10 m away from exterior slope, FOS = 1.265

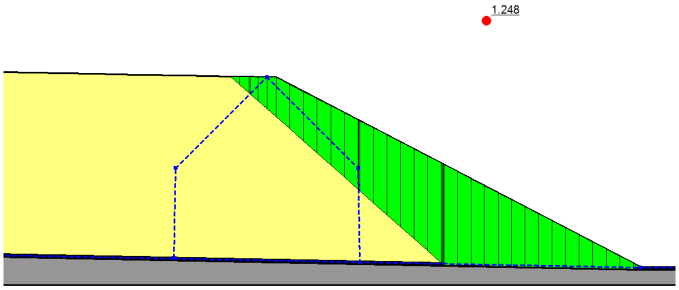

Figure 10: Injection well located 5 m away from exterior slope, FOS = 1.248

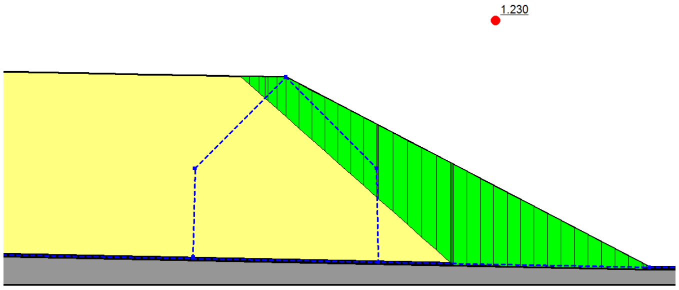

Figure 11: Injection well located at edge of exterior slope, FOS = 1.230

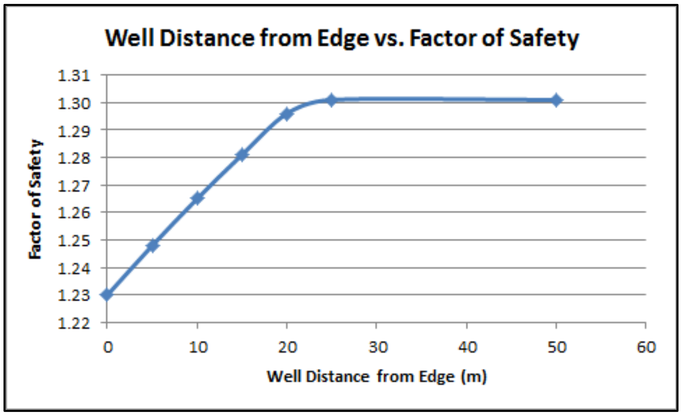

Figure 12: Well distance from edge of exterior slope vs. selected wedge failure FOS

Case 2 scenario

Case 2 assumes a repeat of Case 1 at a well distance of 50 m away from the exterior slope for no gravity flow hydraulic impact to the heap FOS, as shown in Figure 5. An open linear crack is assumed to occur (assuming hydraulic fracturing occurs in loose heap fill along several linear injection well locations) from the surface downward to 5 m, 20 m and 50 m depths below the fill surface with the wedge failure surface adjusted to extend from each crack bottom depth downward to the lined pad grade, as shown in Figures 14 to 16. The results of these analyses are summarized in Figure 17.

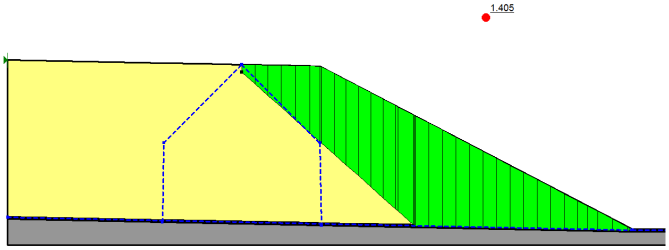

Figure 14: Open crack from surface to 5 m depth at 50 m from exterior slope, FOS = 1.405

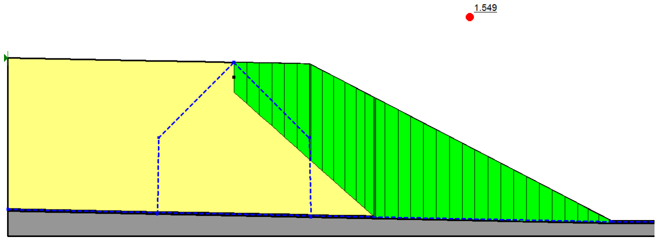

Figure 15: Open crack from surface to 20 m depth at 50 m from exterior slope, FOS = 1.549

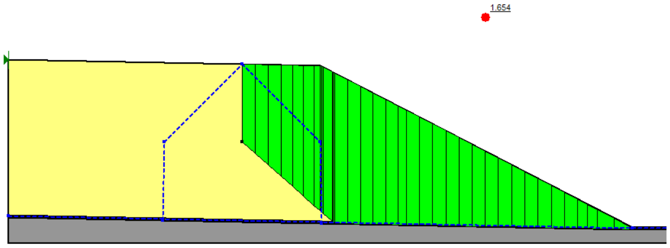

Figure 16: Open crack from surface to 50 m depth at 50 m from exterior slope, FOS= 1.654

The Case 2 trials show that a deep interior crack from gravity flow injection well activity does not impact the heap FOS, as long as the base pad grade remains at the relatively flat 2% grade assumed in the idealized section along with the failure plane extending each time from the bottom of the crack down to the flat pad surface. It can be concluded that any open linear cracks located above steeper interior pad grades or on the exterior slope and subjected to hydraulic well pressures would have lower FOS values.

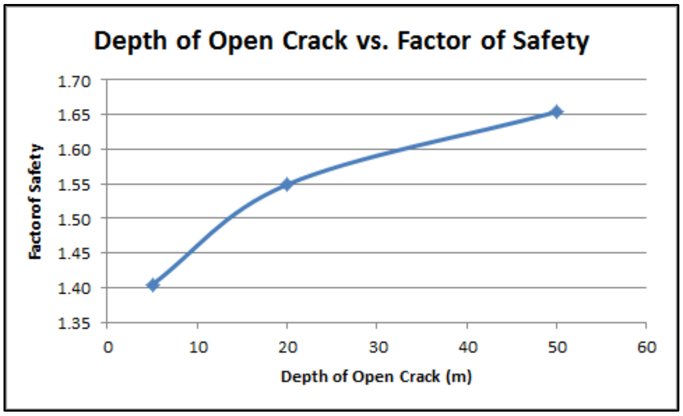

Figure 17: Surface crack depths at 50 m away from exterior slope versus FOS

Case 3 scenario

Case 3 assumes a Case 2 wedge failure 50 m away from the exterior slope and an open crack depth 20 m deep for evaluating the change in FOS for overall steeper pad liner grades beneath the injection well and exterior slope limits. The Case 2 analyses at a 2% pad grade is shown in Figure 15 for a FOS = 1.549. Steepening the overall pad grade from the injection well location to the downhill heap toe limits from 2% to 4 and 6% pad liner grades reduces the FOS from 1.549 to 1.431 and 1.405, respectively, as shown in Figures 15, 18 and 19. A summary of pad liner grade changes versus FOS with the injection well located 50 m away from the exterior slope is shown in Figure 20.

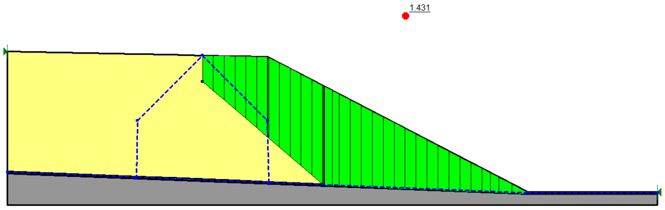

Figure 18: Open crack to 20 m depth at 50 m from exterior slope, 4% pad slope, FOS = 1.431

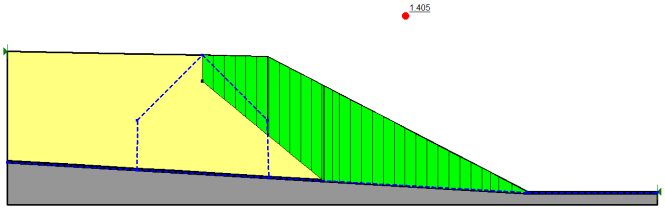

Figure 19: Open crack to 20 m depth at 50 m from exterior slope, 6% pad slope, FOS = 1.405

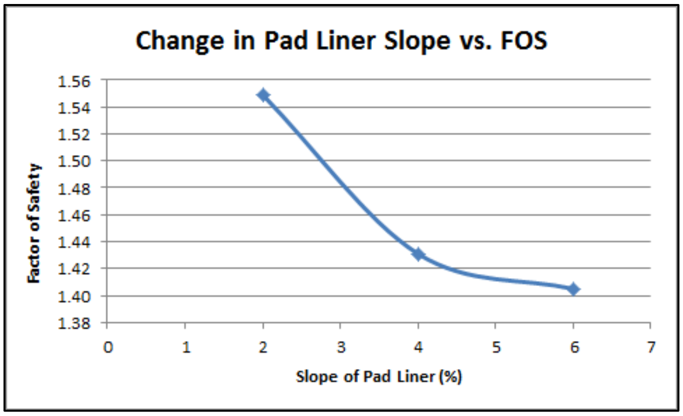

Figure 20: Change in overall pad liner surface grade versus FOS

Case 4 scenario

Case 4 assumes a simplified wedge failure occurring deeper in the interior of the heap at 50 m from the exterior slope, which shows a steady-state gravity flow static FOS = 1.374 on a relatively flat 2% interior pad grade, as shown in Figure 21. However, when injection wells are pressurized from pumping or are connected to higher pressure application pipelines in addition to gravity pressure, the saturation zone will increase in lateral extent over time. This pressurized condition is simulated for illustration purposes in this analyses by doubling the lateral gravity pressure limits to represent a more extreme saturation condition with reduced static FOS = 1.204, as shown in Figure 22. This in turn can impact the static FOS, if the injection well location is moved closer to the exterior slope, and introduces other potential risks of instability related to preferential flow paths towards the exterior slope surface and static liquefaction or temporary loss of fill strength from rapid loading on any deeper saturated ore lifts.

The reason for pressurizing the well pipes on mature ore heaps appears to be related to maximizing the extent of deep lift releaching using the minimum number of injection wells and spacing along slope benches and across the top heap surfaces (continuous saturation impedes metallurgical leaching for less ore recovery). The use of pressurized pipes near or on exterior heap slopes appears to be the biggest hydraulic factor in causing slope failures. A secondary effect of steeper interior lined pad grades is the potential for static liquefaction and differential settlement, which becomes less of a factor for relatively flat pad grades at more distant injection well locations away from exterior slopes. If static liquefaction conditions do occur in the hydraulically reloaded loose ore heap fills, detection of this temporary pore pressure condition or its post-failure verification for analyses is difficult to prove.

Higher injection well pressures above gravity flow conditions can create more rapid hydraulic loading on larger areas of the heap fill, which becomes a problem if the deeper ore lifts have previously become saturated during normal active top surface leaching. Depending on the rapid change in stress to a higher level not experienced in past leaching operations, the end result could be a temporary reduction in lower lift strengths to zero strength, until excess pore pressures can be drained back to fully drained effective stress conditions. Static liquefaction was not considered in these analyses.

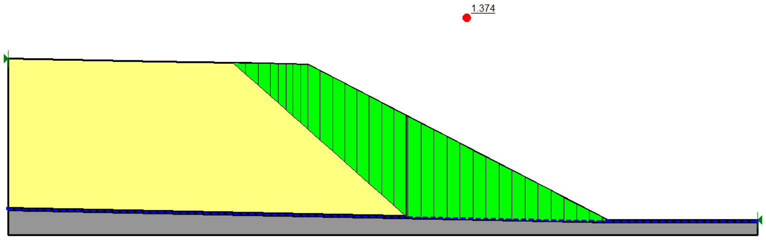

Figure 21: Wedge failure at 50 m from exterior slope with no well injection, FOS = 1.374

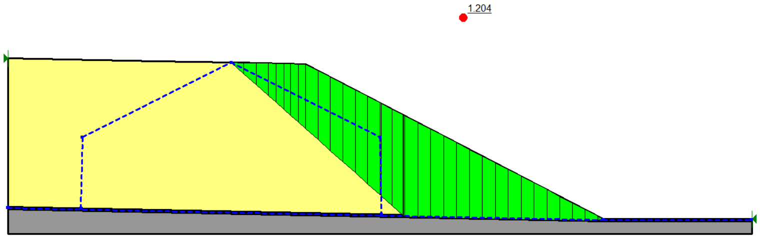

Figure 22: Pressurized well injection at 50 m from exterior slope, FOS = 1.204

Case 5 scenario

Case 5 assumes a repeat of Case 1 at the selected 25 m well distance from the exterior slope, but assumes the peak shear strength of the ore in Case 1 is reduced down to post-peak strengths representing any post-failure slide movements initiated from hydraulic well saturation zones or excess pressures. Past experience in laboratory large-scale direct shear box and triaxial cell testing indicates that slide plane movements in weak ore types remain at low post-peak strength values and do not return back to peak strength values after movement ends.

Assuming a low post-peak strength condition that can be typical for slide movements in saprolitic and volcanic tuff type weak ores of 26 degrees friction (Case 1 at 36 degrees peak strength) and no cohesion with the liner interface strength reduced to 16.5 degrees friction (Case 1 at 18 degrees peak strength) and no cohesion. Case 1 shows a static FOS = 1.301 approaching Case 5 assumed post-failure movement conditions at a static FOS = 1.004, as shown in Figure 23.

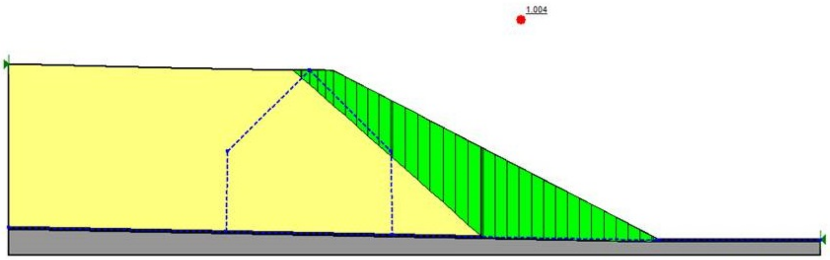

Figure 23: Post-failure lower strength from movement, FOS = 1.004

Conclusion

The recent addition of deep solution injection wells within mature gold, silver and copper ore heaps in the last 10 years has a beneficial economic purpose of releaching deep ore lifts for improved ore recovery. However, this deep injection wetting technique appears to have been the most significant cause for several ore heap slope failures and at least one major solid waste landfill failure in the USA and South America. There are several injection well-related geotechnical and hydrological factors that can impact slope stability, as indicated by the simplified wedge static stability analyses in this technical paper of an idealized ore heap study section subjected to several potential injection well saturation case scenarios. Other significant slope stability factors beyond the focus of these analyses include the effect of seismic earthquake shaking and duration on saturated exterior heap slopes, deep cracks and slide planes related to very steep interior pad grades beneath injection well locations, loss of heap strength in deeper ore lifts due to potential static liquefaction from injection well rapid hydraulic loading conditions, or the potential to apply excessive solution injection pore pressures in loose variable permeability heap fills or relatively light weight solid waste landfills to create unstable exterior slope conditions.

Lessons learned in past heap slope failures indicate there typically are a combination of several geotechnical and hydrologic factors coming together rather than a single isolated factor impacting slope stability (Breitenbach, 1997). The simplified study section and stability analyses in this technical paper selected several injection well case scenarios that could impact heap slope stability and increase the risk of slope failure including the following: 1) the lateral distance and related 3-dimensional linear spacing of injection well locations relative to the exterior slope; 2) the potential for "hydro-fracturing" movements or differential load settlements causing vertical weakened fill cracks in loose or light weight fills; 3) changes in the pad liner grade with open vertical cracks becoming more of a factor in combination with steeper pad liner grades; 4) increasing hydraulic pressures beyond gravity flow conditions by simulated lateral expansion of the saturation zone in a homogeneous fill (preferential flow paths not considered); and 5) potential solution injection slide plane movements that can reduce the fully drained effective stress peak strengths in pre-injection ore materials to lower effective or total stress post-peak ore strengths in subsequent heap operations to closure. Any slide plane movements in ore heap fills are of the greatest concern in saprolite and volcanic tuff ore heap material types due to the potential development of very low post-peak strength conditions that can remain low strength after slide movement has ended.

References

Blight, G.E. and Fourie, A.B. 2004. A review of catastrophic flow failures of deposits of mine waste and municipal refuse, University of Witwatersrand, South Africa.

Breitenbach, A.J. 1997. Overview study of several geomembrane liner failures under high fill loads, Geosynthetics 1997 Conference Proceedings, Long Beach, California, USA.

Breitenbach, A.J. 1998. Heap leach design workshop presentation and discussions with Codelco engineers at Chuquicamata mine site in Northern Chile.

Breitenbach, A.J. and Thiel, R.S. 2005. A tale of two conditions: heap leach pad versus landfill liner strengths, GRI-19 Geosynthetics Conference, Las Vegas, Nevada.

Taylor, J.H. and Whelan, P.F. 1942. Technology and Engineering Proceedings, Metallurgical Society of Canadian Institute of Mining, edited in 2013 by G. Kachaniwsky and C. Newman.

Witkind. 1961. Literature review and Breitenbach past discussions with Phelps Dodge engineers in Arizona.