Technical Note by M.E. Smith and J.P. Giroud

INFLUENCE OF THE DIRECTION OF ORE PLACEMENT ON THE STABILITY OF ORE HEAPS ON GEOMEMBRANE-LINED PADS

ABSTRACT: This technical note deals with the stability of ore heaps placed on a geomembrane liner having a small average gradient, typically 2 to 5%. It is shown that the direction of ore stacking has an influence on ore stability during ore stacking as well as in the long term.

KEYWORDS: Geomembrane, Liner, Heap leach pad, Ore heap, Ore placement, Ore stacking, Stability, Factor of safety, Slide, Shear strength, Mining.

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1 INTRODUCTION

Based on experience, it is believed in the mining industry that ore heaps resting on geomembrane-lined graded pads are more likely to be unstable during stacking if the ore is stacked in the down-gradient direction than in the up-gradient direction. This belief is sometimes questioned because no demonstration is available to the best of the authors' knowledge. This technical note presents a demonstration, which confirms the validity of the belief.

2 HEAP LEACH PAD DESCRIPTION AND OPERATION

A typical heap leach pad is shown in Figure 1. The pad has a gradient to collect the solution that has leached through the ore. In reality, the pad gradient is rarely uniform: it may increase or decrease locally to accommodate the natural ground topography while minimizing earthwork costs. Typically, an overall gradient is specified (e.g. 2%), with a maximum value (e.g. 5%), accepted in localized areas. In addition, the gradient must be positive to ensure proper collection of the solution (i.e. the minimum gradient must be zero). The requirement for a positive gradient is well understood and every effort is generally made in the field to avoid negative gradients (that would result in ponding of the solution). In contrast, the requirement for a maximum slope is not always understood, and, as a result, pads are sometimes constructed with a gradient which, at some locations, is significantly greater than the specified maximum gradient (e.g. the pad gradient may, locally, be 10%). It will be shown in this technical note that high pad gradients may have a detrimental impact on slope stability, especially when associated with stacking of the ore in the down-gradient direction.

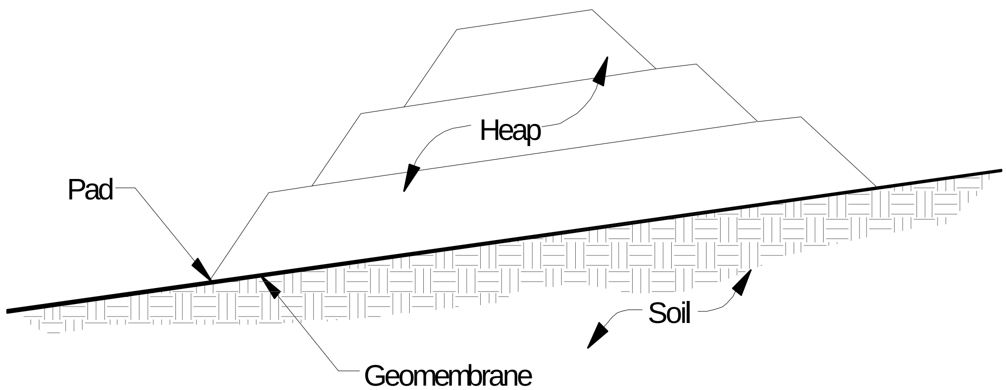

Figure 1. Schematic cross section of a typical ore heap leach pad.
Note: Pad gradient and ore slopes are exaggerated.

The geomembrane used to line the pad has interface shear strengths with the overlying material (ore or geotextile) and the underlying material (soil or geotextile) that are smaller than the internal shear strength of the ore. As a result, potential slip surfaces for an ore slide run through the ore then along the upper or the lower face of the geomembrane.

The ore is stacked in a very loose state, with particular attention paid to avoiding any undue compactive effort to keep the ore as permeable as possible. Therefore, even when it contains fines, ore is generally cohesionless or possessing a relatively low cohesion. As a result, if the ore is dumped or pushed, it will form a slope with the angle of repose, e.g. 35º, i.e. 1 vertical:1.4 horizontal (1V:1.4H). Indeed, in heap leach pads, each lift of ore is typically stacked at the angle of repose. Stacking of the ore can proceed in the down-gradient direction (Figure 2a), in the up-gradient direction (Figure 2b), or in a direction parallel with the pad contours (not shown in the figures).

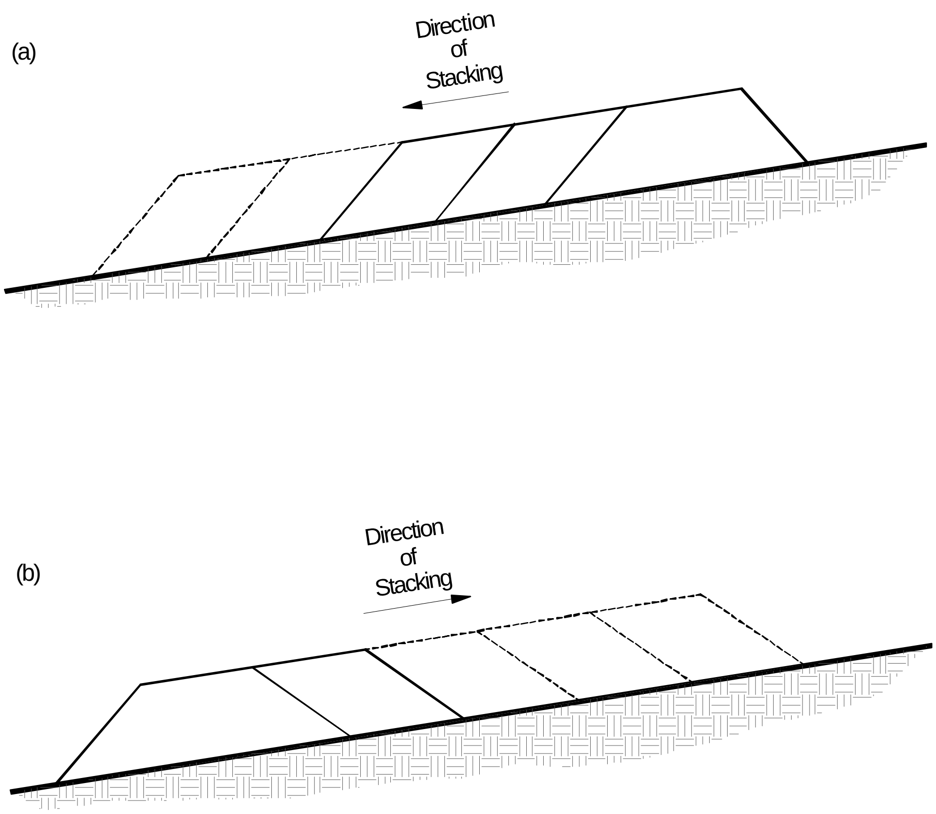

Figure 2. Stacking of ore: (a) down-gradient stacking; (b) up-gradient stacking.
Note: Pad gradient and ore slopes are exaggerated.

A heap is generally constructed in successive lifts, and each lift is irrigated with a leaching solution (typically alkalies for precious metals and acids for base metals) before the subsequent lift is placed. Typical lift heights are 4 to 10 m. At each lift, a bench reduces the average overall slope. Further, as the loose ore is leached, there is a degree of hydraulic compaction, and the additional weight of the subsequent lift further compacts the lower lift(s); the resulting increased density often increases the shear strength of the ore in the lower lift(s). Finally, the importance of equipment loading relative to ore heap weight is greater on the first lift than at subsequent stages when the heap comprises several lifts. Therefore, for the above reasons (decreased average slope, increased shear strength, and lesser relative importance of equipment loading) a heap comprising several lifts with benches is often more stable than the first lift. This statement is valid only: (i) if the cohesion of the ore is zero or small; (ii) for ores that become more dense after initial placement;, (iii) for failure surfaces not limited within the top lift if there is more than one lift;

and (iv) for failure surfaces not involving the foundation of the pad (i.e. for failure surfaces entirely within the heap and the pad). These, in fact, are the most common conditions. In particular, the last two conditions are met if the failure surface is located along the geomembrane, which is likely due to the low interface shear strength associated with the geomembrane.

3 BASIC STABILITY CONSIDERATIONS

First an ideal geomembrane-lined pad with a uniform gradient *i* is considered. If an ore heap with identical slopes on the up-gradient and down-gradient sides (hereafter referred to as the up-gradient slope and down-gradient slope, respectively) is constructed on this pad, the factor of safety of the down-gradient slope is smaller than the factor of safety of the up-gradient slope (Figure 3a), i.e.:

$$FS_d < FS_u \tag{1}$$

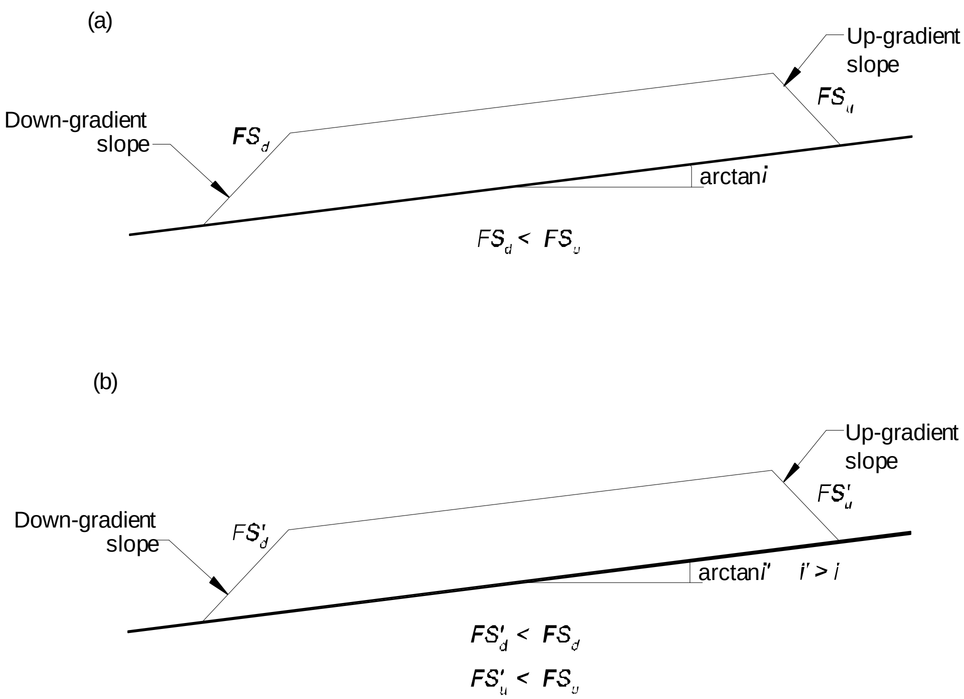

Figure 3. Influence of pad gradient on factor of safety: (a) pad with uniform gradient *i*; (b) pad with uniform gradient *i*.

Note: The four ore slopes are equal.

where: FS_d = factor of safety of the down-gradient slope when the pad gradient is i; and FS_u = factor of safety of the up-gradient slope when the pad gradient is i. Equation 1 is an obvious relationship that can easily be verified by elementary slope stability calculations for the case where the slip surface runs along the geomembrane, in accordance with a statement made in Section 2.

If the same ore heap with the same slopes were constructed on a pad lined with the same geomembrane and having a greater gradient ($i¢ > i$), the following relationships would exist between the factors of safety (Figure 3b):

$$FS¢_d < FS_d \tag{2}$$

$$FS¢_u > FS_u \tag{3}$$

where: $FS¢_d$ = factor of safety of the down-gradient slope when the pad gradient is $i¢$; and $FS¢_u$ = factor of safety of the up-gradient slope when the pad gradient is $i¢$. Equations 2 and 3 are obvious relationships that can easily be verified by elementary slope stability calculations for the case where the slip surface runs along the geomembrane, in accordance with a statement made in Section 2.

According to Equations 2 and 3, increasing the pad gradient decreases the stability of a down-gradient slope and increases the stability of an up-gradient slope. Equations 1 to 3 constitute the basis for the demonstration presented in Section 4.

As a practical matter, many heaps are designed with average overall up-gradient slopes steeper than average overall down-gradient slopes (by using narrower benches on the up-gradient slopes) such that the resulting design factors of safety are approximately equal for the up-gradient and down-gradient slopes.

4 STABILITY DURING STACKING

A geomembrane-lined pad with a gradient that varies locally is considered. The gradient is everywhere equal to or greater than a minimum value (such as zero, as indicated in Section 2). It is assumed that there are "critical zones" in the pad that are sufficiently large and where the gradient is sufficiently high that the factor of safety of a down-gradient slope constructed in such a zone would be less than 1.0. In other words, a down-gradient slope in a "critical zone" would slide. It is assumed that, to have an impact on ore stability, a critical zone should have an extent greater than or equal to the height of the first lift of ore. (The same concept applies to the total heap height, but the analysis is somewhat different and is beyond the scope of this paper.)

If stacking is done in the down-gradient direction (Figure 4a), an ore slide will occur when the ore being stacked reaches a critical zone. In contrast, if stacking is done in the up-gradient direction (Figure 4b), the stability of the ore slope will in fact increase (based on Equation 3) upon reaching a critical zone. An ore slide will occur in the case of up-gradient stacking only if a critical zone is located at the down-gradient edge of the pad (Figure 4c), in which case an ore slide would occur in the down-gradient direction.

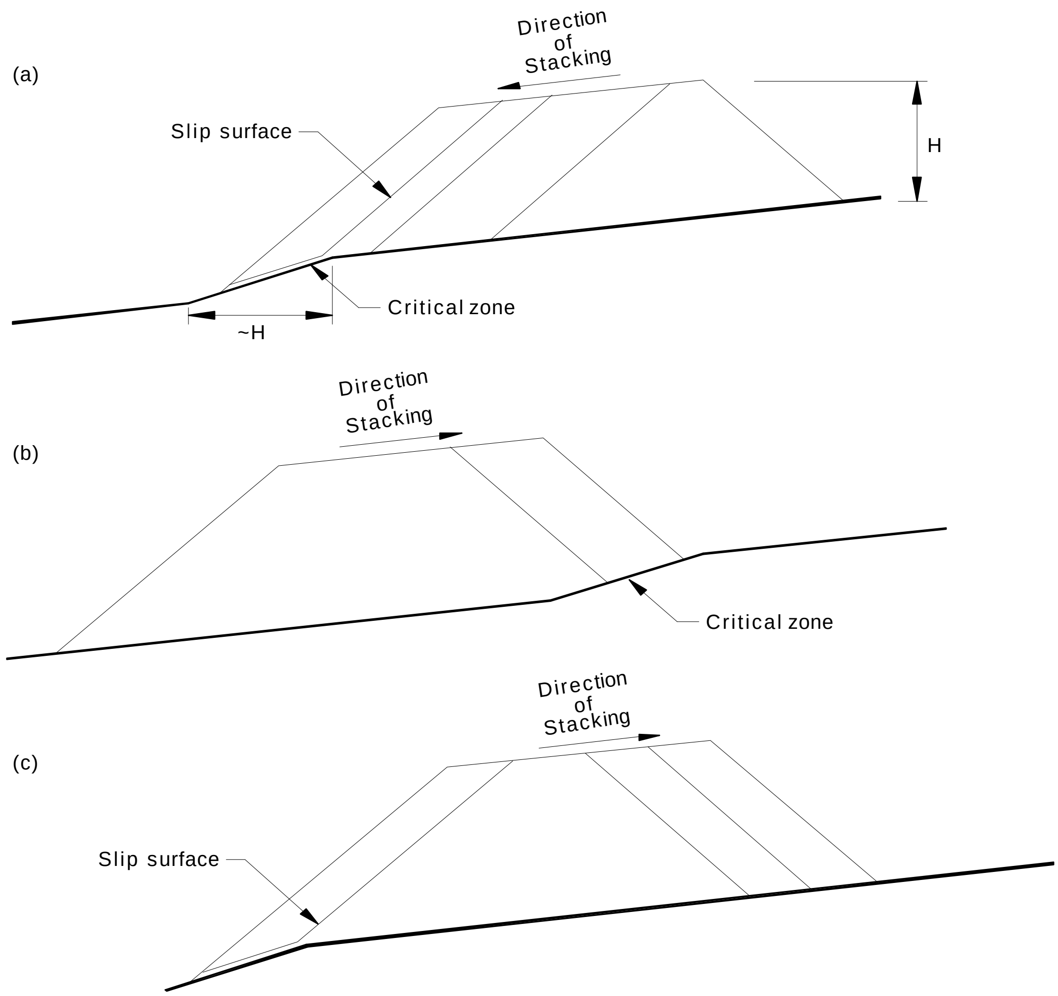

Figure 4. Influence of localized high pad gradient on ore stability during construction: (a) down-gradient stacking; (b) up-gradient stacking; (c) up-gradient stacking with a critical zone at the down-gradient edge of the pad.

Note: The bold solid line represents the geomembrane liner. The solid lines represent successive stages of stacking. The dashed line represents the slip surface.

Ignoring factors other than pad gradient, the probability for a slide to occur is equal to the probability for a critical zone to exist (which is only dependent on pad topography and, therefore, independent of the direction of stacking) multiplied by the probability for such a zone to be located in an area where it impacts stability; the latter is 1.0 in the case of stacking in the down-gradient direction and H/L in the case of stacking in the up-gradient direction, if it is assumed that the distance from the edge of the pad where a critical zone may cause a slide in the down-gradient direction is approximately equal to the height, H, of the ore lift (L being the distance between the down-gradient and up-gradient edges of the pad if the pad slopes in a single direction, or the distance between the edge of the pad under consideration and the top of the pad if the pad slopes in two directions). Therefore, the probability for a slide to occur is L/H times greater if stacking is done in the down-gradient direction than if stacking is done in the up-gradient direction. Clearly there is a far greater risk of ore sliding during stacking if stacking is done in the down-gradient direction.

It results from the above that, if the pad gradient is specified not to exceed a certain critical gradient (divided by a safety factor), no ore slide can theoretically occur when stacking is done in the up-gradient direction. It is very easy and not costly to take this measure that theoretically eliminates the risk of ore instability.

It should, however, be noted that parameters other than the stacking direction (down-gradient or up-gradient) have an influence on ore stability such as ore characteristics and water content which may vary significantly from one point to another and from time to time ; such variations may decrease the gradient required for a zone to become "critical". As there are always uncertainties in such parameters, it is not possible to totally "eliminate" the risk of failure in the case of the up-gradient stacking, but at least this risk can be greatly minimized.

The model considered above is essentially two-dimensional (i.e. only cross sections are considered). As a result, only two directions are involved in the demonstrations, the down-gradient direction and the up-gradient direction. In reality, heap leach pads are three-dimensional and all directions may have an impact on ore slope stability. However, the above discussions show that the only relevant characteristic of a given stacking direction regarding ore stability is whether it is down-gradient or up-gradient. Therefore, the conclusions derived from the above discussions are applicable to actual three-dimensional situations.

In the above discussions, the driving forces likely to cause ore instability were never mentioned. Typical driving forces are the self weight of the ore and the load (including vertical and horizontal components) applied by the stacking equipment. The equipment load often plays an important role because very large equipment is often used over a relatively thin lift of ore. It is important to note that the conclusions drawn from the above discussions are applicable regardless of the type of driving force.

5 LONG-TERM STABILITY

The above discussions clearly show that stability during stacking is affected by the stacking direction. It is also possible that the stacking direction (down-gradient or up-gradient) affects the long-term stability of the ore heap, although this hypothesis is not supported by clear field evidence or experience in the mining industry.

The hypothesis that the stacking direction affects long-term ore heap stability is based on the following considerations:

? An ore heap that is completed or at an advanced stage of stacking contains many internal planes sloping at the angle of repose of the ore (Figures 5 and 6). These internal planes are the temporary ore slopes at each construction phase.

Figure 5. Lateral view of an ore lift showing parallel planes sloping at the angle of repose.

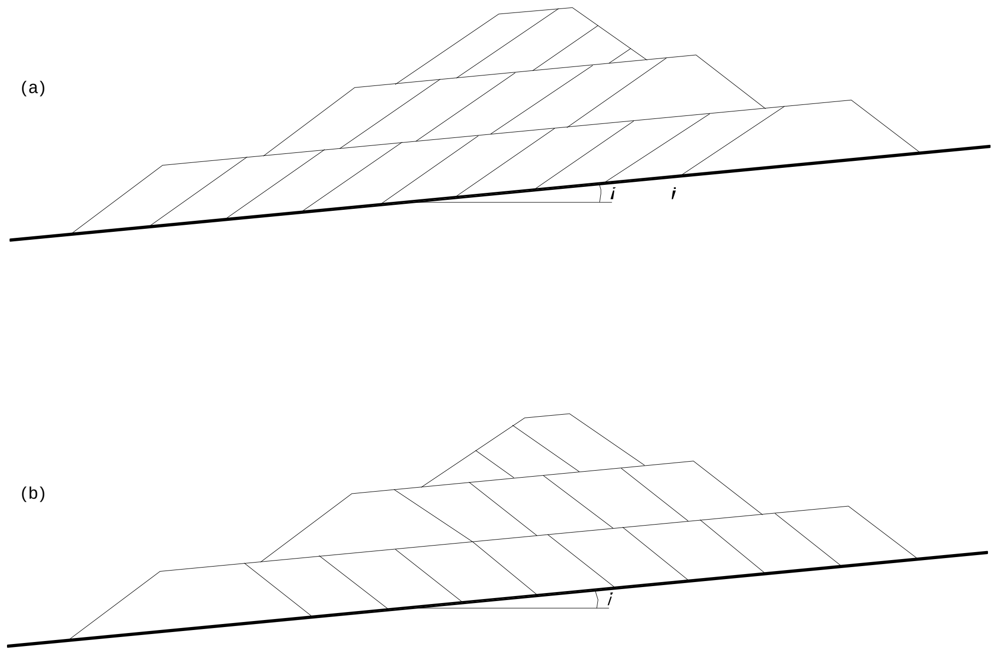

Figure 6. Internal planes in an ore heap: (a) heap stacked in the down-gradient direction; (b) heap stacked in the up-gradient direction.

? It is possible, but not certain, that the ore shear strength along these internal planes is less than along any other surface through the ore. This could be due to less interlocking between ore particles along these planes than within the ore mass. Another factor could be the concentration of finer particles along these planes, as the larger stones tend to roll to the base of the heap (Figure 7). While there is no documented direct evidence that segregation creates weak planes, it is well recognized in the mining industry that this segregation leads to non-uniform flow of solutions within the heap and, in extreme cases, creates zones of instability due to perched water and erosion of the side slopes.

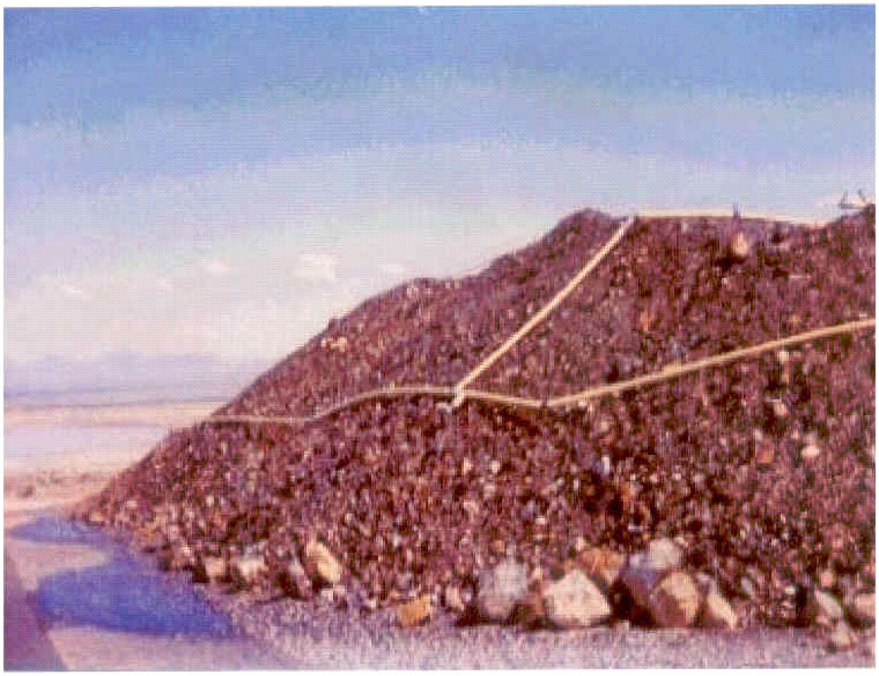

Figure 7. Ore segregation.

? Since ore heap instability is more likely to take place in the down-gradient than in the up-gradient direction, as discussed in Section 3, low shear-strength internal planes will be more likely to cause instability if they are sloping in the down-gradient direction than in the up-gradient direction.

? In an ore heap stacked in the down-gradient direction, the internal planes are all sloping in the down-gradient direction (Figure 6a), whereas in an ore heap stacked in the up-gradient direction the internal planes are all sloping in the up-gradient direction (Figure 6b).

? Based on the above rationale, ore heaps stacked in the down-gradient direction are more likely to be unstable in the long term than ore heaps stacked in the up-gradient direction. However, it should be noted that the above rationale is based on the assumption that low shear strength internal planes result from stacking phases, an assumption that has not been evaluated experimentally.

There is another mechanism through which the stacking direction may impact the long-term stability of the ore heap. Localized failures that occur during stacking, if they are not serious enough to require liner repair, may result in displacements that are such that only post-peak (even only residual) shear strength remains available for future potential slides along the same slip surface. Since localized failures during stacking and failure of the complete ore heap at a later stage are likely to have portions of slip surface in common along the geomembrane liner, the factor of safety for long-term stability of the ore heap is decreased if local failure occurs during stacking. Since the probability of localized failures during stacking is greater with down-gradient stacking than with up-gradient stacking, it results that the probability for decreasing the factor of safety for long-term stability of the ore heap (through the post-peak shear strength mechanism) is greater in the case of down-gradient stacking than in the case of up-gradient stacking.

6 CONCLUSION

It has been demonstrated that, when the pad gradient is not rigorously uniform (which is generally the case), the probability of an ore slide during stacking of ore on a leach pad is much greater if the ore is stacked in the down-gradient direction than in the up-gradient direction. This is consistent with experience in the mining industry. It has also been shown, that, with simple precautions, it is possible to minimize (perhaps eliminate) the risk of ore slide during construction in the case of stacking in the up-gradient direction.

It has also been shown that there is a possibility that an ore heap may be more likely to exhibit long-term instability if it has been stacked in the down-gradient direction than if it has been stacked in the up-gradient direction. However, this possibility has not been evaluated experimentally. Also, it should be noted that, in a number of cases, ore instability is less likely to occur in the long term than during stacking of the first lift for several reasons discussed in this technical note.

Furthermore, it should be noted that in some cases ore heap instability is more likely to occur during ore placement than in the long term because the first lift of ore has a steeper slope than the average overall slope including benches between lifts.

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