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Geomembrane and pipe design issues in deeper heap leach pads

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Abstract

The design of heap leach pads over 150 m thick in large mining projects has occurred often in the last decade due to economic issues, restrictive topographic conditions, lack of space on the property or mine concession boundaries, reduction of closure and remediation costs, and reduction of the availability of agricultural land. In general, the objective has been to reduce the impact of mining activity by designing deeper ore heaps over smaller areas, which requires rigorous design and proper selection of geosynthetic components.

This paper presents the experience of designing deeper heap leach pads, mainly valley fill facilities, in which solutions to the issues related to the high loads affecting the behavior of the geomembrane and solution collection pipes have been successfully implemented in the design and construction of the facilities. Also, a revision of historical high-load pipe deflection tests and numerical modeling is presented. In addition, recommendations for implementation and execution of high-load laboratory puncture tests, the need for high-load large-scale deflection tests in large pipes, and the selection criteria and calibration of numerical models for pipe deflection analysis are presented in order to simulate real and critical field conditions. This may lead to future, more detailed studies.

Introduction

Thiel and Smith (2004) note that when heap leaching first became popular for gold recovery in the 1980s, typical maximum ore depths were around 15 m. By 1990 that limit had been pushed to 50 m by the copper industry. Now most heap leach designs have ultimate target depths of at least 60 m, and several have target depths of over 100 m. At least two are in operation with ultimate depths of 180 m.

Figure 1 shows a valley heap leach pad projected to a 180 m depth in the Peruvian Andes. If conventional heap leach pad design were to be applied to this case, then a very thick geomembrane and very rigid and reinforced collection pipes would have to be selected, increasing the cost of the project.

Therefore, solutions specifically developed for the design of deeper heap leach pads are needed (and presented in this paper) to reduce the overall cost of the project and to obtain a proper performance of the entire facility.

Deeper heaps require rigorous engineering design and proper selection of the geosynthetic components, such as geomembrane and pipes. The geomembrane liner design must consider the potential for punctures produced by the higher heap loads in the contact between the overliner or the ore with the geomembrane liner; sometimes a reinforcement element such as a geotextile is needed instead of increasing the geomembrane thickness, thus decreasing material costs. On the other hand, this reinforcement implies the reduction of the geomembrane/overliner or geomembrane/ore interface shear strength, which increases the risk of heap geotechnical instability and must be considered as part of the geotechnical analysis and design. Also, there is not much experience and few testing results that evaluate the behavior of the collection solution pipes when subjected to higher heap loads. However, in practice additional pipe confinement (by placing them in trenches backfilled with compacted drainage gravel) is required to reduce the risk of pipe large deflections, buckling, and collapse. Geomembrane protection through the use of geotextile inside the trench is also required.

Figure 1: Very deep heap leach pad in the Peruvian Andes

Geomembrane liner

In a heap leach pad, the geomembrane liner is subjected to puncture caused by: 1) the loads of the equipment hauling and spreading the overliner or the ore over the geomembrane liner; and 2) the loads of the ore weight continuously stacked as part of the heap leach pad operation—which is more critical in deeper heap leach pads. For the first case, two conditions can occur:

- When the ore stacked is run-of-mine (ROM) or crushed to a size (usually greater than 38 mm or 1.5 inches) that can damage the geomembrane because of the impact during ore dumping, or when mechanized systems for ore hauling and dumping are used, usually a protection material called overliner or cover is used, which is typically of 38 mm maximum size. The overliner thickness depends of the particle's angularity. It is typically greater than 500 mm (final thickness) and is spread using a D6 dozer (or smaller).

- When the ore size is less than 38 mm, the overliner is not required and the geomembrane puncture is controlled by the ore lift thickness (usually greater than 4 m) which is placed by the hauling equipment (trucks). However, if the ore permeability is relatively low, then an overliner layer helps reduce potentially high piezometric heads on the geomembrane liner.

Geomembrane integrity test (puncture test)

For the second case mentioned above, the effect of the heap ore weight on the liner system is assessed through integrity geomembrane or puncture laboratory tests in which a geomembrane sample, the type and thickness of which have been previously selected for a particular application, is placed over a subgrade material (typically low permeability soil or soil liner) installed inside a device test (square or cylindrical). Then overliner or heap ore is placed over the geomembrane. The package soil liner-geomembrane-overliner (or ore) is gradually loaded up to reach a pressure equivalent to the height of the heap. The authors have routinely performed this test up to 4,400 kPa (about a 250 m heap). The maximum load is held for 48 hours and then the geomembrane sample is removed and evaluated by subjective inspection to determine if minor, moderate, or severeyielding has occurred. Also, a vacuum box is used to physically determine if a hole has occurred. In Figure 2, two types of equipment used to perform puncture tests are presented.

Figure 2: Equipment for puncture testing. (Left) Square box and (Right) Cylindrical box

Puncture severity

Usually in a heap leach pad, the angular soil liner particles are eliminated by hand after a visual inspection, and the surface is repaired with clayey soil. Therefore, a geomembrane puncture is usually caused by the angular particles of the overliner or the ore, both of which are commonly crushed to reduce maximum size.

It is very important to note that the liner damage must not only be assessed to determine the presence of holes (i.e., to check whether the overliner or ore particles have perforated the geomembrane); the puncture severity must also be assessed (to verify if the yield zones on the geomembrane sample have compromised its integrity, which would significantly reduce its thickness, and therefore, its mechanical properties). In Figure 3, two cases demonstrating the difference in puncture severity after integrity tests are presented. In the first case, the geomembrane was subjected to a load equivalent to 100 to 110 m of heap. As is apparent, the sample does not present damage by puncture; instead, only a few minor yield zones are evident. In the second case, the applied load was equivalent to 250 m of heap and one can observe severe punctures with several yield zones, as well as geomembrane perforations.

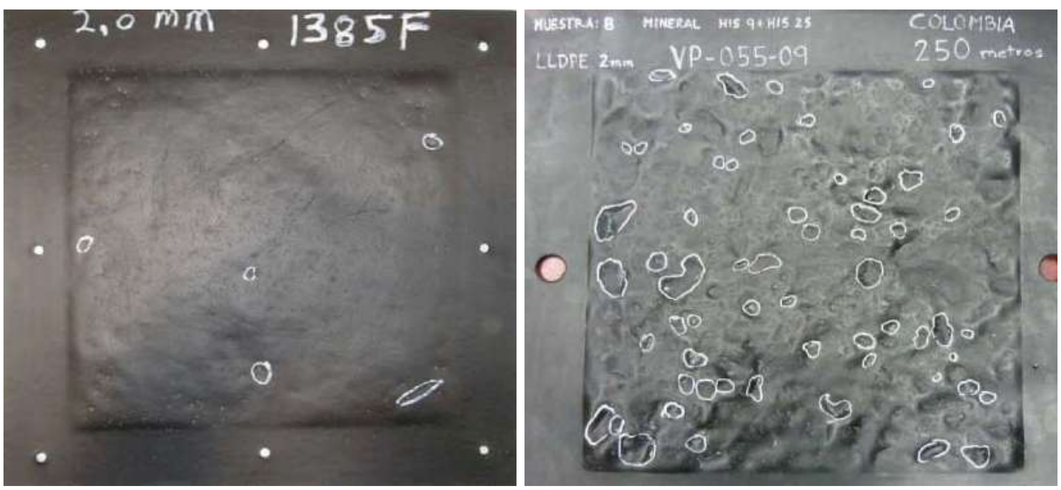


Figure 3: Samples after puncture testing. (Left) No damage. (Right) Severe punctures

The effect of the punctures is particularly important in deeper heap leach pads where the ore load can be higher than 2,200 kPa (as in a heap deeper than 120 m). The experience indicates that even if no perforations are observed for very high loads, in most of the cases tested for vertical stresses higher than 2,200 kPa severe yield zones have been observed, which compromise the geomembrane integrity.

Geomembrane thickness selection and protection

The current practice of heap leach pad design recommends the use of low linear density polyethylene (LLDPE) single side textured (SST) geomembrane, instead of the formerly common high density polyethylene (HDPE). The LLDPE exhibits higher flexibility and elongation which not only allows better contact with the soil liner (thus improving the interface shear strength), but also exhibits better puncture resistance. Though the geomembrane thickness must be based on puncture tests, César et al. (2013) presented a practical rule for this thickness based on the design and construction experience of dozens of these kinds of facilities: 1.5 mm for heaps up to 100 m and 2 mm for higher heaps.

However, when the design deals with very deep heap leach pads, severe punctures are expected and holes are possible even in a 2 mm LLDPE geomembrane. In this case, there are two options available to the design engineer to improve geomembrane behavior:

- Increase the geomembrane thickness to 2.5 mm, or
- Use a geotextile to protect the geomembrane.

In both cases, the area to improve will be that in which damage (severe puncture or holes) is expected to occur. The first option is a little complicated to carry out because the installation has to deal with two different geomembrane thicknesses. On the other hand, the second option is preferred because geotextile is easy to install and much cheaper than a thicker geomembrane. Puncture laboratory tests using a geotextile over the geomembrane liner have shown that the yielding decreases, which indicates that this design achieves its role as geomembrane protection element. Based on this experience, the authors recommend the following:

- Use a 270 gr/m^2 non-woven geotextile or heavier if the heap is very deep.
- The geomembrane protection must be performed in those zones where the heap is deeper than 120 m or 130 m. However, this value must be verified with puncture testing.

In Figure 4, an example of a 160 m deep heap leach pad is shown, as is the area in the pad base (blue hatching zone) where the 2 mm LLDPE SST geomembrane requires protection using a 270 gr/m^2 non-woven geotextile. Figure 5 shows the geotextile already placed and partially covered with the overliner and the ore of the heap.

Geomembrane-geotextile interface

It is also important to consider that the use of a geotextile will generate a new interface between the geomembrane and the geotextile, all the more so because the smooth side of the geomembrane is placed in direct contact with the geotextile. The shear strength of this interface is lower than the geomembrane-soil liner interface; therefore the geotextile must be placed in just those areas of the leach pad where the stability is not compromised. Though the areas subjected to high loads are located in specific zones in the leach pad base (which are relatively far from the critical failure surface influence zone of the limit equilibrium analysis), it is always necessary to determine the geomembrane-geotextile interface shear strength as well as the global heap leach pad stability.

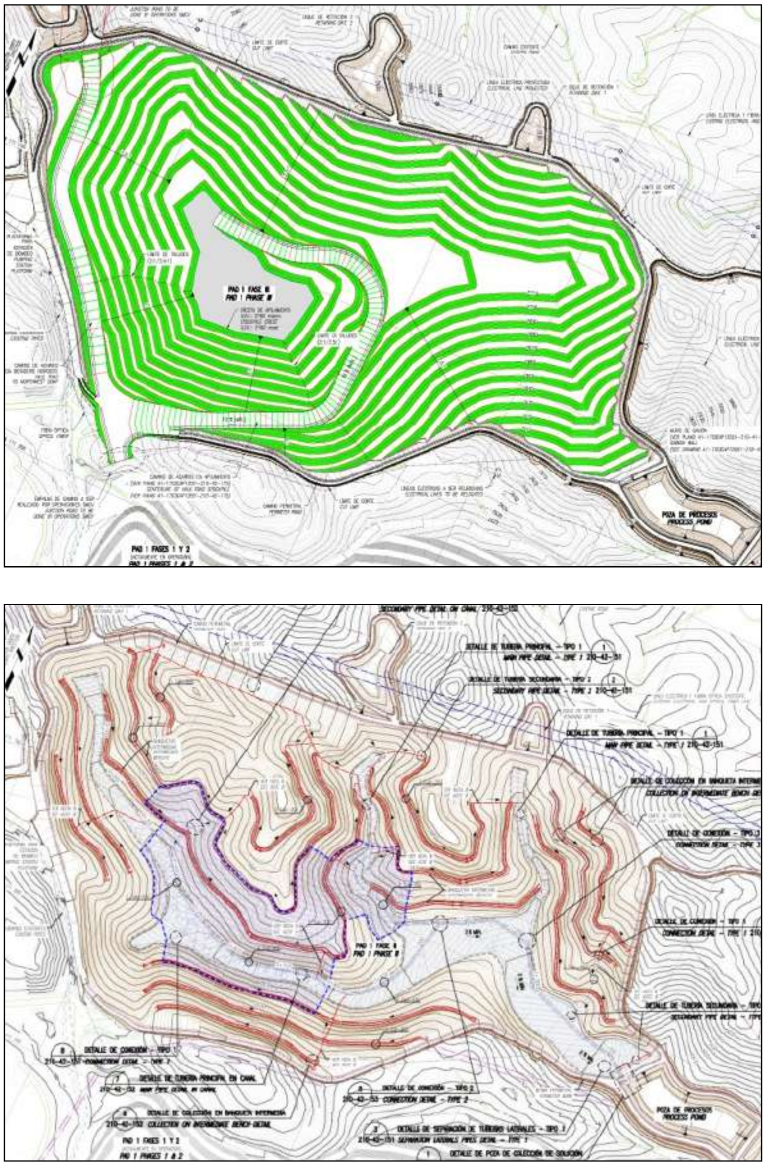


Figure 4: Very deep heap leach pad and area where the geomembrane requires protection

Figure 5: Non-woven geotextile placed for geomembrane protection

Solution collection pipes

Robust drainage systems to collect leach solution are required in order to improve mineral recovery, reduce leaks through the liner system, improve slope stability, and reduce liquefaction potential. ROM or crushed ore heap leach pads are irrigated with solvent solution (dilute alkaline cyanide for precious metals and dilute sulfuric acid for base metals such as nickel and uranium). This solution, along with any storm water, snow melt, and cumulative season surplus water is collected at the base of the leach pad through the solution collection system which typically consists of dual wall HDPE perforated pipes (smooth inner pipes and corrugated exterior pipes). The pipe diameter depends on the catchment area, irrigation rate, and the pipe slope. Bigger diameters correspond to the main headers or primary collection pipes. Diameters up to 600 mm have been used in the industry, but in general the design of the main collection system uses pipes up to 450 mm because bigger pipes will show more deflection, buckling, and potential collapse. On the other hand, laterals or secondary pipes are smaller. These are usually 100 mm, though in on/off leach pads, 50 mm pipes are used.

The behavior of the collection pipes and their durability when subjected to the loads of the heap depends mainly of the rigidity not only of the pipe but, more importantly, the surrounding soil. With respect to the pipe, the bigger the diameter the lower its rigidity. For that reason, large diameter pipes are not recommended because of the risk associated with large deflections, buckling, joint separation, and collapse. It is preferable to increase the number of the pipes instead of their diameter. The problems mentioned above would generate a decrease in the pipe flow capacity and the sufficiency of the collector system for evacuating the leach solution. Though part of the flow would be captured by the drainage gravel surrounding the pipe, there is a risk of an increase in the solution level inside the heap leach pad, which would generate a potential static instability, saturated ore liquefaction, and seismic instability. The last condition is not very common but is possible (Castillo et al., 2005).

High-load pipe deflection testing

Based on actual high-load deflection tests performed at the Vector Engineering Laboratory on loads up to 2,000 kPa (about 100 to 120 m of simulated heap depth), Smith (2004) concluded that up to approximately 30% vertical deformation (+/−5% depending on the pipe weight and structural design), the pipe would show dimpling from the adjacent gravel, but no noticeable buckling. Above this level the pipe would begin to exhibit buckling and approach a binocular shape. Tests were conducted on approximately 30 combinations of soil and pipe (dual wall HDPE) using nominal pipe diameters of 100 mm, 150 mm, and 180 mm. Figure 6 shows the pipe deflection test apparatus and the pipe interior after loading.

Figure 6: (Left) Pipe deflection test apparatus. (Right) Pipe after 2,000 kPa loading

Similar results were reported by Smith et al. (2005) on tests of 152 mm dual wall HPDE pipe. When deflections up to 25% were obtained for a maximum load of 1,900 kPa, the pipes retained structural integrity and no buckling was observed. However, other testing found that buckling of the pipe occurs with vertical deformations between 25% and 35% of original inside diameter.

In both cases cited above, buckling results in significant loss in flow area (as much as 50%) and loss of structural integrity, which compromises the pipe's ability to withstand subsequent load increases and the integrity of the joints. Also, Smith et al. (2005) remark that the soil properties must be well known and a numerical model should be selected and calibrated to actual laboratory data in order to predict deflections of various other combinations of overliner materials, overburden pressures (heap depths), and (mainly) pipe diameters, because it is hard to perform tests on large diameter pipes.

Pipe protection

Currently, lateral pipe design practice uses 100 mm dual wall HDPE of 485 kPa with a minimum stiffness at 5% deflection that weighs at least 850 grams per meter length. Also, the test results presented by Smith (2004) show that the 100 mm pipe exhibits a deflection of about 15%, that is, less deflection compared to the larger (as expected). Though the high-load deflection tests cited above were for cases where the pipe was placed directly on the geomembrane and additional test data is needed for a final conclusion, good performance is expected for the 100 mm pipe as the lateral collector for deeper heap leach pads. Therefore, the authors strongly recommend against using pipes larger than 100 mm for laterals in deeper heap leach pads.

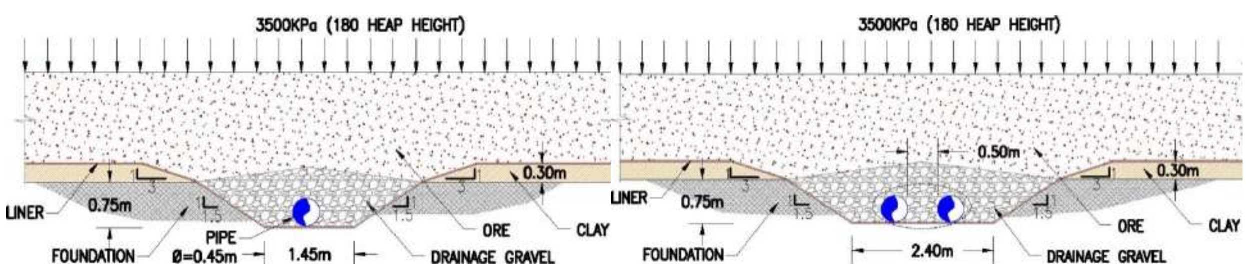
However, main headers are at least of 300 mm diameter which obviously represents a pipe that is less stiff than smaller pipes. Therefore, the main headers need additional support (as compared to the lateral pipes) and one of the best ways for doing this (as recommended by the authors) is to provide additional confinement by placing the pipes into trenches that will facilitate the compaction of the drainage gravel. This increases their rigidity and provides protection to the pipe.

Based on the authors' experience, we recommend that the pipes be buried in trenches when the heap is equal to, or deeper than, 120 m.

Numerical modeling of the pipe protection in trench

Numerical simulation of pipe deflection was performed by Castillo (2005) on 450 mm dual wall HDPE pipes for a 180 m heap height. The Fast Langrangian Analysis of Continuum (FLAC) finite difference code (Itasca, 2004) was used in the analyses. Two cross sections were analyzed, as shown in Figure 7. The trench layout with one and two pipes used for the numerical modeling is shown in this figure.

As part of the modeling, a parametric linear analysis was performed by changing the soil's elastic properties. Additionally, a nonlinear analysis was performed based on the published technical references for the drainage gravel and foundation soils. Typical pipe deflection results are shown in Figure 8. The vertical deflections determined in this modeling effort ranged from 9.2% to 22.4%, which indicates that for several combinations of soil properties, the pipe layout into trenches provided reasonable protection. However, as there was no previous experience in pipe survival under a 180 m heap height, the author recommended performing triaxial shear strength laboratory testing in the drainage gravel and foundation soils, along with large pipe deflection testing, so that the model can be calibrated and better refined for modeling other trench geometries and pipes locations.



(a) (b)

Figure 7: Trenches for confinement and protection with (left) one pipe and (right) two pipes

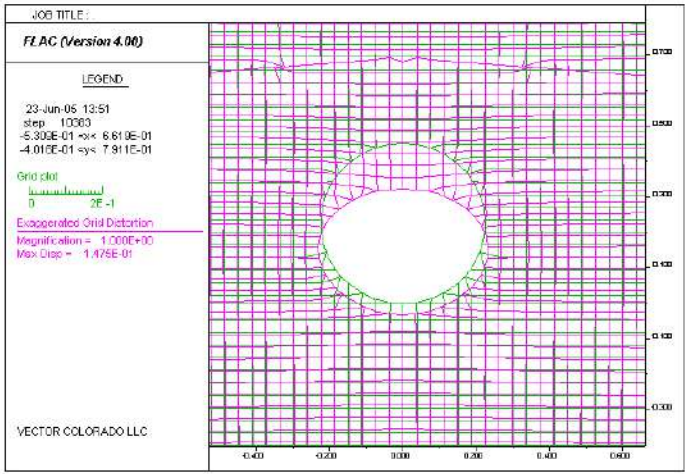


Figure 8: Pipe deflection results in 450 mm HDPE pipe

Large-scale pipe deflection testing

Knight Piésold and Co. (2007) performed large pipe deflection testing for Advanced Drainage Systems (ADS) to evaluate the performance of nominal 600 mm HDPE dual wall pipe under vertical load in a large-scale laboratory test simulating a 160 m and 170 m deep heap leach pad. The testing program was performed at the facilities of the US Bureau of Reclamation (USBR) in Denver, Colorado.

A 2.1 m wide × 2.1 m long × 1.2 m high steel box was used for the test. A 200 mm thick compacted layer of soil liner was placed in the bottom of the box, then three different geomembrane samples were selected and placed in pieces on the soil liner after surface preparation: 2 mm DST LLDPE, 2 mm smooth LLDPE, and 2 mm SST LLDPE. Thereafter, a protective layer material was spread over the geomembrane panels and compacted to a minimum thickness of 100 mm. The soil liner and the protective layers were compacted to a minimum of 95% of the maximum dry density as determined by ASTM D698. Then the pipe was placed on top of the compacted protective layer, and finally an uncompacted drainage layer was placed over the protective layer until the box was full.

Loads were applied incrementally to the soils in the box simulating heap heights of up to 160 m and 170 m. A total vertical displacement of 312.4 mm of the top of the drainage layer was measured during the test as the result of the drainage layer material being loosely placed into the box, which facilitated subsequent material re-arrangement, crushing, and settlement during loading.

The test report indicates that, at a load that corresponds to about an 80 m heap height, localized crimping/buckling along the left and right walls of the pipe appeared to start. At the end of the test that simulated a 170 m heap height, an average decrease of 177.8 mm in vertical diameter was measured, which represents a reduction of about 29% of the original pipe diameter. Flow capacity of the deformed pipe was reduced to about 62% of its non-deformed capacity, which represents a reduction of about 38%.

Though the drainage layer was loosely placed in the box, the high loads applied and the effect of the box size relative to the pipe outside diameter generated a compaction of this material, which provided a confinement effect to the pipe in a similar manner to the trench discussed previously. Again, as stated before, placing the pipes in trenches and compacting the drainage gravel provide protection to the large pipes used as main headers.

Geomembrane overstressing

Based on finite element models run and calibrated to both small- and large-scale laboratory tests, Leduc and Smith (2004) reported significant reduction in the load (as compared to the overburden stress) immediately below the pipe. But the load increased to about 125% of overburden at a distance of one pipe diameter, and the zone of overstress extended to about 4 pipe diameters. These results mean that there are narrow strips of geomembrane on either side of each collection pipe that are receiving a higher stress than commonly considered. The authors mentioned that the 25% overstress will vary depending on the rigidity of the pipe, the type and the degree of compaction of the material surrounding it, and the height of the heap.

On the other hand, the results of the numerical modeling performed by Castillo (2005) of the cases shown in Figure 7 indicate that for a single pipe the vertical stress on the liner close to the pipe increases in about 14% of overburden for 130 m heap and 13% for the ultimate height of heap (180 m). The analysis with two pipes shows that the vertical stress increases on the liner in about 15% of overburden for a 180 m heap. In addition, stress increments were observed between 14% and 29% at the upper part of trench slope.

Based on the findings above, geomembrane protection inside the trench using a non-woven geotextile is also needed in a similar way to that suggested for areas in the heap where the loads are very large. Figure 9 shows a typical detail of a main header in a trench designed to protect the pipe. Shown also are the connecting laterals and the geotextile covering the whole trench for geomembrane protection. Figure 10 shows main header installation work in trenches.

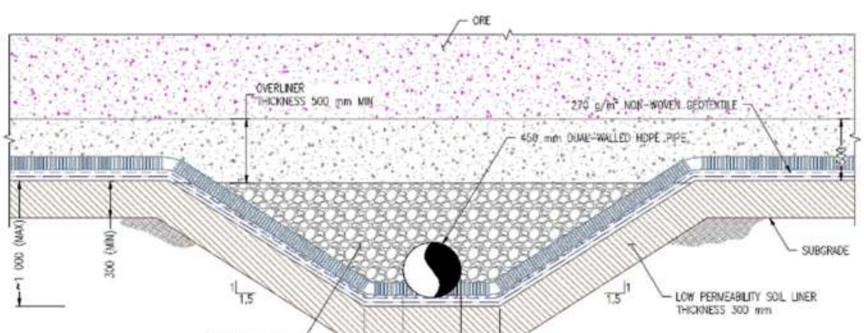


Figure 9: Main header placed into trenches for pipe protection

Figure 10: Main header installation works in trenches

Conclusions

When conventional design is applied to deeper heap leach pads, an increase of the capital cost of the project is expected. Therefore, solutions specifically developed for the design of deeper heap leach pads are needed and presented in this paper in order to reduce the overall capital cost of the project and to obtain a proper performance of the entire facility.

Geomembrane integrity or puncture testing should be performed using robust equipment with enough capacity to simulate the height of the heap. An additional 25% of the maximum load should be planned for, which accounts for the effect of the geomembrane overstressing because of the influence of the solution collection pipes.

The damage to the geomembrane liner should not be based solely on the fact that holes are present. It should also take into account the severity of the puncture, and should determine if yielding has compromised the geomembrane integrity. This would significantly decrease the effective thickness of the liner and therefore its mechanical properties.

Geomembrane punctures caused by the high loads of a deeper heap leach pad can be relatively easy to avoid through the use of a geotextile, preferably non-woven. Based on the results of puncture tests, a 270 g/m^2 or heavier geotextile should be used for very deep heap leach pads. A practical recommendation indicates that geotextile protection should be used when the heap is equal or deeper than 120 m depth.

Main headers for solution collection should be placed in trenches backfilled with compacted drainage gravel. The authors recommend burying the pipes in trenches when the heap is equal to, or deeper than, 120 m.

Additional high-load, large-scale pipe deflection tests should be carried out when dealing with very deep heap leach pads. Although these tests are expensive, data obtained will be very useful in preventing design defects and potential problems.

A numerical model for pipe deflection analysis should be properly selected and calibrated to actual laboratory data so that designers can predict the deflections associated with various other combinations of overliner materials, overburden pressures (heap depths), trench geometries, pipe locations, and (mainly) pipe diameters. It is difficult and expensive to perform such tests for large pipe diameters. As the behavior of the pipe depends also on the type and compaction of the material surrounding it, soil properties must be well defined through shear strength laboratory testing.

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