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Total and differential settlement of a heap leach pad founded on an existing mine waste dump

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Abstract

As a part of a heap leach pad expansion program of a mining project located in the south of Peru, this article shows the immediate settlement analysis of a heap leach pad designed on an existing mine waste dump, total and differential settlement of the foundation were calculated in order to ensure the serviceability of the leach solution collection system and the integrity of the liner system, several iterations were made in the grading design plan to address settlement to guarantee a suitable foundation grade of at least 2%, the construction process were taking into account by applying a staged construction analysis. Therefore the structure components will not be damaged as well as the leach drainage paths and construction design requirements.

Additionally, the behavior of the heap leach undergo irrigation was evaluated to verify the serviceability of the leach drainage paths. The initial and the final slope in terms of vertical displacements of the liner system are presented on a critical section with the materials involved in the settlement analysis. The settlement analysis were made with the FEM (Finite Element Method), the behavior of the materials were modeled using the linear elastic perfectly plastic Mohr-Coulomb model and Hardening Soil model.

Introduction

According to Lupo (2005) a critical component to the operation of a heap leach facility is the liner system and when properly designed and constructed is an environmental and operational benefit to the facility. Lupo (2005) highlighted the relevance to include the interaction between the various liner system components such as foundation, underliner soils, geomembrane, overliner materials and collection piping in the liner system design. Lupo (2005) recognized that the understanding of liner systems for heap leach facilities has evolved in response to several factors i.e.: long-term response of geosynthetics under high loads; significant ore loads (up to 3 MPa); spatial variability of foundation materials; improvements in solution collection techniques for better recovery and the commitment of mining companies to local, national and international environmental standards.

Later César et al. (2014) added other factors to be included in the liner system design, mainly due to the fact that in the last decade the construction and operation of heap leach facilities over 150 m thick in large mining projects has become a common practice in the mining industry because of 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.

Additionally, César et al. (2014) developed some solutions to ensure geomembrane integrity for the design of heap leach facilities with significant ore loads (up to 3 MPa), the main issues were the punctures caused by high loads and in some cases severe yield zones have been observed, which compromise the geomembrane integrity. To avoid damage César et al. (2014) recommended increasing the geomembrane thickness to 2.5 mm or using a 270 gr/m^2 non-woven geotextile or heavier depending heap load increments. Geomembrane protection with non-woven geotextile must be performed in zones where the heap load is 120 m or 130 m which has to be verified with puncture testing. Also César et al. (2014) considered that the use of geotextile will generate a new interface between the geomembrane and the geotextile so it must be applied far from the critical failure surface influence zone of the limit equilibrium analysis.

Considering authors points of view (Lupo, 2005; César et al., 2014), is necessary to prevent any damage to geomembrane by developing innovative solutions and taking into account several factors due to significant ore loads, in addition specially care need to be considered when it comes down to foundation conditions because one of the most important aspects of liner system design is foundation conditions and foundation materials (Lupo, 2008). The ideal foundation is firm and homogeneous to reduce settlements under loads which will induce strains on the geomembrane liner and piping networks. Unfortunately, as stated by Lupo (2005), ideal foundation conditions are rarely encountered in mine sites located in high Andean mountains of South America.

In the present paper considerations made by Lupo (2005) and César et al. (2014) were taken into account in the liner system design of a heap leach pad extension called phase A and B with 2,2 MPa of a maximum ore load. Phase A founded partially on an existing mine waste dump (MWD) in the south and on an existing heap leach pad called phase 2 to the north and phase B founded entirely on the existing MWD as can be seen in Figure 1. Part of the existing MWD was unfinished so in this study the final stacking plan was modified to address stability and settlements prior heap leach pad construction.

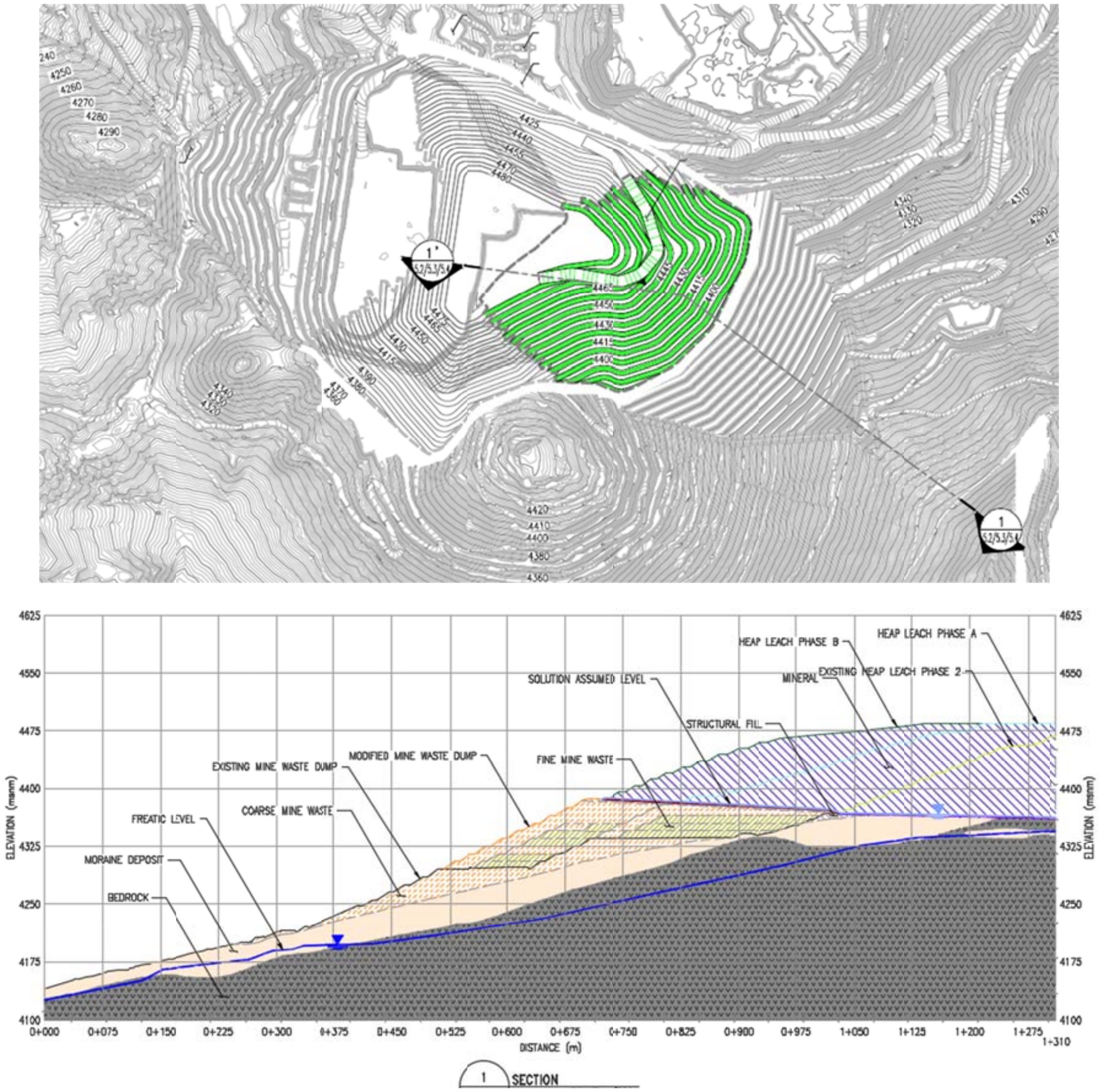

Figure 1: Plan view and representative cross section of the heap leach extension

The grading plan was defined by foundation conditions since the heap leach extensions (phase A and B) were founded on an existing MWD. The grading plan was modified after an iterative process by running numerical analysis based on finite element method then the calculated foundation settlements were integrated into the grading plan for the heap leach extensions.

Case study geotechnical overview

The case study presented is a heap leach pad extension (HLP) design project, located in the southern of Peru, developed for one of the most important gold mines in the region. A new HLP with a capacity of 17 Mm^3 (13 Mm^3 for phase A and 4 Mm^3 for phase B) and maximum height of over 120 m was needed in the short term for the future development of the mine. Due to lack of space and suitable locations the HLP was designed on top of an existing MWD. The HLP was designed in stages, where Phase A was founded partially on the existing MWD in the south and on an existing HLP called phase 2 to the north and phase B founded entirely on the existing MWD. Based on previous geotechnical investigations the foundation condition of the existing MWD and HLP was mainly composed by a large and heterogeneous moraine deposits, residual deposits and bedrock. The new HLP will be founded on top of the existing MWD which is composed by coarse and fine mine waste, therefore, immediate settlements due to fine mine waste, rotational and translational failures along the foundation and interface of the new HLP and seismic permanent displacements in the new HLP and MWD due to coarse and fine mine waste were expected.

The liner system design behavior due to immediate settlement is cover in this paper.

Soil profile model

In general, the foundation conditions fulfil the requirements to be a firm foundation duo to pre-loading of the existing HLP called phase 2, and with foundations levels varying from 0,5 m to 1,5 m composed by residual and moraine deposits. However, the new HLP (phases A and B) were designer on top of the exiting MWD so this was the worse foundation condition in the entire project. The soil profile for the new HLP in this area was composed by moraine deposits, an intercalation between fine mine waste (30 m thick) and coarse mine waste (up to 50 m thick) and structural fill (2,2 m thick). The mining company provided designers as-built drawings before MWD construction and geotechnical investigations of the existing HLP as well as as-built drawings, additionally some laboratory tests were carried out in order to properly determine the spatial variability and geotechnical properties of fine and coarse mine waste due to lack of information.

Determination of geotechnical parameters

Physical and mechanical properties of materials which were considered in the numerical model were estimated based on previous geotechnical studies, geotechnical site investigations, field tests and laboratory tests.

Geotechnical parameters

The following materials were considered in the numerical model:

- Mineral
- Coarse mine waste
- Fine mine waste
- Moraine deposit

- Structural fill
- Bedrock

Two constitutive models were used to model soil behaviour, Mohr-Coulomb model (MCM) and Hardening Soil Model (HSM) both implemented in Plaxis 2D 2016 software.

Soil parameter determination

Structural fill and Moraine deposit were modelled with MCM because of its little effect on settlement calculation; similarly Bedrock was modelled with Linear Elastic model. On the other hand, HSM were applied to fine, coarse mine waste and mineral to address settlement, specifically their great impact on settlement calculation.

Soil parameters from laboratory tests

According to Gebreselassie et al. (2005), there are three terms often mentioned and discussed nowadays in computational mechanics these are verification, validation and calibration. The author considers that calibration is the process of adjusting physical or numerical modeling parameters to improve agreement with laboratory or experimental data.

For fine and coarse mine waste and mineral, a calibration process was carried out by using some tools for instance Plaxis SoilTest which can be used to simulate laboratory soil tests and its Parameter Optimisation function, also some criteria were applied during calibration process taking into account the influence of each HSM parameters that can be summarized in Table 1.

Table 1: Influence of Hardening Soil Model parameters on material model parameter determination (modified after Gebreselassie et al., 2005)

Soil parameter	Stress - Strain behavior		Volume change	Strength at limit state
	Triaxial loading condition			
	Loading	Un/reloading		
E_{50}^{ref}	✔✔✔	X	✔✔	X
E_{oed}^{ref}	✔	X	✔✔✔	X
E_{ur}^{ref}	✔	✔✔✔	X	X
m	✔✔✔	✔	✔✔✔	X
υur	X	✔	X	X
K_o^{nc}	✔	X	✔	X
R_f	✔✔	X	X	X

✔✔✔ = has a considerable effect ✔✔ = has an effect ✔ = has a slight effect X = has no effect

Several iterations were made in HSM parameters until a good agreement was observed between simulated and laboratory data of stress-strain curves along with volume change. MCM and HSM parameters used in the present paper are summarized in Table 2.

Table 2: Soil parameters for settlement calculations

Soil parameter	Moraine deposit	Structural fill	Bedrock	Fine mine waste	Coarse mine waste	Mineral
E_{50}^{ref} (MPa)	-	-	-	24	35	50
E_{oed}^{ref} (MPa)	-	-	-	15	35	40
E_{ur}^{ref} (MPa)	-	-	-	70	105	120
m	-	-	-	0,92	0,3	0,05
ν_{ur}	-	-	-	0,2	0,2	0,3
K_o^{nc}	-	-	-	0,67	0,38	0,36
R_f	-	-	-	0,9	0,9	0,9
K_0	-	-	-	-	-	-
E (MPa)	70	60	1000	-	-	-
v	0,3	0,3	0,15	-	-	-
Cohesion (KPa)	10	1	-	17	15	14
Friction (^{a})	28	36	-	19,5	38	39,5
Unit weight (KN/m^3)	18	19	23	15	16	17
Saturated unit weight (KN/m^3)	19	20	24	16	17	18

Finite element model and calculation stages

The finite element model is shown in Figure 2. The model is extended to a depth of 100 m where a fully fixed boundary is imposed, lateral boundaries are horizontally fixed and top surface has a free boundary condition. The size of the model as a whole is 900 m wide and 200 m high. Triangular elements with 15 nodes were used in generating the mesh. This element provides a fourth order interpolation for displacements and it involves twelve numerical integration stress points (Gauss points) (see Plaxis 2D reference manual). The model has 8608 elements, 69545 nodes and 103296 stress points.

The following construction stages have been followed in the computation:

- Stage 0: Generation of the initial stresses (Gravity loading method), including a modified design of the existing MWD and optimized grading plan

- Stage 1 to stage 15: Application of ore loads for phase A (activating lift by lift, each of 8 m thick, up to maximum height 120 m)
- Stage 16: Application of fine and coarse mine waste loads for MWD expansion
- Stage 17 to 31: Application of ore loads for phase B (activating lift by lift, each of 8 m thick, up to maximum height 120 m)

Total and differential settlement, analysis of results

Prior settlement calculation 5 control points (A, B, C, D and E) were placed along the liner system for phase A and phase B, each of them corresponding to vibrating wire settlement cells. The proposed instrumentation will allow designers to calibrate the numerical model during HLP construction and operation. Control points are presented in Figure 2. The initial foundation grade was 5% along the liner system between the new HLP and the existing MWD.

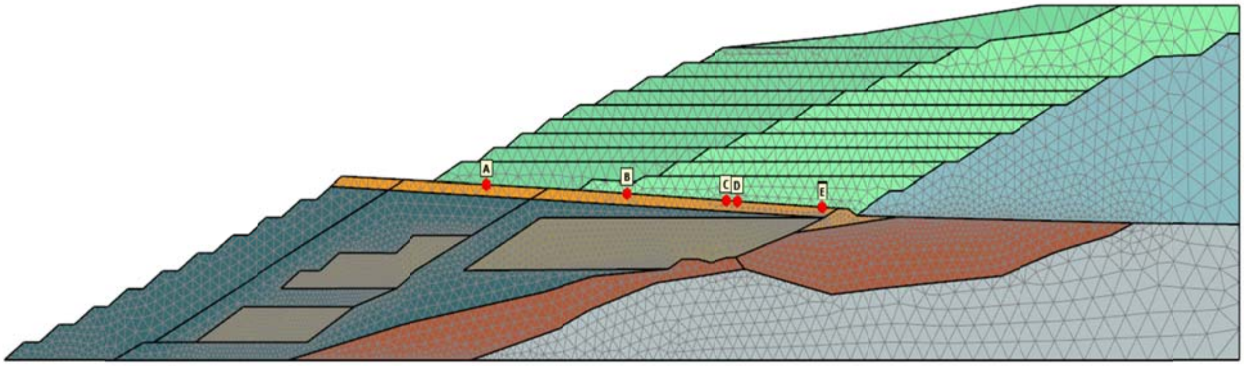

Figure 2: Control points A, B, C, D and E

Settlement calculation: phase A

Settlement analysis between phase A and the existing MWD give a maximum settlement of 1,2 m near C and D control points. The results of vertical displacements in control points located along the liner system showed a minimum variation of foundation grade with foundation grades varying from 6,2% to 4,2%. As expected the foundation grade has a slight increase in zones with smaller ore loads compared to zones with higher ore loads in other words some areas present an increase and others a reduction of foundation grade, which can be appreciated in Figure 3 where blue line represent initial foundation grade and red dashed line the final foundation grade. In Figure 3 the vertical scale was intentionally exaggerated. Additionally a summary of total settlement calculation for phase A is presented in Table 3, horizontal settlement were neglected because of its small values.

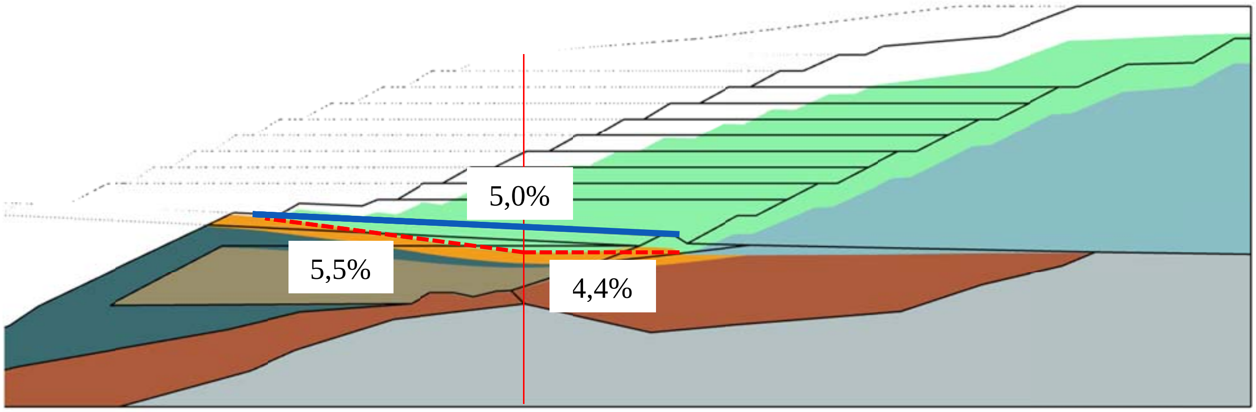

Figure 3: Foundation grade along liner system between phase A and the existing MWD (initial and final foundation grade)

Table 3: Total settlement calculation results for phase A

Cross section	Control points	Initial elevation (msnm)	Final elevation (msnm)	Total settlement (m)	Foundation grade (%)	
					Initial	Final
Seccion 1-1' / Phase A	A	4403,4	4403,4	0,0	-	-
	B	4398,2	4397,7	0,5	5,0	5,5
	C	4394,6	4393,4	1,2	5,0	6,0
	D	4394,2	4393,0	1,2	5,0	5,0
	E	4391,1	4390,3	0,8	5,0	4,3

Differential settlement: phase A

A LLDPE geomembrane was selected considering that geomembrane type should be compatible with predicted foundation settlements; therefore, geomembrane integrity was verified according to differential settlement. Differential settlements are summarized in Table 4. Differential settlements were calculated between B-C and D-E control points and settlement ratio along B-C or D-E.

Table 4: Differential settlement calculation results for phase A

Reference	Distance between control points	Differential settlement	Settlement ratio
B-C	75	0,7	0,009 L
D-E	60	0,4	0,007 L

Settlement calculation: phase B

Settlement analysis between phase B and the existing MWD give a maximum accumulated settlement of 2,1 m near C and D control points. The results of vertical displacements in control points located along the liner system showed a minimum variation of foundation grade with foundation grades varying from 5,7% to 3,5%. As expected the foundation grade has a slight increase in zones with smaller ore loads compared to zones with higher ore loads in other words some areas present an increase and others a reduction of foundation grade, which can be appreciated in Figure 4 where blue line represent initial foundation grade and red dashed line the final foundation grade. In Figure 4 the vertical scale was intentionally exaggerated. Additionally a summary of total settlement calculation for phase A is presented in Table 4, horizontal settlement were neglected because of its small values.

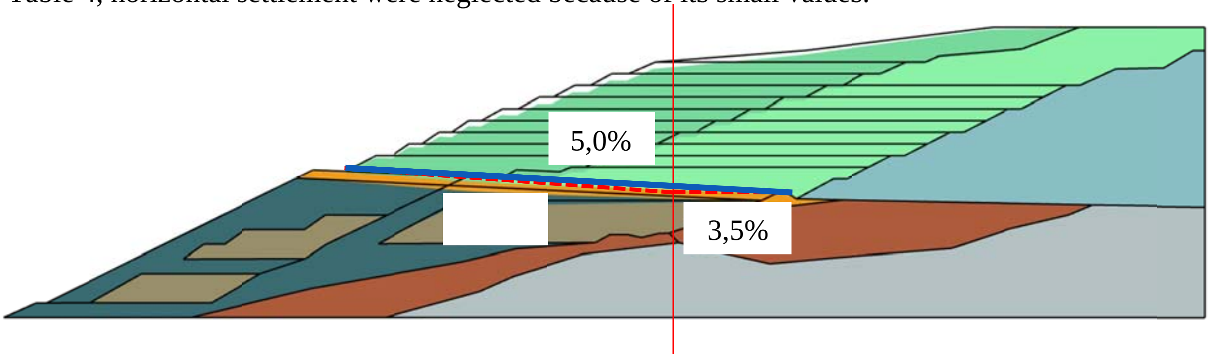

Figure 4: Foundation grade along liner system between phase B and the existing MWD (initial and final foundation grade)

Table 4: Total settlement calculation results for phase B

Cross section	Control points	Initial elevation (msnm)	Final elevation (msnm)	Total settlement	Foundation grade (%)	
					Initial	Final
Seccion 1-1' / Phase B	A	4403,4	4402,0	1,4	-	-
	B	4398,2	4396,2	2,0	5,0	5,6
	C	4394,6	4392,5	2,1	5,0	5,1
	D	4394,2	4392,1	2,1	5,0	5,0
	E	4391,1	4389,9	1,2	5,0	3,5

Differential settlement: phase B

A LLDPE geomembrane was selected considering that geomembrane type should be compatible with predicted foundation settlements; therefore, geomembrane integrity was verified according to differential settlement. Differential settlements are summarized in Table 5. Differential settlements were calculated between A-B, B-C and D-E control points and settlement ratio along A-C, B-C and D-E.

Table 5: Differential settlement calculation results for phase B

Reference	Distance between control points	Differential settlement	Settlement ratio
A-B	105	0,6	0,006 L
B-C	75	0,1	0,001 L
D-E	60	0,9	0,015 L

Analysis of results

Several investigations demonstrated that large area or total settlements, which are relatively uniform, will induce little additional strain and tensile stress in HDPE geomembranes (Bonaparte et al. 1987; Duvall et al. 1992; Berg et al. 1993), therefore, the increase in geomembrane tensile stress is associated with the magnitude of differential settlements rather than total settlements (Warith, 1994), besides geomembrane strain or stress concentrations as a result of an abrupt change in geometry may induce failure even though the average strain or stress on the geomembrane is not enough to cause failure (Giroud, 2005).

The maximum allowable strain (MAS) of geomembranes is in general related to physical and mechanical properties, government regulations or designer criteria. For instance, some researchers found that the allowable strain could be as low as 3% if the yield strain for an HDPE is 11 to 14% (Arab, 2011) or 10% for LLDPE with densities greater than 0,935 g/cm^3 due to its higher relaxation rate (Peggs, 2005).

On the whole, small areas with an abrupt change in geometry and higher differential settlement is prone to fail, in the present study these factors are not applicable since the HLP is placed over a large area and because the calculated settlements are relatively uniform along the interface.

Verification of leach drainage paths

Slide software was employed to determine the leach drainage paths after immediate settlements have been occurred along the HLP foundation. This analysis was performed only to verify the serviceability of the final grading plan by assuming a uniform permeability for leach ore and an irrigation rate of 11 l/h/m^2 (0.26 m/d) according to mining design criteria.

The required leach area was calculated from equation 1.

$$\text{Required leach area, m}^2 = \frac{\text{production (tpd)xleach cycle (days)}}{\text{Density}\left(\frac{\text{t}}{\text{m}^3}\right)\text{xLift thickness (m)}} \qquad \text{(eq. 1)}$$

In the present study the resultant required leach area was 100000 m^2 (also minimum crest area), assuming a production of 21000 tdp, ore density equal to 1.65 t/m^3, leach cycle 60 days and lift thickness

8,0 m as stacked and 7,5 m as settled. For 2D infiltration analysis the irrigation length along the HLP surface was calculated for a square area equal to the required leach area, therefore, the irrigation length was 316 m long. A transient analysis was carried out for the HLP taking in to account the leach cycle (60 days) with an isotropic permeability of 1e-1 cm/s for crushed ore. As can be seen in Figure 5, the leach drainage path follows the resultant liner system (after settlement has been occurred).

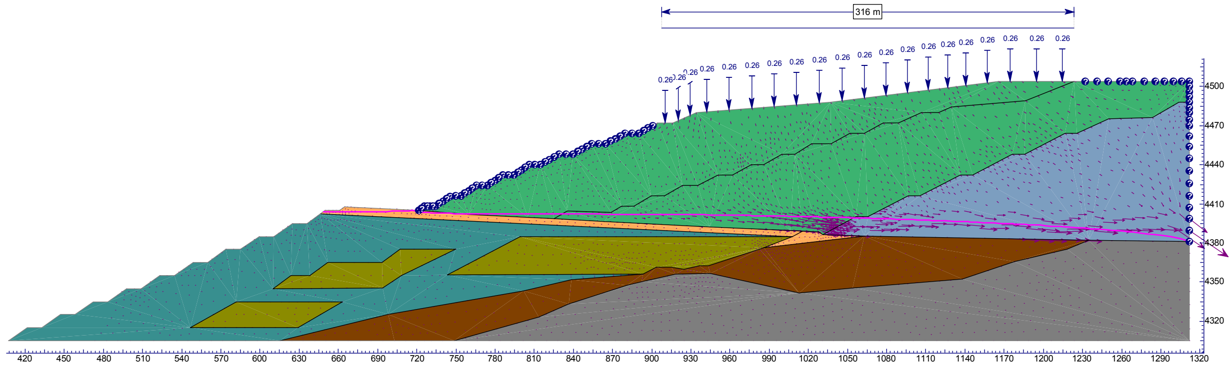

Figure 5: Infiltration analysis results after one leach cycle (60 days)

Conclusions

Since ideal foundation conditions are rarely encountered in mine sites located in high Andean mountains of South America, especially care need to be considered in the liner system design, for instance, in the present study liner system design was highly dependent of foundation conditions due to total and differential settlements.

To address total and differential settlements, advanced numerical models have proven to be useful to integrate settlements into liner system design, however, when calibration process is carried out is recommended to consider the influence of constitutive model parameters, for instance, Hardening soil model parameters to model loading or unloading/reloading conditions are totally different, therefore, in this study the influence of each parameter as a result of parametric study is include as a criteria for calibration process.

Settlement calculations allow designers to decide whether changing geometry of HLP or foundation grade would ensure geomembrane integrity, increase solution recovery and fulfil environmental regulations. In this study was necessary to change initial grading plan from 2% as minimum grade for solutions recovery to 5% considering change of initial grade because of immediate settlements along with random (aleatory) and subjective (epistemic) uncertainty.

During construction of HLP phase A, foundation grade changed from 5% to 6% in areas with small ore loads (at the toe) and from 5% to 4,3% for higher ore loads. Then for phase B settlement along liner system is generally uniform (about 2,0 m) along the interface between HLP (phase A and B) and the existing MWD, therefore, factors that increase the probability of failure of the liner system for instance small areas with stress and strain concentrations, abrupt change in geometry and higher differential settlement are not applicable since the HLP is placed over a large area and because the calculated settlements are relatively uniform along the interface.

The infiltration analysis showed that the leach drainage paths successfully follow the resultant liner system (after settlement has been occurred). A required leach area (100000 m^2), leach cycle (60 days) and an isotropic permeability of 1e-1 cm/s for crushed ore were used as input parameters.

The LLDPE nonlinear behaviour, stress and strains concentration along the liner system can be evaluated considering the LLDPE geomembrane as a structural element with two shear interfaces (above and below the geomembrane).

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