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Consolidation and deformation analysis for the stability assessment of a heap leach pad

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Abstract

The rapid growth of mining operations in Peru has brought many new challenges to the already difficult task of designing, building and operating heap leach pads in the aggressive Andes terrain. Consultants usually deal with delicate issues such as specific construction techniques, complex terrain geometry, high seismic activity, and limited suitable locations.

This paper presents a case study of a heap leach pad designed on top of an existing mine waste dump, which itself was built over a heterogeneous and complex deposit of alluvial and residual soft clayey soils. Among other geotechnical issues, it was necessary to assess the short-term stability of both structures, as well as determine the settlements due to consolidation of foundation soils and deformation of mine waste, which threatened the overall stability and operation of the heap leach pad. Using a large set of geotechnical information, several cross-section, finite-element staged construction analyses were carried out to estimate consolidation times and settlements. This evaluation led to a detailed construction schedule to allow pore pressure dissipation and use of buttresses for early stages of construction, and to include precambering to guarantee both stability and optimal operation conditions, given the mine waste settlement and its influence on the liner system. The analysis and design showed the importance of the assessment of both short-term stability and deformation of soils. Furthermore, the construction schedule for both structures, which ensured their short-term stability, highlighted the importance of planning and coordination between the designers and mine operators.

Introduction

Since the beginning of the 21st century, the mining industry in South America, particularly in Peru and Chile, has experienced rapid growth. Most of the mine sites in Peru are located in the Andean region, above 2,500 m.a.s.l., where the geological conditions allow mining companies to extract gold, copper and other minerals, making the Peruvian mining industry one of the top gold, silver and copper producers in the world.

Recent development of mining operations in Peru has been related to extensive use of the heap leaching technique. Since 1998, when the Pierina heap leach project was constructed, major heap leach pads (HLP) have been designed, constructed and operated in the Peruvian Andean region. However, in the last five years several issues have arisen that have complicated the civil and geotechnical design, as well as the construction work. Special construction techniques and criteria for the use of geomembranes, geosynthetics and earthworks have been addressed by César et al. (2013), Garay et al. (2014) and César et al. (2014). The limitations of the 2-D approach and the advantages of 3-D slope stability analysis due to the aggressive Andes terrain have been discussed by Reyes et al. (2014). However, issues such as the need to design HLP on poor foundation areas given the lack of adequate terrain, or even on top of other earth structures, have not been extensively analyzed. Moreover, the increasing need for larger and higher HLP has caused geotechnical designers to evaluate the resistance of both leach ore and liner material interface for confining pressures from 1 to 3 MPa, thus highlighting the need for larger and more powerful laboratory devices. Finally, the high seismic activity in Peru, which is generated by subduction of the Nazca plate beneath the South American plate, almost always defines the design of most earth structures. HLP are particularly sensitive to seismic forces due to the economic and environmental consequences of leakage of pregnant solution through tears in the geomembrane that can be caused by seismically induced permanent displacements.

This paper presents a case study of a HLP that, given the lack of an adequate location, was designed on top of a mine waste dump (MWD) that itself was built over a heterogeneous and complex deposit of alluvial and residual clayey soils. Challenges such as a staged construction plan due to consolidation of foundation soils, estimation of the settlements of mine waste resulting from the ore loading, and related geotechnical analysis are explored in detail.

Case study general background

The case study presented is a HLP design project, located in northern Peru, developed for one of the most important gold mines in the region. A new HLP with a capacity of 40 Mm^3 and a maximum height of over 100 m was needed in the short term for the future development of the mine. However, there were limited suitable locations, forcing the designers to place it on top of an existing MWD. This facility was also in design stages: phase 1 was under the last stage of construction and phase 2, with a maximum height of 140 m, was still in design. Previous geotechnical investigations had shown that the foundation of phase 2 was composed of large and heterogeneous deposits of alluvial and residuals soils that were over 80 m deep. Clayey, silty, sandy and gravelly soils were distributed over the area; consequently, settlements due to consolidation of these soils, as well as settlement caused by the deformation of the mine waste, were expected.

Preliminary stability analysis showed that for short-term conditions, which included undrained resistance of clayey soils, phase 2 of the MWD and the HLP were unstable. It was decided that, in permanent coordination with the mine owner, a staged construction analysis was needed to develop a detailed construction plan for both structures. Thus, complementary site investigations as well as laboratory tests were carried out to define in detail the geotechnical properties required for the short-term stability assessment and staged construction analysis. The long-term stability condition of both structures, particularly when including seismic forces, is dealt with by Reyes et al. (2015).

Geotechnical site investigations

A large complementary geotechnical site investigation program was carried out in order to properly determine the spatial variability and geotechnical properties of the foundation soils. Previous site investigations and stratigraphy were described by Reyes and Parra (2014). A total of 210 test pits, 41 dynamic penetrations tests, 115 standard penetrations tests, 65 large penetrations tests and 26 geotechnical boreholes were included within an area of over 1,000 Ha. Laboratory tests included a total of 6 undrained (UU), 14 consolidated undrained (CU) and 7 consolidated drained (CD) triaxial tests, as well as one-dimensional consolidation and permeability tests on most soils. A range of geophysical investigations was also performed. All of this information allowed the authors to describe and discretize the foundation soils, mine waste and leached ore in more detail.

Foundation soil stratigraphy and properties for phase 1 of the MWD were described by Reyes and Parra (2014). However, foundation soils of phase 2 of the MWD proved to be softer and/or looser and more heterogeneous, and required more and longer geological-geotechnical cross-sections and additional laboratory tests to properly describe them. For the particular case of residual and alluvial clayey soils, laboratory tests were performed on undisturbed samples obtained from large test pits and boreholes.

The particle size distribution (PSD) of mine waste and leached ore was determined in the field by several excavations in both the existing MWD and HLP, respectively, determining maximum sizes of over 12 inches for both materials. In each excavation, almost 1 ton of mine waste or leached ore was evaluated, first weighting the whole sample and then separating particles with sizes smaller than 3 inches. Using large sieves, as presented in Figure 1, the PSD of all material larger than 3 inches was determined in situ. Complementary laboratory tests on the smaller size particles completed the global PSD curve. Figure 2 shows the average global PSD of both mine waste and leached ore.

Due to the large size of mine waste and leached ore particles, two parallel gradation curves to the original PSD curves were developed for each material, which are shown in Figure 2, using a maximum particle size of 1 inch, so that no scalping would be needed when tested on a 6 inch diameter drained triaxial test. The technique used to develop the curves was first developed by Lowe (1964), and then extensively used by Marachi et al. (1969), Thiers and Donovan (1981) and Varadarajan et al. (2003) to perform drained triaxial tests on rockfill, crushed rock and alluvial soils. In the last decade, many researchers, particularly Gesche (2002), De La Hoz (2007), Dorador (2010) and Ovalle et al. (2014), and practitioners such as Linero et al. (2007) and Palma et al. (2009), have used this technique when testing alluvial and waste rock materials. The laboratory tests performed for this case study were used to obtain the shear strength properties for phase 1 and provide representative stress-strain curves for the numerical models.

Figure 1: In situ determination of the global particle size distribution of coarse granular materials

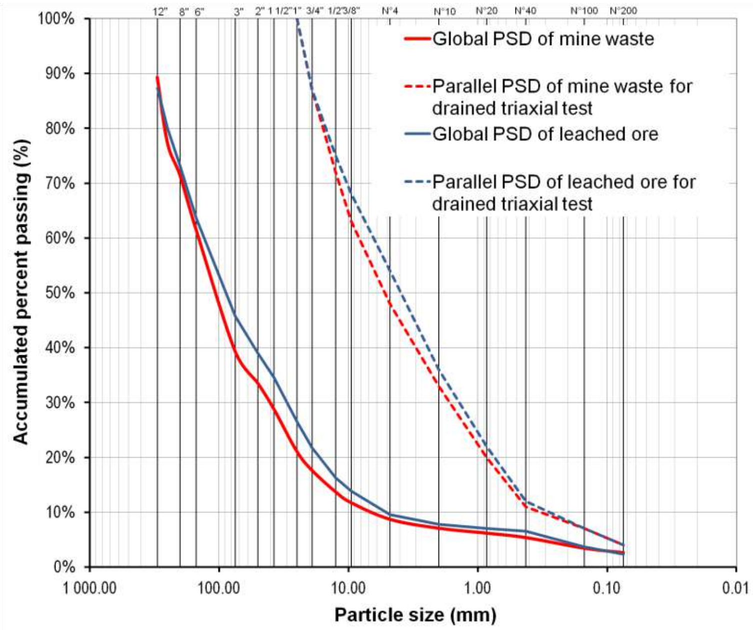


Figure 2: Global and parallel particle size distributions of the mine waste and leached ore

Geotechnical properties

Table 1 and 2 show all materials involved in the short-term analysis of the HLP and their geotechnical properties for both limit equilibrium and finite element analyses, respectively. Since translational failures through the liner system of the HLP were not critical and were not related to the short-term behavior of foundation soils, their properties were not included in this paper.

Table 1: Geotechnical properties for short-term limit equilibrium analysis

Materials		Total unit weight (kN/m³)	Saturated unit weight (kN/m³)	Drained shear strength c' (kPa)	Drained shear strength ϕ' (°)	Undrained shear strength c (kPa)	Undrained shear strength ϕ (°)
Leached ore		20	21	Non-linear envelope		–	–
Mine waste		20	21	Non-linear envelope		–	–
Aluvial soils	Gravelly	19	20	0	30	–	–
	Sandy	18	19	0	33	–	–
	Silty and clayey	18	20	–	–	15	12
Intrusive residual soils	Gravelly	19	20	10	28	–	–
	Sandy	18	19	5	25	–	–
	Silty and clayey	17	19	–	–	60	–
Sandstone residual soil		19	20	20	25	–	–
Bedrock	Quartz sandstone	23	24	140	25	–	–
	Intrusive	23	24	130	25	–	–
	Lutite	22	23	120	20	–	–

The drained triaxial tests on mine waste and leached ore allowed defining non-linear envelopes of resistance, as these materials were considered cohesionless with a reducing friction angle as confining pressure increased. The range of variation of the friction angle was defined from 40 to 35° and 42 to 35° for the mine waste and leached ore, respectively. The Hardening Soil (HS) model (Brinkgreve et al., 2014) was employed for the numerical modeling of the deformational behavior of these materials, calibrating it with the resulting stress-strain curves from the triaxial tests. The HS is an advanced model for simulating the behavior of different types of soil, both soft and stiff (Schanz, 1998). It is based on the Duncan and Chang (1970) hyperbolic model, introducing the theory of plasticity rather than elastic theory and including soil dilatancy, a yield cap and a Mohr-Coulomb failure envelope (Brinkgreve et al., 2014). Another feature of the HS model is the stress dependency of the stiffness, which allowed performing a properly staged construction model of the HLP. Figure 3 shows the original triaxial stress-strain curves and the ones generated by the calibrated HS model for both materials.

Table 2: Geotechnical properties for short-term stress-strain analysis

Materials		Drained shear strength		Deformational parameters					
		c' (kPa)	ϕ' (°)	υ	E_{ref} (MPa)	E_{edo} (MPa)	E_{ur} (MPa)	C_c	C_s
Leached ore		Non-linear envelope		–	80	80	400	–	–
Mine waste		Non-linear envelope		–	30	30	150	–	–
Aluvial soils	Gravelly	0	30	0.3	50	–	–	–	–
	Sandy	0	33	0.3	45	–	–	–	–
	Silty and clayey	30	19	–	–	–	–	0.251	0.125
Intrusive residual soils	Gravelly	10	28	0.3	45	–	–	–	–
	Sandy	5	25	0.3	40	–	–	–	–
	Silty and clayey	25	17	–	–	–	–	0.310	0.154
Sandstone residual soil		20	25	0.3	25	–	–	–	–
Bedrock	Quartz sandstone	140	25	0.25	4,000	–	–	–	–
	Intrusive	130	25	0.25	4,000	–	–	–	–
	Lutite	120	20	0.25	4,000	–	–	–	–

Consolidations tests performed on undisturbed samples of clayey alluvial and residual soils showed normally consolidated conditions. Consequently, undrained conditions were considered when defining its short-term resistance. The UU triaxial test results were used in the preliminary limit equilibrium analysis. The Soft Soil (SS) model (Brinkgreve et al., 2014) was employed for the numerical modeling, using consolidation, CD and UU triaxial tests. The SS model was calibrated using simulations of drained and undrained triaxial tests as well as consolidation tests. The SS model is a Cam-Clay type constitutive model implemented in PLAXIS, specifically meant for primary compression of near normally consolidated clay-type soil. Some of the features of the SS model include a stress dependent stiffness (based on a logarithmic compression behavior), distinction between primary loading and unloading-reloading, and failure behavior according to the Mohr-Coulomb criterion, among others (Brinkgreve et al., 2014). It is important to mention that the properties defined for the SS model were for drained conditions; the calibration stage allowed adjusting the undrained resistance. Figure 4 shows the stress strain curves and consolidation calibration of the SS model for the clayey alluvial soil.

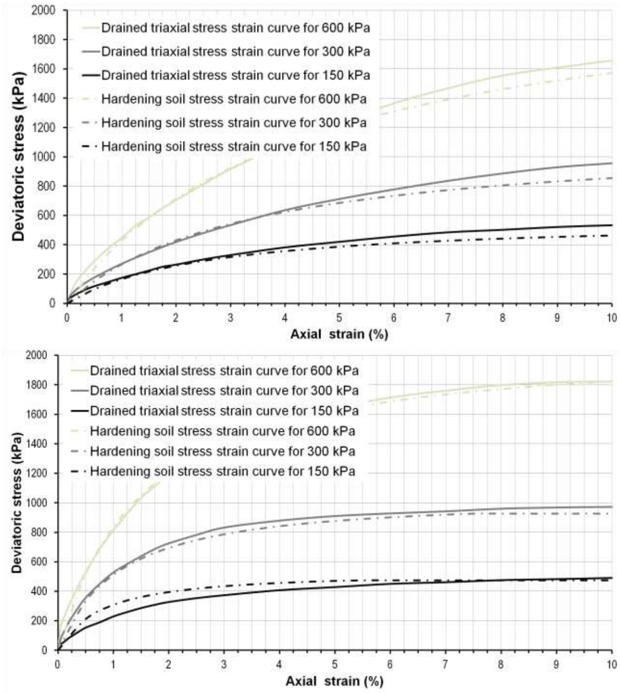


Figure 3: Calibrated stress strain curves from HS model for the mine waste (left) and leached ore (right)

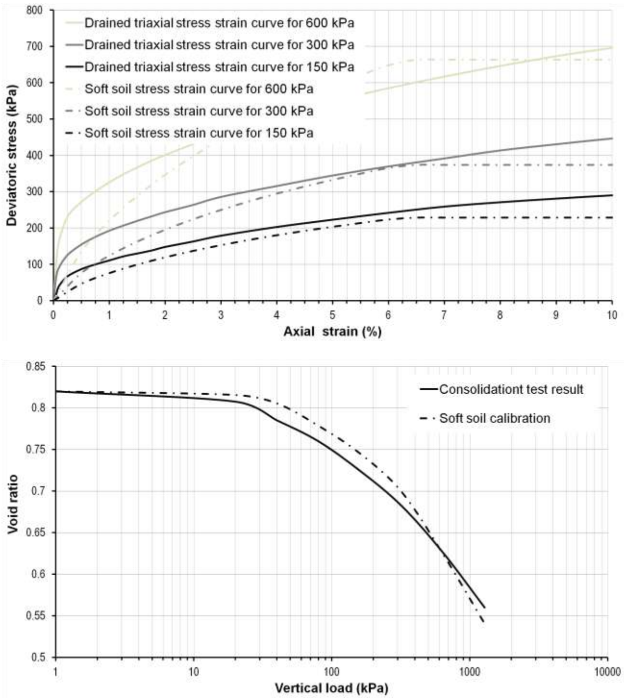


Figure 4: Stress-strain curves (left) and consolidation test results (right) for the calibrated SS model of the clayey alluvial soil

Geotechnical analysis

As mentioned before, this paper deals with the short-term stability of both HLP and MWD. The long-term stability condition of these structures, particularly when including seismic forces, is dealt with by

Reyes et al. (2015). Nine geological-geotechnical cross-sections were developed using the geotechnical site investigations, all needed to capture the heterogeneous stratigraphy and the HLP and MWD layouts complexity. Figure 5 show a plan view of the layout of the HLP on top of phase 2 of the MWD and its cross-sections.

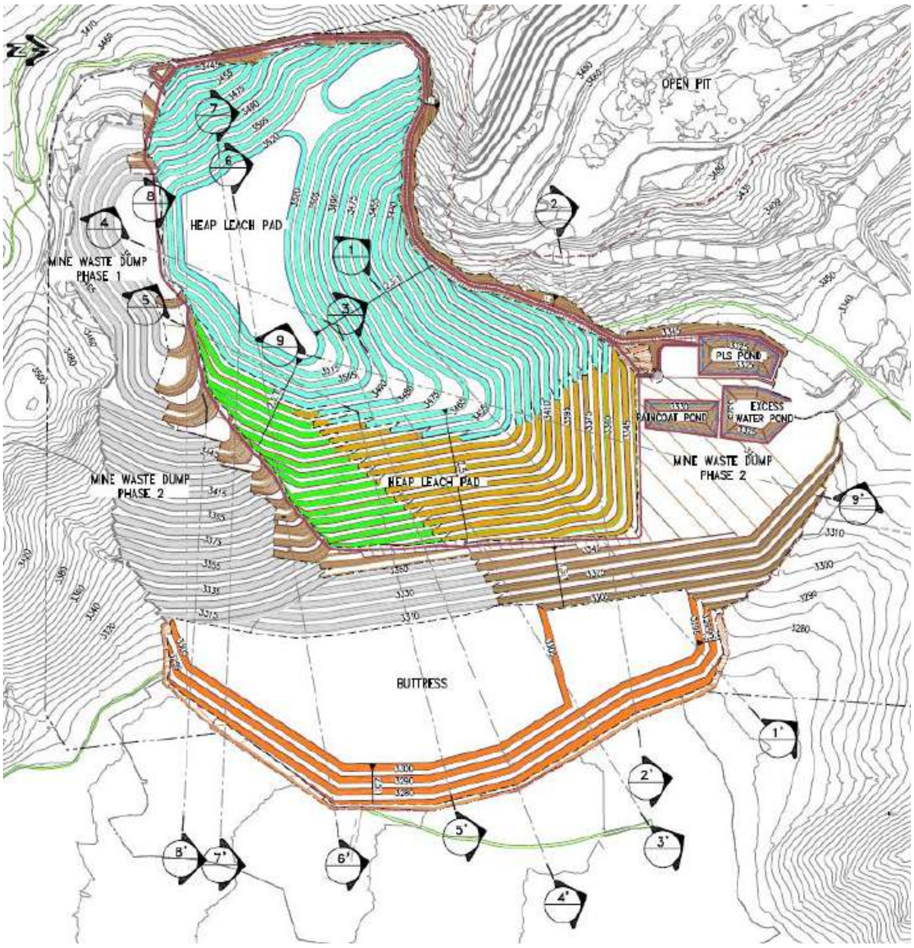
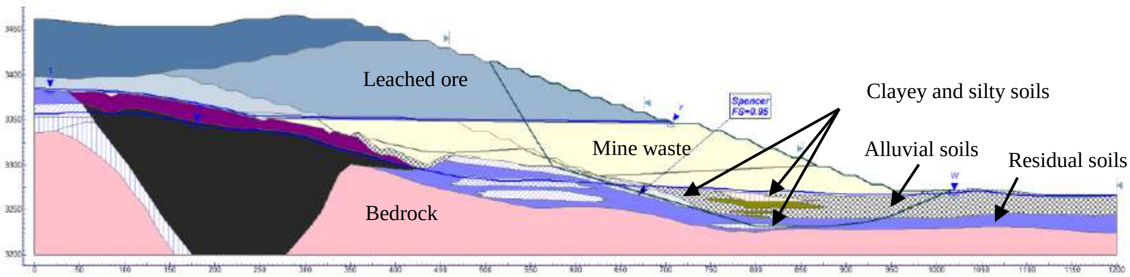
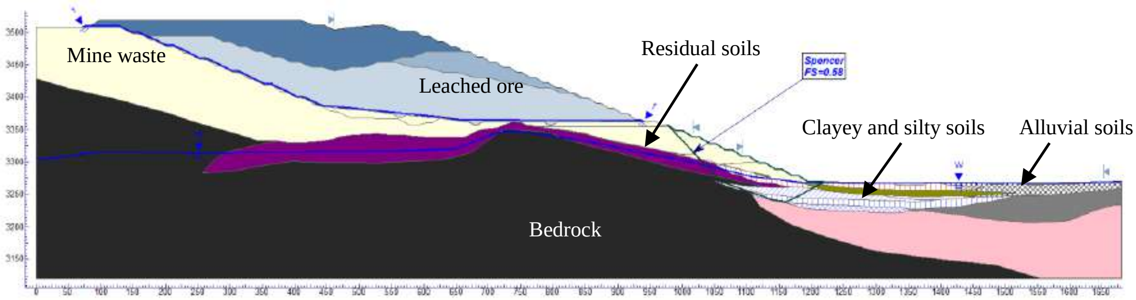


Figure 5: Plan view of the heap leach pad and mine waste dump

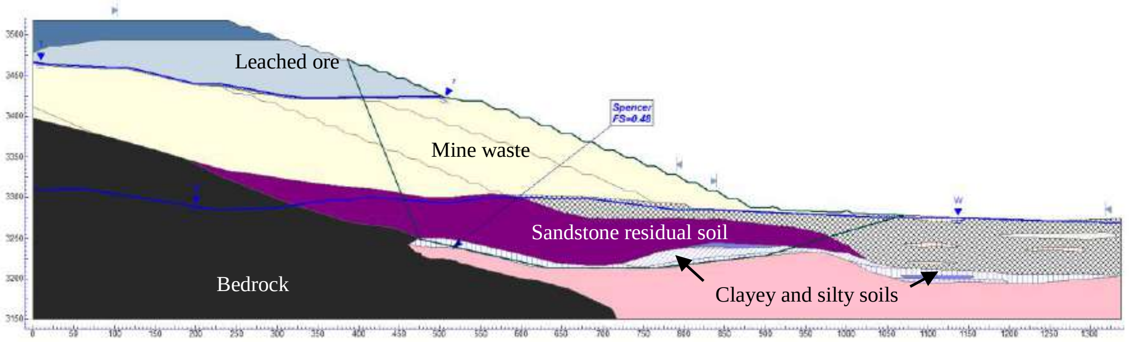
Preliminary short-term limit equilibrium analysis carried out with Spencer's (1967) procedure and making use of undrained resistance for clayey soils, showed two-dimensional (2-D) factors of safety (FS) to be very variable among all the cross-sections, both considering only phase 2 of the MWD and including the HLP. Table 3 shows FS when considering both structures for short-term conditions and failures that cross foundation soils. FS for short-term conditions considering only phase 2 were also critical. The heterogeneity of the FS is more pronounced than the ones obtained in the design of phase 1, which was described by Reyes and Parra (2014). All critical failure surfaces were of translational and compound nature, being determined using the "simulated annealing" algorithm as programmed in the software SLIDE. Figure 6 shows 3 of the cross-sections with the lowest FS and their respective failure surfaces that, as in all the others, crossed clayey soils strata.



(a)



(b)



(c)

Figure 6: Cross-sections (a) 1-1', (b) 4-4' and (c) 6-6' and their failure surfaces

Based on the results, a large buttress was required to improve the stability of both MWD and HLP for short-term conditions. However, it was unclear when it was needed and whether the increase in resistance of the clayey soils as a consequence of the process of consolidation would result in a smaller buttress. Given these needs, a staged construction analysis in PLAXIS was carried out with the objective of representing the constructive stages of both structures and estimating the necessary consolidation time to allow pore pressure dissipation, to increase the resistance of the clayey soils and, as an outcome, to improve its stability for each stage and structure. Also, settlements due to consolidation of foundation soils and deformation of mine waste induced by the ore loads were calculated and its influence on the heap leach pad design were also evaluated. Additionally, the dimension of the buttress would be optimized, compared with the one previously estimated with the limit equilibrium analysis. The 3 cross-sections of Figure 6 were chosen for evaluation, because of their low FS and representativeness of the northern, central and southern regions of the HLP, respectively.

Table 3: 2-D factors of safety from limit equilibrium analysis

Cross-section	Factor of safety	
	Undrained short-term conditions	Drained conditions including buttress
1-1′	0,95	1,84
2-2′	0,93	2,02
3-3′	1,49	1,83
4-4′	0,58	1,62
5-5′	0,61	1,75
6-6′	0,48	1,67
7-7′	1,37	1,62
8-8′	1,54	1,72
9-9′	1,73	2,11

The PLAXIS models for each section included the modelling of clayey soils using the SS models as well the HS models for mine waste and leached ore described previously. All other materials were modeled using the linear elastic and perfectly plastic Mohr Coulomb model. No deformation/strain analysis was performed on the geomembrane. The modeling stages consisted of:

- Generation of initial stresses for the original terrain.
- Staged construction of phase 1 of the MWD considering the actual time employed to build each lift of the dump. Displacements were reset to zero after the last stage.
- Staged construction of phase 2 of the MWD. Time necessary to allow partial or total pore pressure dissipation and to obtain a FS over 1.3 was calculated for each stage.
- Staged construction of the HLP on top of phase 2. FS above 1.3 were verified for each stage.

The authors agreed with the mine owner on the value of 1.3 for the short-term FS, as it is common practice in Peruvian mining where values ranging from 1.3 to 1.35 are chosen for short-term conditions and 1.5 for long-term stability. It is important to mention, however, that the FS of 1.3 was verified for stages with failure surfaces with a depth of 40 m or more. Failure surfaces with depths less than 40 m were verified for a FS of 1.35. This consideration was made for the following reason: the larger the failure surface the higher the 3-D effect of the geology of these area, as shown by Reyes and Parra (2014); consequently, smaller failure surfaces would not be subjected to this effect and required much more care. Nevertheless, it is the opinion of the authors that the stability of major earth structures should be not only evaluated with FS calculations but also with risk and/or probability of failure analysis. Results obtained from of each model provided useful information, which is summarized in the following points:

- Phase 1 of the MWD did not induce important increments of pore pressure in the foundation. All settlements in these stages were caused by the "immediate" deformation of both foundation soils and mine waste, not influencing the analysis or results of the following stages.
- Phase 2 of the MWD was placed in some areas directly on top of clayey soils and required consolidation times up to 45 days per stage or lift to obtain a minimum FS of 1.3.When over 45 days of consolidation time was needed, a buttress of 30 to 40 m of height was included, which was substantially smaller than the one estimated by the limit equilibrium analysis. Table 4 shows the consolidation periods for each stage or lift of the MWD and for the 3 cross-sections evaluated. Table 3 shows the FS calculated on drained conditions and including the buttress, which ultimately was to be enlarged due to long-term seismic stability.
- Failure surfaces obtained for each stage were of a translational or compound nature, with the results very similar to those obtained in the limit equilibrium analysis by the "simulated annealing" algorithm of SLIDE.
- In general, as phase 2 of the MWD was finished, most clayey soils exhibited consolidation degrees of over 80%, and failure surfaces and their respective FS for the HLP were not influenced by any undrained resistance of these soils. Maximum settlements due to consolidation in the foundation of phase 2 for each section and all over the MWD area are shown in Table 4 and in plan view in Figure 7, respectively.
- Settlements due to the consolidation of clayey soils were negligible during the final stages of phase 2. Hence, only settlements caused by the deformation of mine waste were considered to influence the HLP. These settlements are shown in Table 4 for each section and in plan view in Figure 8 for the entire HLP area.

For operational reasons, some consolidation times were increased to match the ones from other sections. The mine owner acknowledged the importance of these periods of time and made a compromise to follow them, as the results proved to be sufficient to cover their mine waste and leached ore production. Several vibrating wire piezometers and settlement cells were included in the design, enabling the verification of the results of these analyses and calibration of the parameters selected in the evaluation, particularly the ones for the clayey and silty soils. The mine owner was also aware of the amount of settlement due to consolidation of the clayey soils and aware that, by the end of the construction of phase 2, these would be negligible. Settlements caused by deformation of mine waste were dealt with by introducing precambering that increased the inclination of the liner system of the HLP from 2-3% to 8-10%. With this increase, settlements induced by placing leached ore on top of the mine waste would only reduce the inclination of the liner system from 8-10% to 5-6%, which was required to ensure both an adequate collection of the pregnant solution and to improve the translational stability of the HLP.

Table 4: 2-D factors of safety from limit equilibrium analysis

Cross-section	Maximum settlement (m)		Consolidation time per lift of the phase 2 of the mine waste dump (days)									
	Only due to consolidation	Only due to deformation of mine waste	Lift									
			1	2	3	4	5	6	7	8	9	10 - more
1-1′	3,0	2,8	15	15	30	30	30	30	15	15	15	15
4-4′	5,0	5,0	30	30	30	45	45	45	45	45	15	15
6-6′	5,0	4,5	15	15	15	15	15	15	15	15	15	15

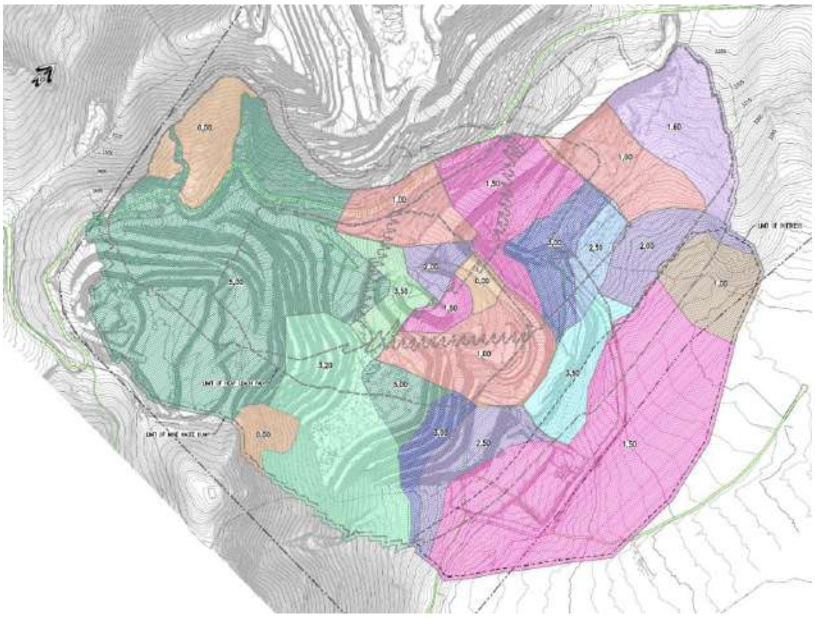


Figure 7: Settlements on the foundation soils only due to consolidation

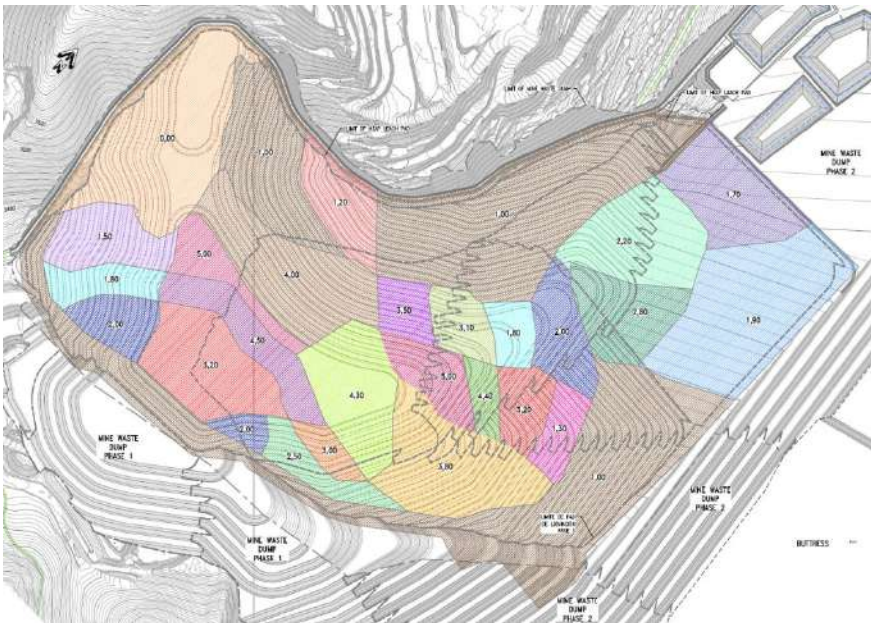


Figure 8: Settlements on the foundation soils only due to deformation of mine waste

Conclusions

Current state of practice of the design of HLP in the Andean region poses many challenges that have complicated its civil and geotechnical design, as well as its operation. Special considerations when designing HLP in marginal locations require additional geotechnical investigations and detailed analysis to support its design.

This case study presented a HLP that was designed, given the challenges of the location, on top of a MWD that itself was built over a heterogeneous and complex deposit of alluvial and residual clayey soils. Problems such as short-term stability assessment, settlements of the foundation soils due to consolidation of clayey soils, and settlements of the liner system due to the mine waste deformation induced by ore loading, were dealt with using a staged construction analysis. Advanced constitutive models used in the finite-element analysis were based on state of the art techniques, such as parallel gradation for the testing of large-sized mine waste and leached ore. State of practice drained and undrained triaxial tests, as well as field tests, were carried out to characterize all other materials involved. The geological complexity and spatial variability of the foundation demanded the use of several cross-sections for the analyses. The results provided useful information that allowed the detailed determination of settlements due to consolidation of clayey soils, consolidation periods, an optimized design of a buttress, precambering of the liner system, and overall deformation of mine waste due to ore loading.

The results of the short-term stability assessment and settlement calculations profoundly impacted the design and overall philosophy of the future construction stages and highlighted the importance of planning and coordination between the designers and mine operators. Construction schedules set up for both structures were agreed between both parties. Also, it was clear that real-time geotechnical monitoring of pore pressures and settlements through geotechnical instrumentation would validate the findings of the analysis. The resulting monitoring can be used to validate the parameters of the advanced constitutive models used for the characterization of mine waste, leached ore, and clayey foundation soils.

References

Brinkgreve, R.B.J., Engin, E. and Swolfs, W.M. 2014 PLAXIS 2014 Material Models Manual, The Netherlands: Plaxis bv.

César, C., Mendoza, J. and Parra, D. 2013. Heap leach pad design in very aggressive terrain, in D. van Zyl and J. Caldwell (eds), Proceedings Heap Leach Solutions 2013, Vancouver, Canada: InfoMine Inc.: pp. 308–320.

César, C., Parra, D. and Mendoza, J. 2014. Geomembrane and pipe design issues in deeper heap leach pads, in D. van Zyl and I. Gonzáles (eds), Proceedings Heap Leach Solutions 2014, Lima, Peru. Vancouver, Canada: InfoMine Inc.: pp. 167–179.

De la Hoz, K. 2007. Estimación de los parámetros de resistencia al corte en suelos granulares gruesos, Undergraduate and Masters dissertation, Universidad de Chile, Facultad de Ciencias, Físicas y Matemáticas, Santiago de Chile, Chile.

Dorador, L. 2010. Análisis experimental de las metodologías de curvas homotéticas y corte en la evaluación de propiedades geotécnicas de suelos gruesos, Undergraduate and Masters dissertation, Universidad de Chile, Facultad de Ciencias, Físicas y Matemáticas, Santiago de Chile, Chile.

Duncan, J.M. and Chang, C.Y. 1970. Nonlinear analysis of stress and strain in soil, ASCE Journal of the Soil Mechanics and Foundation Division, 96: pp. 1629–1653.

Garay, H., Mendoza, J., César, C. and Najar, E. 2014. Evaluation of geosynthetic clay liners in heap leach pads, in D. van Zyl and I. Gonzáles (eds), Proceedings Heap Leach Solutions 2014, Lima, Peru. Vancouver, Canada: InfoMine Inc.: pp. 317–329.

Gesche, R. 2002. Metodología de evaluación de parámetros de resistencia al corte de suelos granulares gruesos, Undergraduate dissertation, Universidad de Chile, Facultad de Ciencias, Físicas y Matemáticas, Santiago de Chile, Chile.

Linero, S., Palma, C. and Apablaza, R. 2007. Geotechnical characterization of waste material in very high dumps with large scale triaxial testing, in Y. Potvin (ed), Proceedings International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Perth, Australia: Australian Centre for Geomechanics: pp. 59–75.

Lowe, J. 1964. Shear strength of coarse embankment dam material, Proceedings 8th Congress on Large Dams: pp. 745–761.

Marachi, N.D., Chan, C.K., Seed, H.B. and Duncan, J.M. 1969. Strength and deformation characteristics of rockfill materials, Report No. TE-69-5, Department of Civil Engineering, University of California, Berkeley.

Ovalle, C., Frossard, E., Dano, C., Hu, W., Maiolino, S. and Hilcher, P.-Y. 2014. The effect of size on the strength of coarse rock aggregates and large rockfill samples through experimental data, Acta Mechanica, 225: pp. 2199–2216.

Palma, C., Linero, S. and Apablaza, R. 2009. Caracterización geotécnica de materiales de lastre en botaderos de gran altura mediante ensayos triaxiales y odométricos de gran tamaño, III Conferencia Sudamericana de Ingenieros Geotécnicos, Córdoba, Argentina.

Reyes, A. and Parra, D. 2014. 3-D slope stability analysis by the limit equilibrium method of a mine waste dump, Proceedings 18th International Conference on Tailings and Mine Waste 2014, Keystone, Colorado: Colorado State University: pp. 257–271.

Reyes, A., Garma, P. and Parra, D. 2014. 3-D slope stability analysis by the limit equilibrium method of a heap leach pad, in D. van Zyl and I. Gonzáles (eds), Proceedings of Heap Leach Solutions 2014, Lima, Peru. Vancouver, Canada: InfoMine Inc.: 257–271.

Reyes, A., Valvivia, M., Tapia, E. and Salas, L. 2015. 1D seismic response analysis for seismic permanent displacements estimation on a heap leach pad, to be published in Proceedings Heap Leach Solutions 2015, Reno, Nevada. Vancouver, Canada: Infomine Inc.

Schanz, T. 1998. Zur Modellierung des Mechanischen Verhaltens von Reibungsmaterialen. Habilitation, Stuttgart Universitat.

Spencer, E. 1967. A method of analysis of stability of embankments assuming parallel inter-slice forces, Geotechnique, 17(1): pp. 11–26.

Thiers, G.R. and Donovan, T.D. 1981. Field density, gradation and triaxial testing of large-size rockfill for Little Blue Run Dam, in R.N. Yong and F.C. Townsend (eds), Laboratory shear strength of soil, ASTM STP 740, American Society for Testing Materials: pp. 315–325.

Varadajan, A., Sharma, K.,Venkatachalam, K. and Gupta, K. 2003. Testing and modeling two rockfill materials, Journal of Geotechnical and Geoenviromental Engineering, 129(3): pp. 206–218.