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Geotechnical Evaluation of Properties and Liquefaction Potential Using CPTu for Heap and ROM Leaching Facilities

Guillermo Torres, Geotechnos, Chile
Sergio Pinos, Geotechnos, Chile
Camilo Soto, Geotechnos, Chile
Ricardo Moffat, Universidad Adolfo Ibáñez, Chile

Abstract

In the mining industry, the evaluation of geotechnical properties and the liquefaction potential has been a challenging task for large leaching operations over heap or ROM materials. The technique of using CPTu measurements has become a useful and practical means for evaluating the geotechnical conditions within the soil mass, considering the material variability and the fact that the ore may acquire more complicated geotechnical properties due to its fines content.

In northern Chile, large mine operations have begun confronting the need for deeper and more reliable geotechnical assessments of their leaching operations due to the height that facilities have reached after several years of leaching process, as well as the rigorous permit requirements and the risk potential for operations, installations, and environment.

Geotechnos was required to conduct a Geotechnical Field Campaign to assess the geotechnical properties on a heap and ROM leaching operation where facilities reached up to a height of one hundred metres. The main purpose was to evaluate the liquefaction potential and determine the existence of a perched water table; which along with determining ore resistance properties allows for the evaluation of liquefaction risk.

The field campaign executed CPTu tests in 19 selected points with penetration depths of 25 to 30 m on the heap facility and in 22 selected points with penetration depths between 15 to 30 m on the ROM facility. The tests included records for pore pressure, down-hole at selected depth, and sampling of selected materials for moisture content. The total length of executed tests was 486 m for the heap facility and 373 m in the ROM facility. All work was done in a period of 2½ months.

The location of the testing points was discussed with the operation and the Review Board of Experts with a view to assessing the most likely portions of ore that might experience difficulties or require solutions.

For the interpretation of data several correlations were used to define the stratigraphic profile according to the standard penetration test (SPT) interpretations referred to as SBT (soil behaviour type). The interpretation allows the geotechnical evaluation of ore variability and consistency of the material profile, showing a more homogeneous material in heap ore and more heterogeneous material in ROM. The data interpretation permitted the determination of the following geotechnical parameters: Ksbt (permeability based on SBT), N60, Young's Modulus, Relative Density, Friction Angle, Elastic or Contraction Modulus, Shear Modulus, Undrain shear resistance, Overconsolidation Ratio, and Unit Weight.

Introduction

Safety in heap leaching operations has been an enduring preoccupation of geotechnical engineers, who have focused on providing the best possible understanding of the behaviour of the material subject to leaching under different physical and environmental conditions. It has been a challenge to provide a characterization of materials that adjusts to the reality of each operation, due to the great variability over time of the materials of the original mineral matrix, caused by the high exploitation tonnages and large geological areas involved in the process, and also the difficulty of ensuring a homogeneous operation in terms of wetting the heap.

These recurring issues in all leaching operations must be carefully focused upon. In each operation, the size of the heaps and the variation of the type of ore over time present new requirements that must be addressed in order to develop reliable geotechnical studies of stability and ensure operational continuity in the recovery of metals.

Moreover, long years of exploitation of surface minerals, generally associated with oxides, have resulted in operations moving to the exploitation of a deeper mineral matrix, with different geotechnical qualities and a greater exploitation of sulfide ore that has been processed for leaching. In addition, the grades of copper contained in the mineral bodies have decreased, so the heap leaching units are increasingly larger; therefore, obtaining representative parameters is a great challenge.

Techniques to characterize a large mass of soil include a wide variety of invasive and non-invasive methods, comprising a combination of classical surveys with sampling and tests of specimens in the laboratory and geophysics, which have been widely validated for the development of studies in stacks due to their reasonable cost. The incorporation of drilling is also considered an alternative to calibrate geophysical results.

For geotechnical studies to ascertain the properties of soils and assign parameters to the integral mass of soil, the varieties of penetration test have excellent and proven results when the soils present granulometric characteristics of a type of fine gravel or smaller particle size and have relatively homogeneous environmental and geotechnical conditions. However, the limitations in granulometric terms restrict the widespread use of the method due to high cost, and the high probability of not achieving favourable results when applied in heterogeneous soils with sizes of particles with a high content of gravel or blocks. This is because there is a probability of encountering a particle that blocks the penetration path, causing the test to stop. In particular, measurements with DCPT, CPT or CPTu methodology have been widely used and with very good results in tailings sands and, moreover, there is a wide variety of formulations and calibration to adjust the results to this type of soil.

As geotechnical specialists, we have sought ways to adjust techniques or derive results in different media and applications in engineering projects for projects involving large soil masses, such as tailings dams, leach pads, and dumps. In consideration of the particle size and homogeneous characteristics of the leached material, Geotechnos began to provide services by performing measurements using the DCPT technique in ripios dumps from dynamic heaps. After several application campaigns with good results, it was proposed by a mining operation to apply the CPTu technique to a high-rise leach pad and on a ROM dump leach operation, to assess whether the results would be consistent and reliable for use in geotechnical stability and deformation studies and to evaluate the liquefaction potential of heap and dump.

The following sections present a summary of the application of CPTu measurements in a crushed ore leach pad and a ROM ore dump. The technique is complemented with geophysical measurements and laboratory tests that were integrated to calibrate the measurement results and confirm if they are consistent to be used in stability and deformation studies. Finally we highlight the advantages and disadvantages of the application of the method in heaps and dumps and present recommendations for improvements in the application in these kinds of facilities.

Technical framework

The evaluation of the liquefaction potential is expressed as a safety factor against the occurrence of liquefaction. If the cyclic stress caused in the ground by a seismic event CSR (Cyclic Shear Stress Ratio) is greater than the cyclic resistance of the ground, CRR (Cyclic Resistance Ratio), liquefaction may occur.

The factor of safety is determined by the following equation:

a) F.S. = CRR/CRS

b) The following figure shows a summary of the Boulanger and Idriss (2014) method applied.

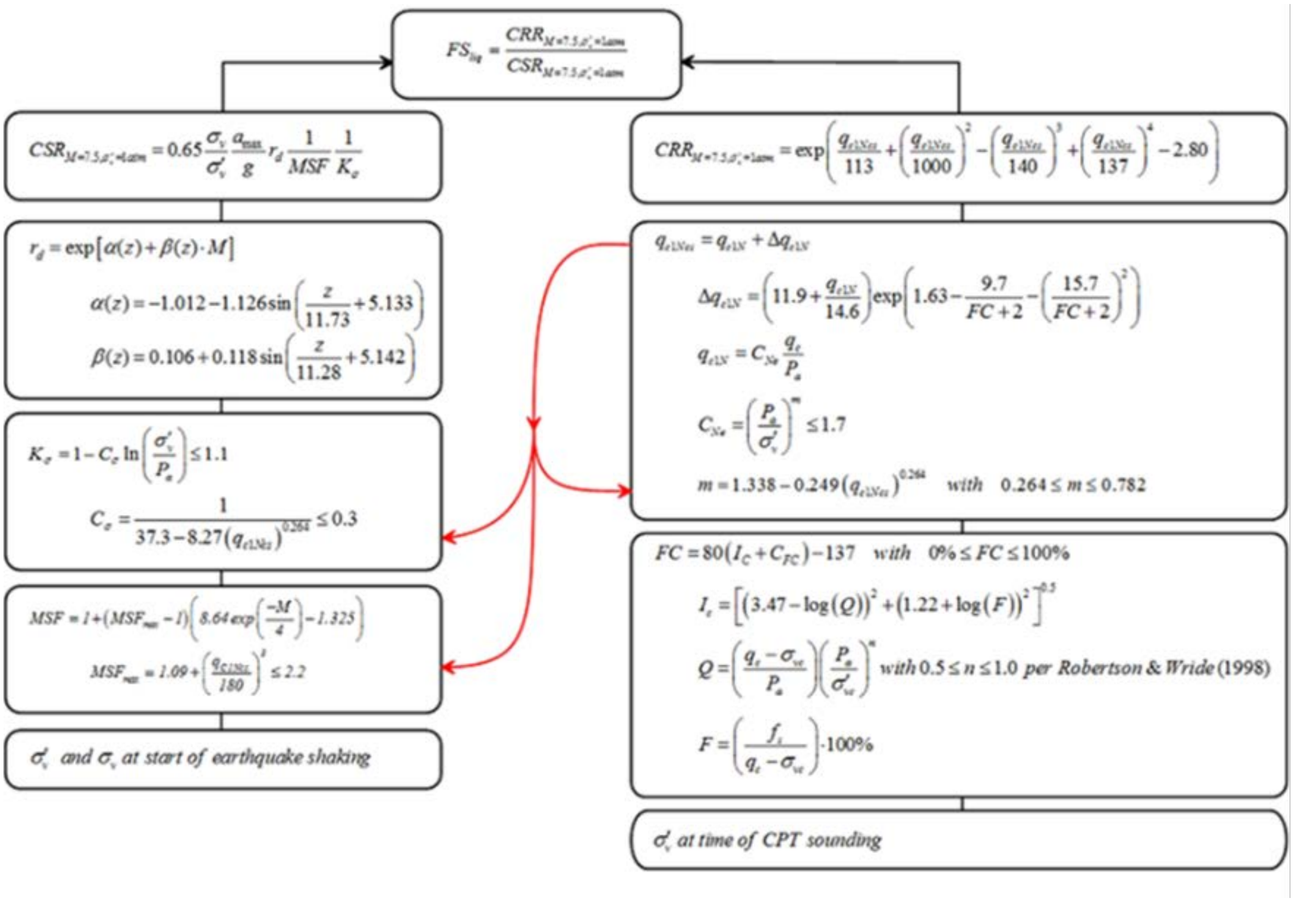


Figure 1: Summary of the Boulanger and Idriss (2014) method applied

CPTu application in heap and leaching dump

Geotechnos was retained to conduct a study to define the liquefaction potential of the heap through the execution of CPTu tests, measurements of pore pressure dissipation and down-hole tests, to measure shear wave velocities (Vs). As part of the work, the taking of samples, laboratory tests, determination of the stratigraphic soil profile and geotechnical parameters have also been included.

Field work

It was planned to execute 19 CPTu drillings located in defined sectors on the surface of the heap with a total of 485.75 linear meters executed. In Figure 2 below, the location of the CPTu tests over the heap are shown in red.

Figure 2: Location of CPTu tests in heap

For reference, the data output from part of the tests is presented in Figure 3, which includes the total tip resistance, shaft resistance, and pore pressure measured for the CPTu tests.

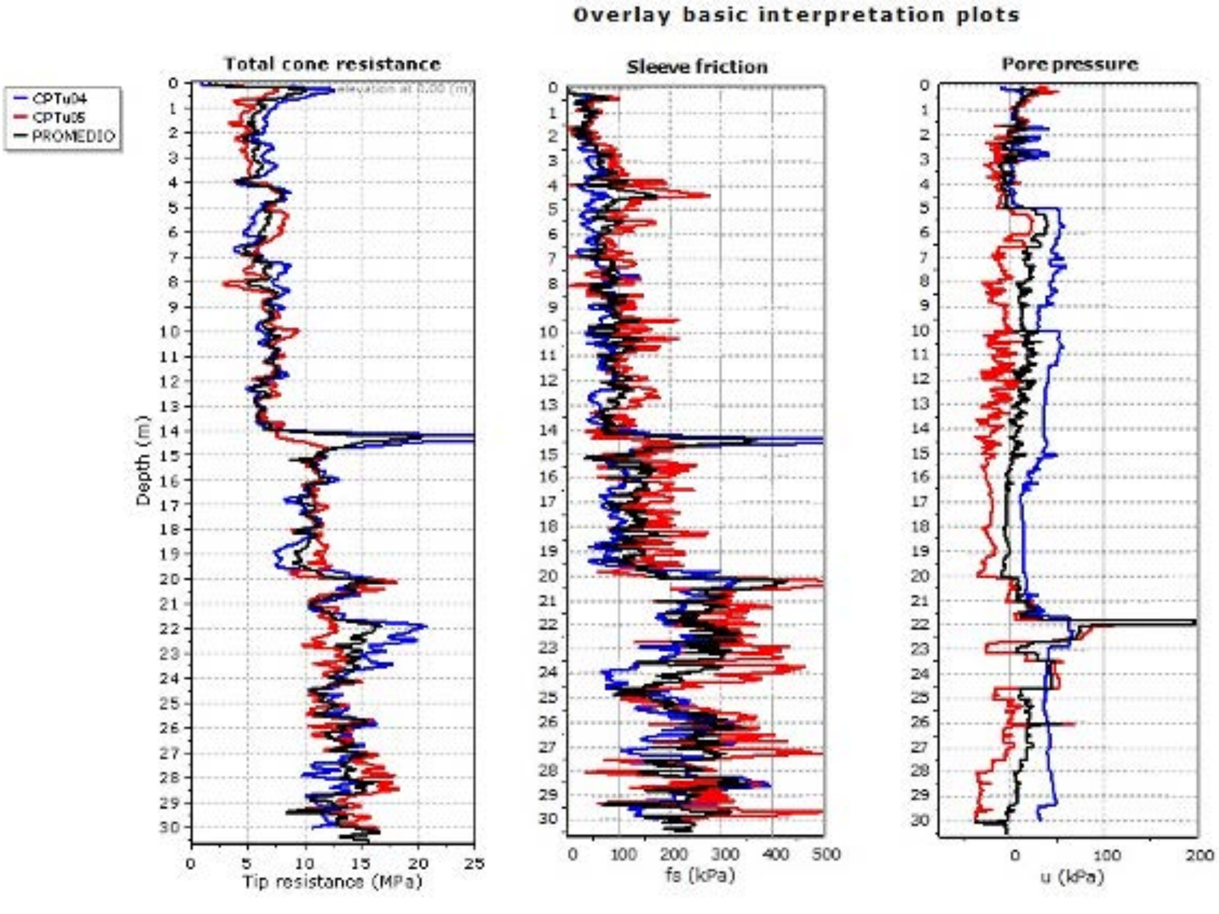


Figure 3: Summary data output of CPTu assays

In addition, a total of 10 down-hole tests were conducted, considering the ratio of 1 D-H test for every two prospections.

Next, in Figure 4, a record of part of the results obtained from the test for a particular CPTu test is presented.

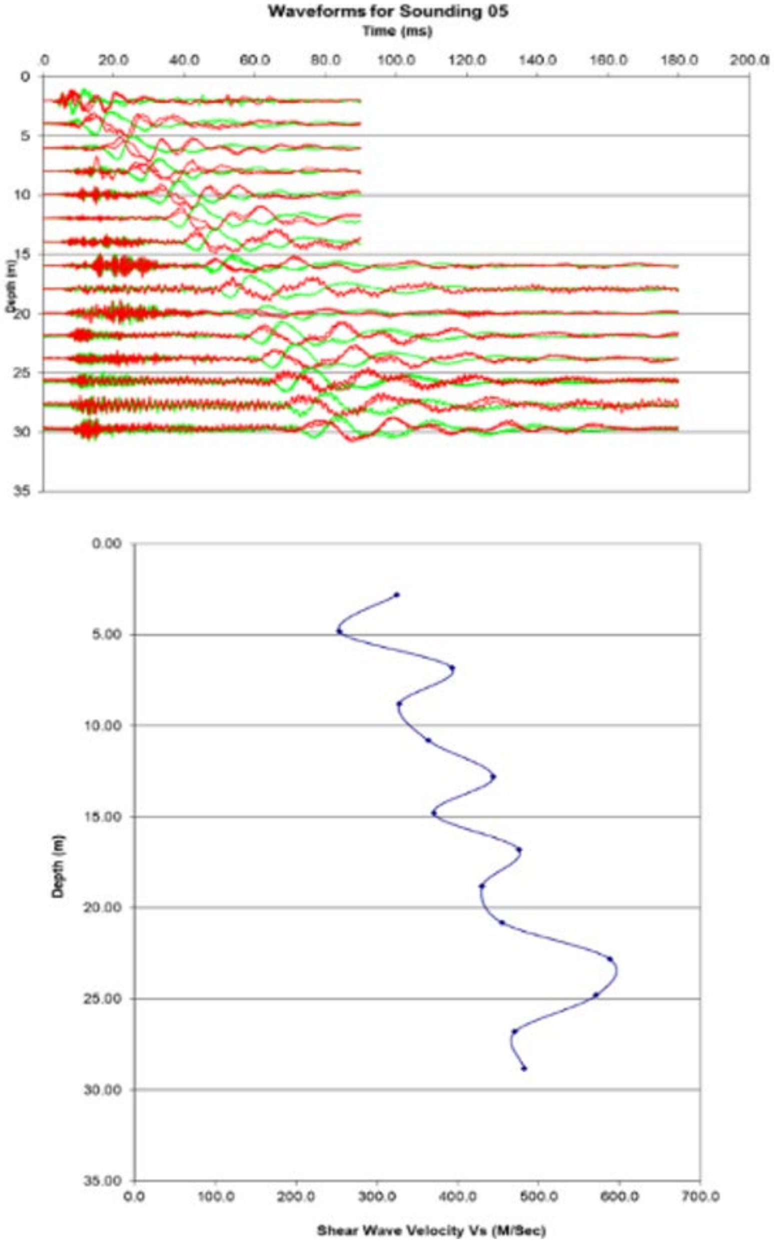


Figure 4: (Top) Shear wave log; (bottom) wave velocities in depth, CPTu

As part of the measurement requirement, it is necessary to determine the degree of saturation of the ore mass in the heap/dump, for which dissipation tests were conducted at different depths at each CPTu test point. The log presents the dissipation of pore pressure (kPa) as a function of a given amount of time (s). The analysis depths correspond to 5, 10, 15, 20, 25, and 30 m, depending on each drilling.

Next, Figure 5 presents a record of the results obtained from the dissipation test in CPTu drilling.

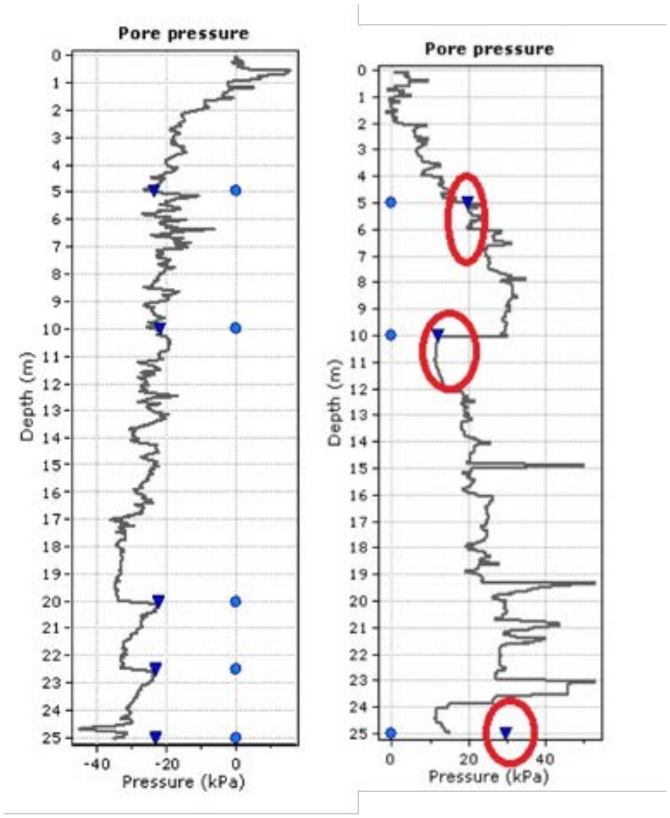


Figure 5: Dissipation tests in CPTu drilling

Pore pressure dissipation test results show zones with negative pore pressures and zones with positive pore pressures close to zero (see Figure 5, left). However, in some dissipation tests possible saturated zones are observed (see Figure 5, right).

The results of the test indicated the level of saturation of the material from 5.0 m deep, and the value of the pore pressures at depth; in this way it is possible to indicate the presence of a water table inside the heap. In some points values close to 0 (equilibrium) of pore pressures were obtained, and in others values were slightly negative and positive.

Sampling

To calibrate the stratigraphic interpretation of the CPTu measurements and the results of dissipation tests, obtaining undisturbed samples was considered to determine their USCS classification and moisture content in the laboratory. The samples were obtained at depths of 5 and 10 meters and although they had high humidity, they were not saturated, confirming that there was no groundwater at those depths. Figure 6 shows the condition of the samples obtained at the point of a CPTu test.

Figure 6: Condition of sample at 5 m depth (top), and sample at 10 m depth (bottom)

The samples were sent to the laboratory for the preparation of the following tests:

- Determination of granulometry (8.102.1 MC Vol 8, December 2003).
- Liquid limit determination (NCh 1517/1 Of. 1979).
- Plastic limit determination (NCh 1517/2 Of. 1979).
- Density of solid particles under sieve No. 4 (NCh 1532. Of. 1980);
- Moisture content (NCh. 1515 Of. 1979)

Stratigraphic profile

It should be noted that the CPTu cannot provide precise information on the physical characteristics of the soil, such as grain size distribution, but it can provide a guide to the mechanical characteristics of the ground and the behavior in-situ in the immediate area of the drilling. From the above, the estimation of the soil type based on the CPT tests is referred to as SBT (soil behavior type).

Robertson proposed the first graphs (SBT) using the basic parameters of cone resistance (qt) and friction ratio (Rf). When penetration resistance and shaft resistance increase in depth, the CPT data requires normalization for overburden stress. Finally, the full normalized plots include an additional plot, based on the normalized pore pressure parameter (Bq).

From the above, it was possible to represent the results in stratigraphic profiles; Figure 7 presents the estimation of the profiles.

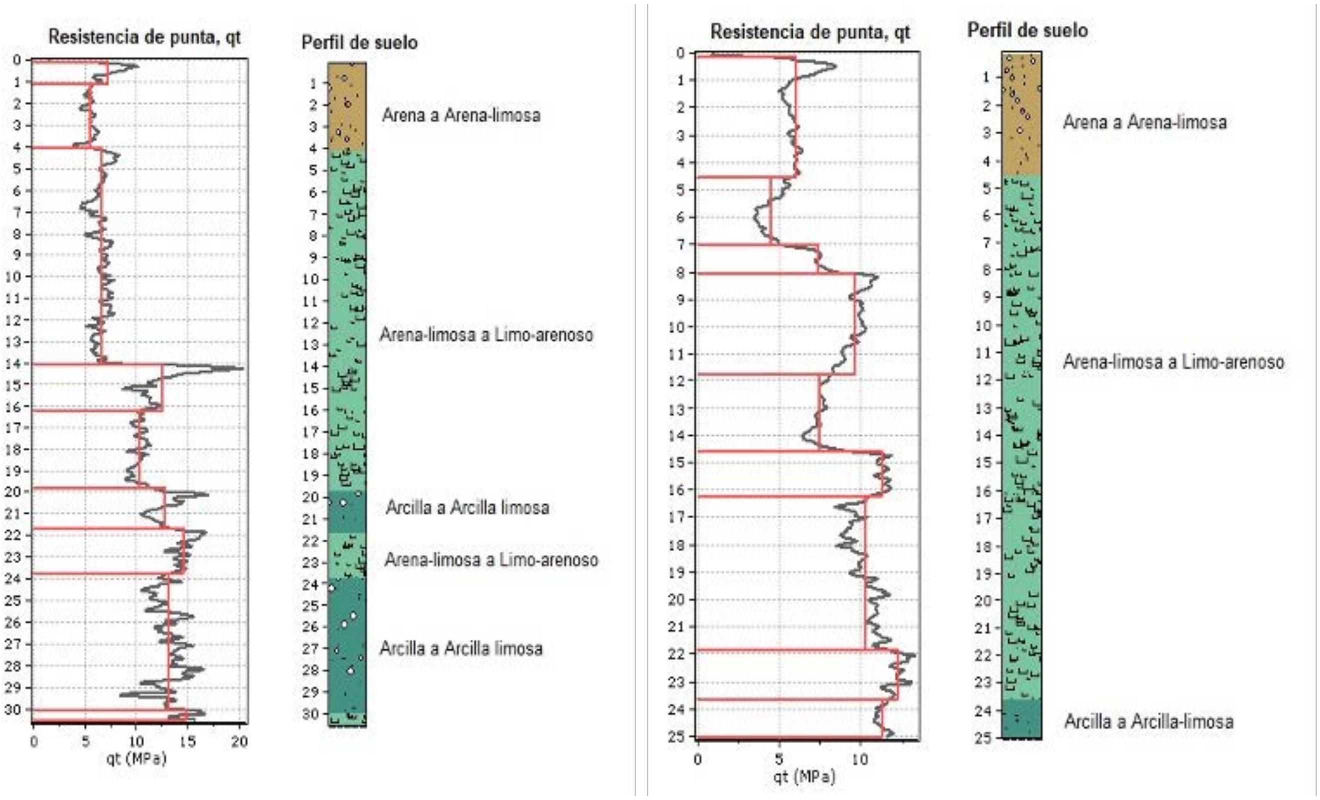
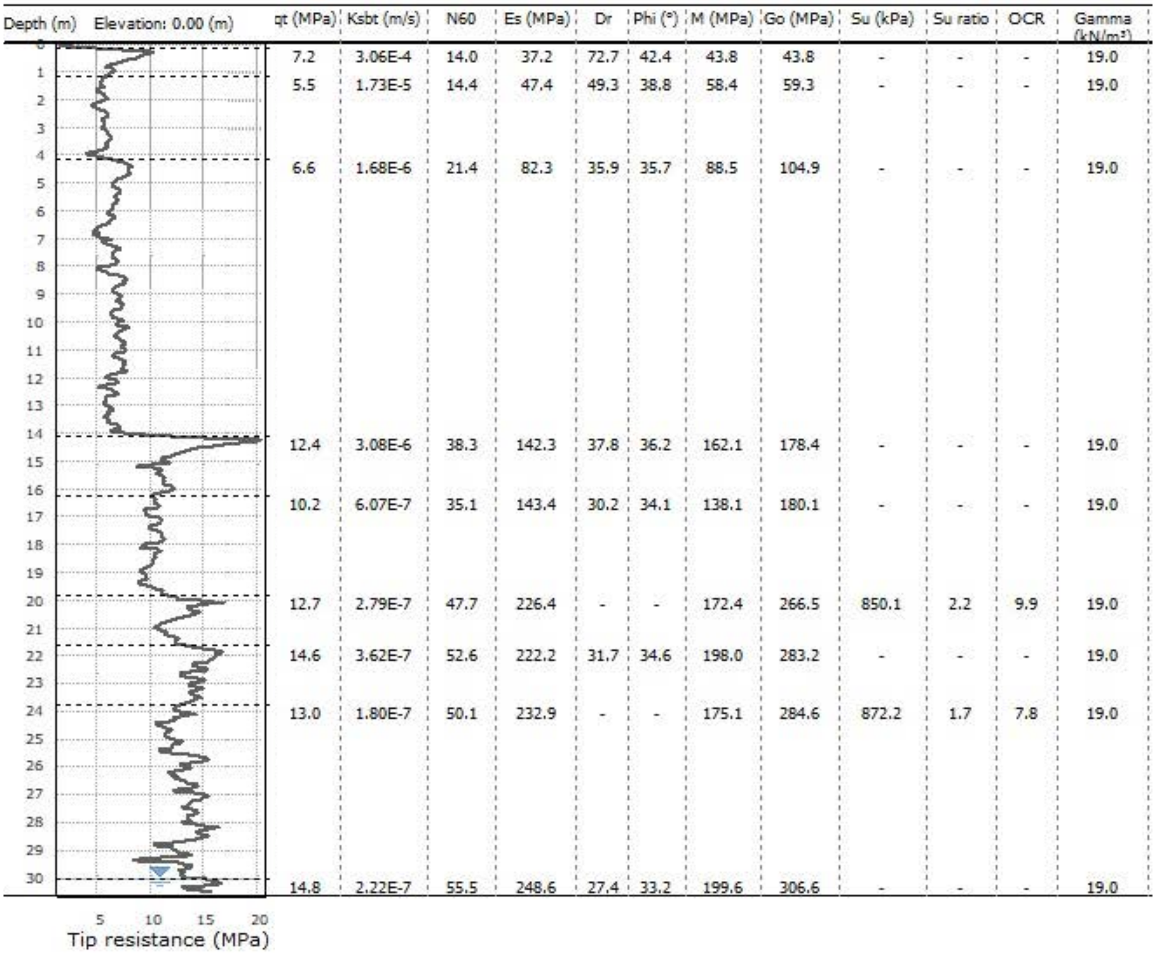


Figure 7: Stratigraphic profile for different CPTu tests

According to Figure 7, it is possible to observe that the profile varies from sand to silty sand in the superficial strata to soils with a higher content of fines (silt and clay) at depth, which is considered consistent with the expected soil profile.

Definition of geotechnical parameters

Together with the stratigraphic profile, it is possible to estimate the profile by layers of geotechnical parameters in depth. In Figure 8, the geotechnical parameters for a particular CPTu test are presented.



qt (MPa)	Ksbt (m/s)	N60	Es (MPa)	Dr	Phi (°)	M (MPa)	Go (MPa)	Su (kPa)	Su ratio	OCR	Gamma (kN/m³)
7.2	3.06E-4	14.0	37.2	72.7	42.4	43.8	43.8	-	-	-	19.0
5.5	1.73E-5	14.4	47.4	49.3	38.8	58.4	59.3	-	-	-	19.0
6.6	1.68E-6	21.4	82.3	35.9	35.7	88.5	104.9	-	-	-	19.0
12.4	3.08E-6	38.3	142.3	37.8	36.2	162.1	178.4	-	-	-	19.0
10.2	6.07E-7	35.1	143.4	30.2	34.1	138.1	180.1	-	-	-	19.0
12.7	2.79E-7	47.7	226.4	-	-	172.4	266.5	850.1	2.2	9.9	19.0
14.6	3.62E-7	52.6	222.2	31.7	34.6	198.0	283.2	-	-	-	19.0
13.0	1.80E-7	50.1	232.9	-	-	175.1	284.6	872.2	1.7	7.8	19.0
14.8	2.22E-7	55.5	248.6	27.4	33.2	199.6	306.6	-	-	-	19.0

Figure 8: Geotechnical parameters deduced from the CPTu test

Liquefaction analysis procedure

The evaluation of the liquefaction potential was conducted using the analysis method proposed by Boulanger and Idriss (2014) and through the measurements of CPTu drilling every 5 cm of depth, the seismic stress (CSR) and the resistance of the material (CRR) were evaluated.

Seismic stress (CSR) is evaluated using the simplified method initially proposed by Seed and Idriss (1967), in which the PGA value is of vital importance for the analysis.

The cyclic resistance (CRR) of the material is evaluated using the measured values of resistance of the soil through the CPTu drilling.

For the liquefaction analysis, the following moment magnitude of the earthquake was assumed:

- Mw: 8.0 (momentum magnitude of the earthquake).

Regarding the maximum acceleration on the surface, a sensitivity analysis was conducted considering the following three cases of maximum acceleration on the surface (PGA):

- 0.3g.
- 0.4g.
- 0.5g.

These three cases consider three return periods (100, 475, and 975 years).

In a first analysis, therefore, it is considered that the material is completely saturated (S = 100%, conservative case) and that the equilibrium pore pressures are equal to 0 throughout the depth analyzed. This scenario corresponds to one with a lower probability of occurrence, but with a higher risk for the operation.

Results with S = 100% and pore pressure u = 0, in depth

a) PGA = 0,3 g:

With the average values of measurements of tip, shaft, and pore pressure of CPTu drillings executed in the area, the results shown in Figure 9 below are obtained for PGA = 0.3 g.

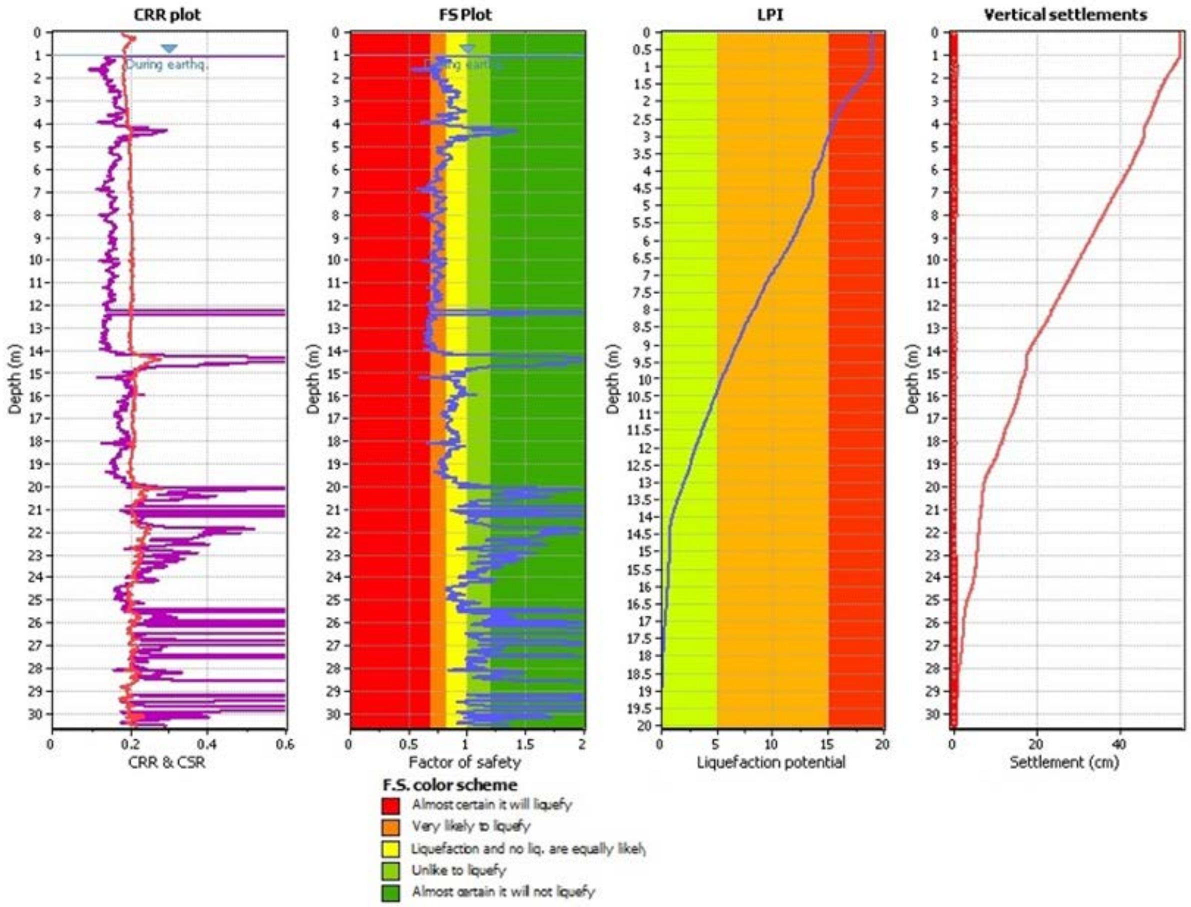


Figure 9: CRR&CSR; F.S; liquefaction and settlement potential, PGA = 0.3 g

b) PGA = 0,4g:

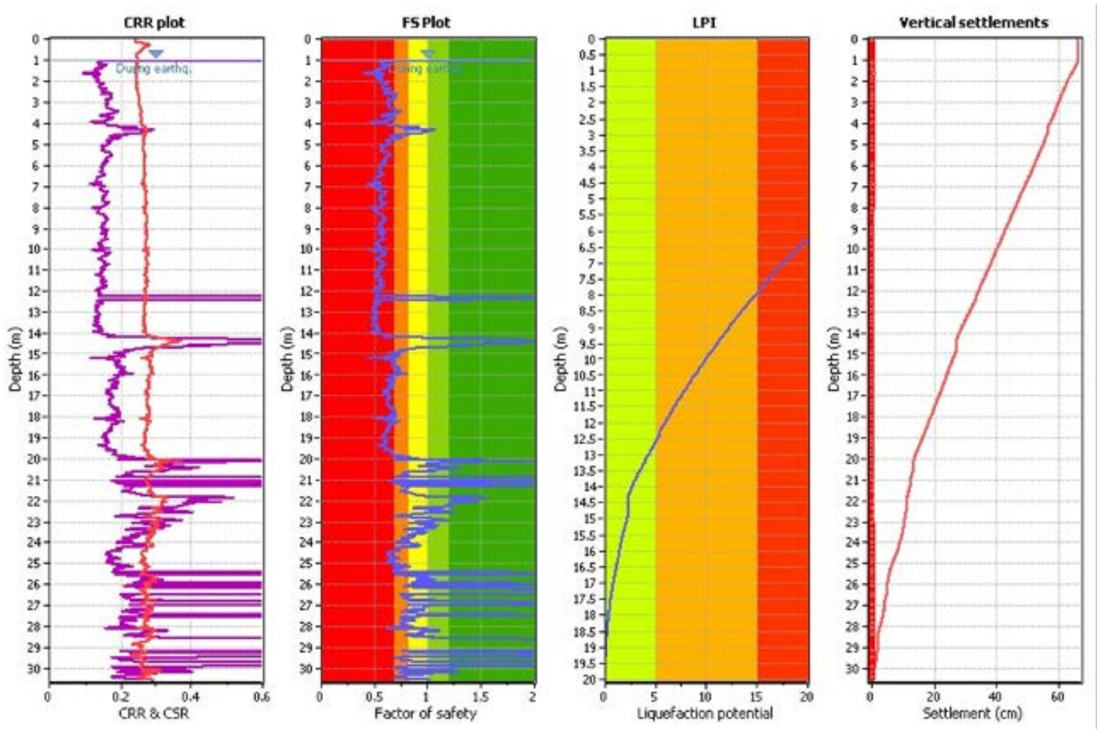


Figure 10: CRR&CSR; F.S; liquefaction and settlement potential, PGA = 0.4 g

c) PGA = 0,5g:

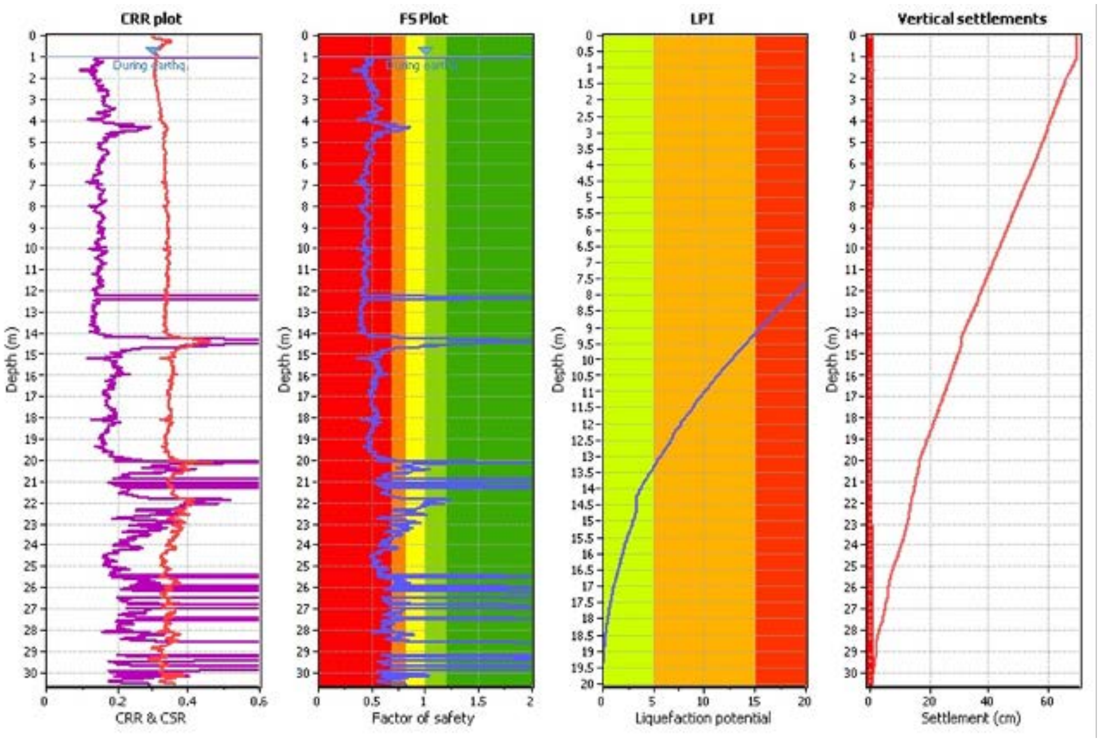


Figure 11: CRR&CSR; F.S; Liquefaction and settlement potential, PGA = 0.5 g

In summary, the liquefaction analysis in the heap shows that there is a risk of liquefaction down to at least 15 to 25 m depth, depending on the sector. The factor of safety tends to increase with depth because the lower layers have had a longer time to consolidate and are subject to greater confinement.

This scenario corresponds to a more unfavourable situation due to a condition where there is a saturation level of 100% and pore pressure = 0, and it corresponds to a less probable case, but with greater risk.

Influence of the saturation degree of the material in the heap

The results of the estimation of the degree of saturation in depth are shown in Figure 12. In general, it can be seen that the samples obtained during the prospecting are not saturated. This coincides with the appreciation in the field when obtaining the samples.

There is no clear trend as to whether the saturation goes up or down with depth; this depends on the location observed and probably when the measurement is made.

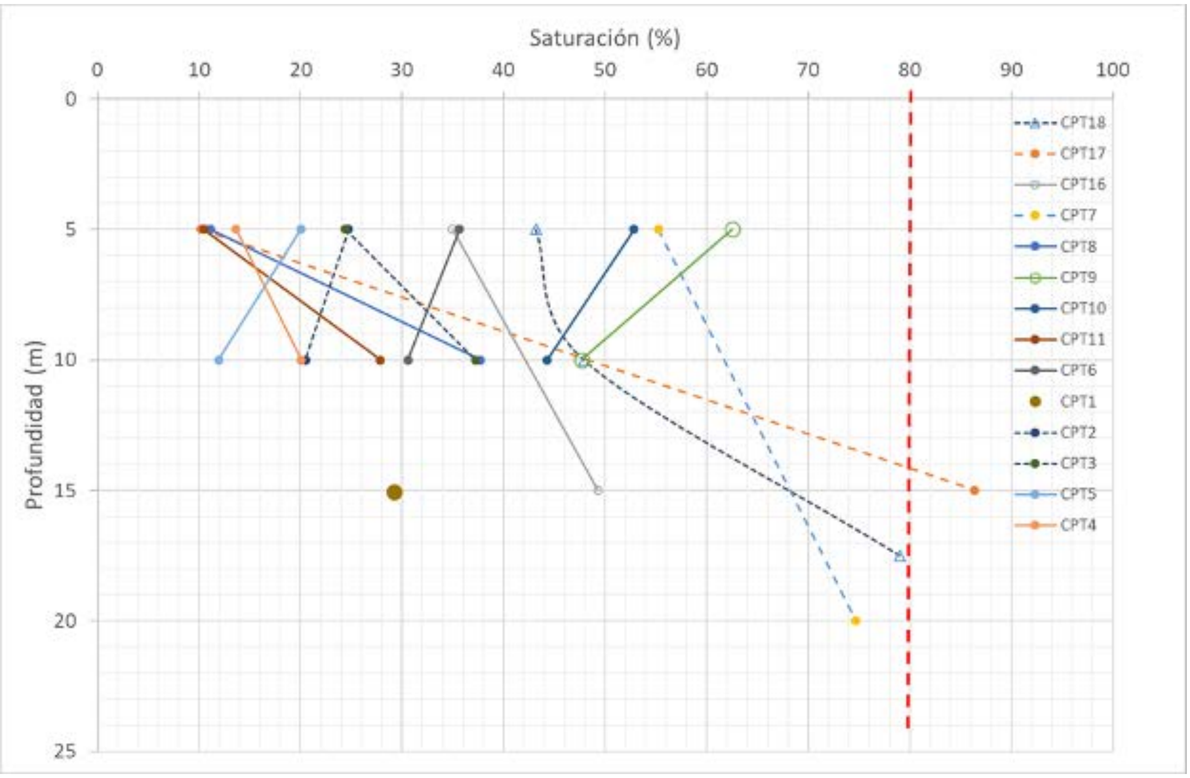


Figure 12: Degree of saturation deduced

Figure 12 shows that the maximum saturation found is 86%. Of the latter, only one sample is above the 80% observed in the CPTu-14H probe, the rest of the samples remain below 80%.

It is important to mention that it has been found that resistance to liquefaction rises rapidly for degrees of saturation below 98%, and that below 90% it is very difficult to achieve this phenomenon in practice (Yang et al., 2004; Eseller-Bayat et al., 2013).

Based on the foregoing and considering conservatively as 80% the saturation limit below which liquefaction would not be generated, then it can be considered that there is, at the time the campaign is conducted, a low probability that a liquefaction phenomenon will be generated in the heap. It is estimated that for closure the situation would be similar with a partially saturated material, which would improve over time due to the drainage that would occur inside the heap.

CPTu over dump leach

The same methodology was intended for application over a dump leach at the same operation. Since scope, objectives, and methodology were the same as previously described, no further details will be included in this section.

The application of the method was conducted with difficulty since there was much blocking experienced in the penetration phase, and in some cases the penetration did not reach a depth of more than 1 or 2 m. In some measurements it was necessary to repeat the execution at a nearby point. In the case of the dump leach, the effort was much higher than in the case of the heap leach, and results and interpretation are to be used with discretion, considering that a much more detailed evaluation by geotechnical experts and operations records will indicate whether CPTu may proceed, since technical and economic efforts are high, and the probability of encountering a good deal of blocking due to boulders and oversize material might make it impossible to proceed.

Conclusions

Conclusion 1

It is deduced that the tested areas of the heap consist mostly of silty sand on the surface, sandy-silt in the center, and clay materials at the bottom of the heap. These types of materials are consistent with what is expected based on mine activity.

Conclusion 2

According to the results of CPTu soundings, dissipation tests, and data obtained from piezometers, no hydrostatic pore pressure (as water table) is detected in the heap. Readings from CPTu soundings do not agree with the presence of an actual phreatic surface. This is attributed to the fact that heap leaching is an operation that consists of material being deposited in layers with high moisture content. The degree of saturation of the material in the heap varies due to changes in moisture content during deposition, evaporation, and consolidation of this earth structure. To determine the degree of saturation with higher confidence, it was necessary to complement the readings from CPTu, with soil samples obtained at different locations and depths. Variations in degree of saturation were found in this study; some zones were found to be close to complete saturation and others had a degree of saturation as low as 10 to 20%.

Conclusion 3

The liquefaction potential of the heap was evaluated for the most unfavourable condition (S = 100%, conservative case). A conservative analysis shows that there is a risk of liquefaction down to at least 15 to 25 meters depth, depending on the analyzed area; pore pressures are considered equal to 0 throughout the analyzed depth to calculate effective stresses.

Conclusion 4

A sampling program was carried out to analyze the influence of the degree of saturation in the heap. It was observed that, in general, soil samples obtained during the in-situ testing program, except for one point (S = 86%), are not close to saturation, which coincides with observations made in the field when obtaining the samples. There is no clear trend as to whether the saturation increases or decreases with depth, this depends on the location observed and probably the time of the year when the measurements are made.

Conclusion 5

Conservatively assuming a saturation threshold of S = 80%, below which liquefaction would not occur, it can be deduced that there is a low probability of triggering a liquefaction phenomenon in the heap at the time the campaign was conducted.

Conclusion 6

In terms of the CPTu application, this testing is considered to be adequate for its use in heap leaching and the results from this execution are considered to be consistent with what was expected geotechnically. The value of the gathered information is of very high importance and the use of CPTs soundings is considered a suitable alternative for geotechnical characterization for heap leach facilities.

Conclusion 7

On the other hand, the difficulties encountered for the execution over the dump leach leads to the recommendation that even though the method should not be totally discarded, the geotechnical conditions must be evaluated in advance and if there are very heterogeneous materials, the cost and effort should be reviewed before proceeding.

Acknowledgements

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