Crushed Leached Ore Characterization, Response, and Liquefaction Potential

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Abstract

Heap leach pads are an attractive cost-benefit extraction technique for low-grade gold, silver, and copper ores around the world. In South America the complex terrain features, high altitude, extreme weather conditions, high seismic activity, and limited suitable locations impose a series of engineering constraints for designing a heap leaching operation. Therefore, one of the critical steps is an adequate field and laboratory investigation to perform an optimal geotechnical characterization to ensure a correct geotechnical and especially seismic performance.

This paper presents a practice-oriented methodology for the evaluation of the seismic performance of under-operation leach pads in a case study. Input data for this methodology consists of geotechnical investigations of the stacked crushed ore, such as test pits, geophysical surveying, and CPTu; complemented with a robust geotechnical laboratory testing program. Similar to tailings dam engineering, the crushed ore response is classified as dilatant or contractive depending on the in-situ soil behaviour, drainage (drained or undrained) conditions present within the ore; and appropriate strength parameters corresponding to each type of ore are assigned.

This approach allows one to characterize a heap leach pad, identifying areas of material with contractive or dilatant behavior. Further, the assessment of the liquefaction potential is performed on the locations where CPTus are available, and a combination of CPT triggering procedures and specific site response analyses is suggested to this end. With this information, the geotechnical characterization is complemented by assessing the liquefaction potential of the crushed leached ore within the heap leach pad.

Introduction

A heap leach pad (HLP) is a heterogeneous structure with the stacked leached ore having variable geotechnical properties due to factors that modify their nature such as geology, mineralogy, and alteration of the deposit, ore degradation during leaching, operational issues, engineering design changes, and environmental factors. From an engineering point of view, understanding the heterogeneity in the ore is key to ensure the correct performance of the facility; this is even more relevant in regions with high seismic activity.

This paper describes the geotechnical characterization and evaluation of the main section of a typical HLP of crushed ore based on cone penetration tests (CPTu), complemented with test pits, boreholes, and laboratory tests. The investigations and analyses are focused on the assessment of the liquefaction potential for a design earthquake scenario. Supporting laboratory tests were performed, and the results were used to determine the ore drained and undrained strengths. It was found that the combination of comprehensive field and laboratory testing campaigns produced a high-quality characterization of the stacked crushed leached ore for liquefaction potential assessment.

In the following sections, representative results and trends are presented and discussed.

Geotechnical characterization of crushed leached ore

The geotechnical characterization of stacked leached ore is challenging. In this study three types of crushed ore were identified depending on the mine production: sand-like, transitional, and clay-like. The crushed stacked ore forming the heap is highly influenced by the production schedule; hence, coarse and fine ores are not uniformly distributed within the HLP. The geotechnical characterization procedure described in this paper helps to identify the location and extent of each type of crushed ore within the HLP and provides an estimate of the type of mechanical response.

The type of response is classified as contractive and dilative; thus, these classifications can be outlined: sand-like contractive/dilative, transitional contractive/dilative, and clay-like contractive/dilative. Thus, beyond the very useful CPTu field data, one-dimensional consolidation tests, consolidated undrained (CU) triaxial tests, consolidated drained (CD) triaxial tests, and hydraulic conductivity tests were performed as part of the investigation program. A series of 09 CPTu were performed along the main cross section of the HLP, located at different elevations, and reaching depths ranging from 10 m to 60 mm as shown in Figure 1. Pore pressure dissipation tests (PPDT) were performed to determine levels of saturation within the HLP. Shear wave velocities (Vs) were estimated based on the Robertson and Cabal (2015) correlation.

To classify the crushed ore into coarse or fine, the soil behaviour type (I_c) of Robertson and Wride (1998) was employed in addition to index laboratory tests. The crushed ore was considered to be sand-like if $I_c \leq 2.5$, transitional if $2.5 < I_c < 2.7$ or clay-like if $I_c \geq 2.7$. The hydraulic conductivity (k_v) tests indicate k_v values of 1.0E-04 to 1.0E-03 m/s for the coarser ores, and of 1.0E-08 to 1.0E-05 m/s for the finer ore. These k_v values agree well with the CPT-based characterization. Grain-size distributions and 1D consolidation tests also support the CPT-based classification. The determination of the response of the stacked crushed leached ore was based on tailings dams engineering design, which uses the approaches of

Robertson (2016) and Jefferies and Been (2016) to distinguish between contractive and dilative soils. The Robertson (2016) approach employs the clean sand equivalent normalized cone resistance ($Q_{tn,cs}$) where the limit between contractive and dilative responses is $Q_{tn,cs} = 70$. The approach of Jefferies and Been (2016) employs the state parameter (ψ) with the contractive/dilative threshold located at $\psi = -0.05$ following the findings of Shuttle and Cunning (2007).

The undrained strength envelope was initially estimated from the p'- q plots derived from CU triaxial tests as shown in Figure 2. Then, the trends in the data were verified with a simplified Cam-clay based expression for the normalized undrained strength (S_u/σ_v'), which is found to vary within 0.26 to 0.28.

In addition, CD triaxial tests were considered to evaluate the peak drained strength of the crushed ore (see Figure 3), which was first estimated from the envelope resulting from the test results. Then, the plane stress invariants *t* and *s*' of Wood (1994) were used to determine the drained friction angle, which varies within 35 to 38 (see Figure 3). Table 1 summarizes the parameters estimated for the crushed leached ore according to its behaviour.

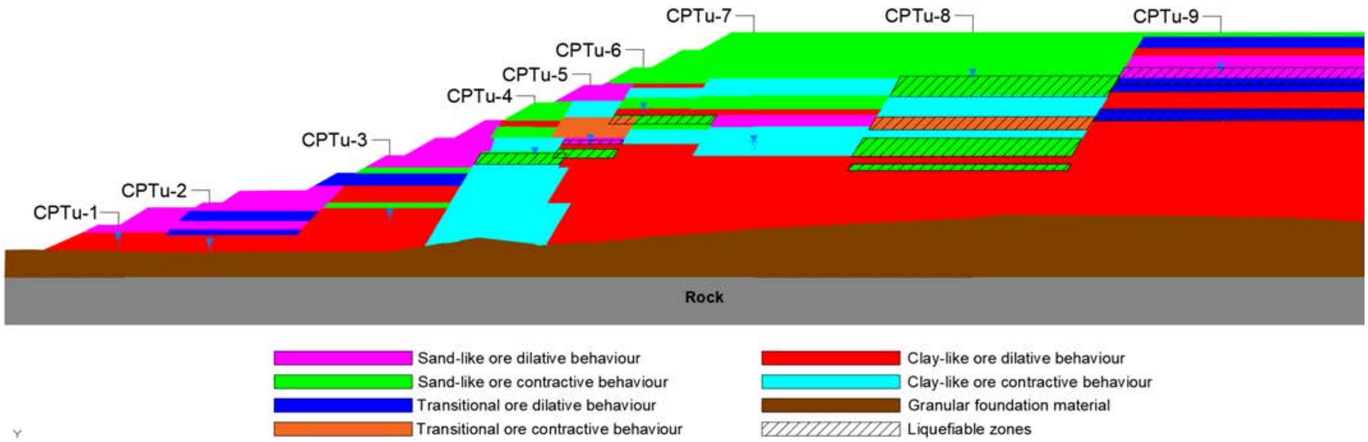

Figure 1: Representative cross section showing material characterization

Table 1: Summary of crushed ore strength parameters

Material	Type of response	Strength parameters		
		c'	phi'	S_u/σ_v'
Coarse ore	Contractive	–	–	0.28
	Dilative	0	38	–
Fine ore	Contractive	–	–	0.26
	Dilative	0	35	–

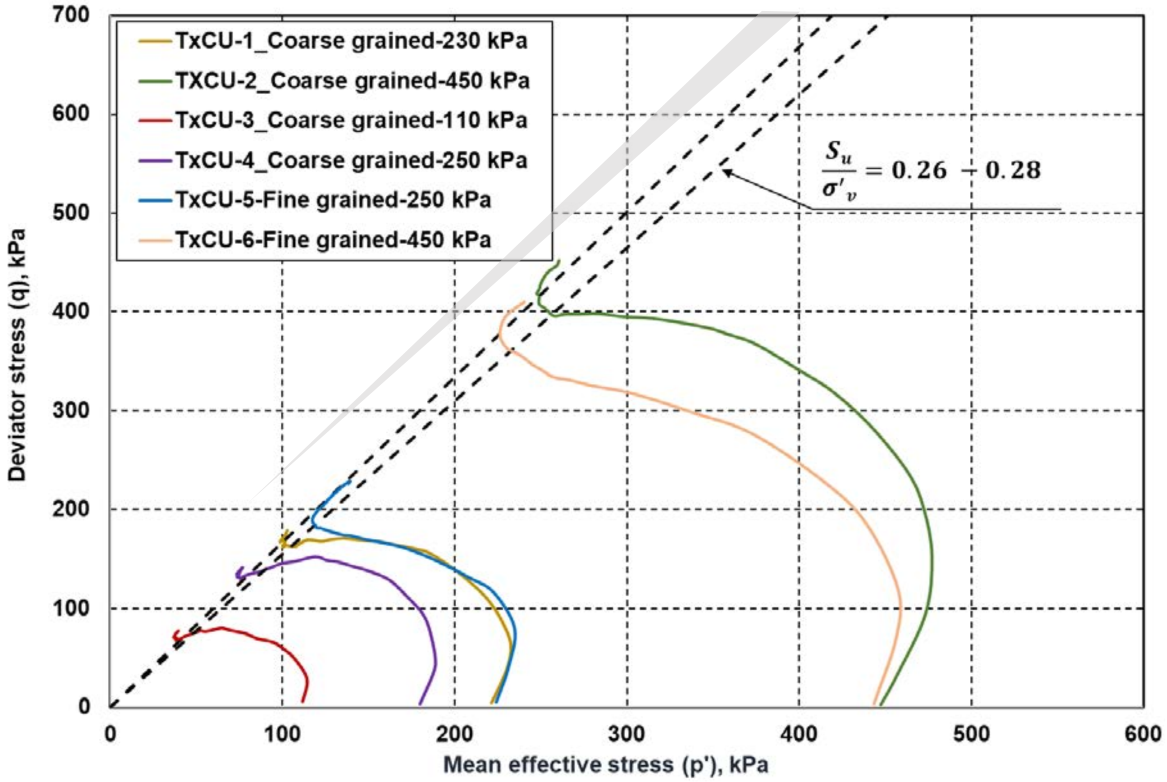

Figure 2: Estimation of crushed ore undrained strength

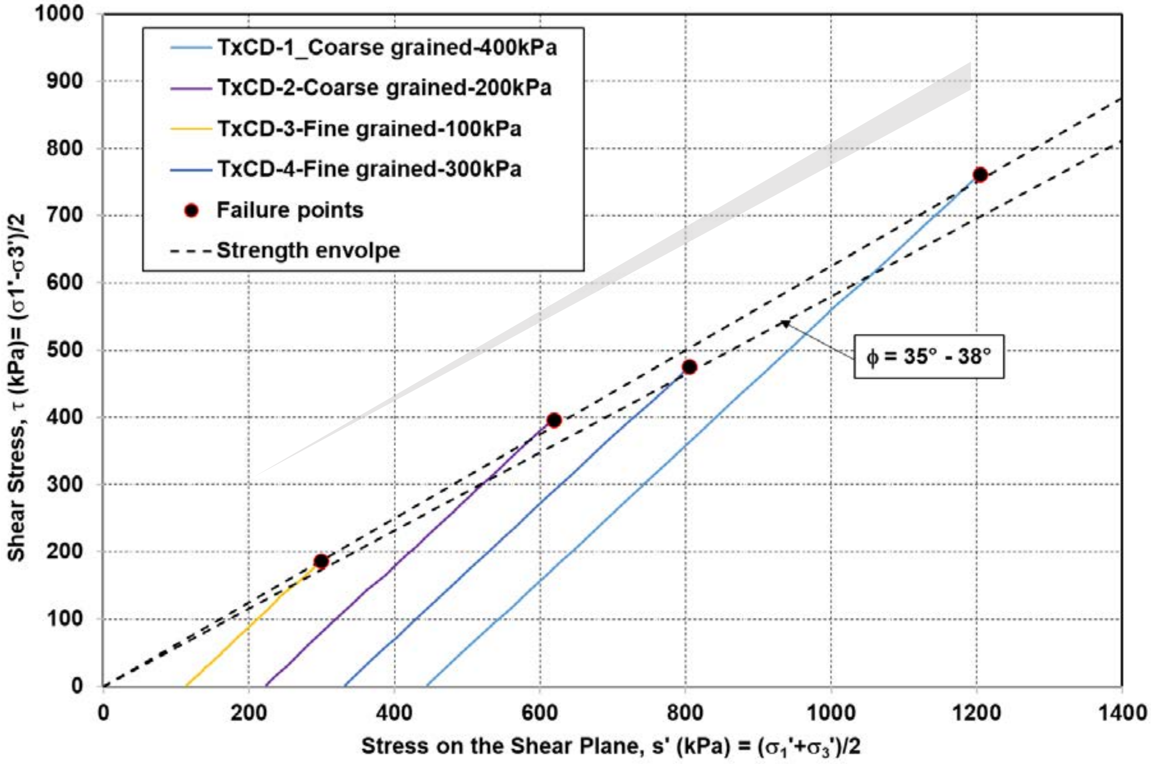

Figure 3: Estimation of crushed leached ore drained strength (Wood, 1994)

Seismic response assessment

One-dimensional nonlinear time-domain site-response analyses (SRA) were carried out at each CPT location using the DEEPSOIL V.6.1 program developed at the University of Illinois at Urbana Champaign, with the objective of developing profiles of induced acceleration and of induced peak shear stresses. Each soil column considered from the bottom up: an elastic half space rock basement, a granular foundation material, and a layered system of fine (clay-like material) and coarse (sand-like and transition material) ore.

To model the stress-strain response, the DEEPSOIL general quadratic model (GQ/H) that considers a nonlinear backbone formulation was employed. An impermeable boundary condition was set at the bottom of the profile with the water table location obtained from the pore pressure dissipation tests. G/G_{max} and damping curves for the fine and coarse ores were modeled with the Darendeli (2001) formulation, while the granular foundation was modeled with the curves of Menq (2003). The authors analyzed the effect of modeling the low permeability interface between the foundation and the ore using the procedure of Yegian et al. (1988), but smaller amplifications were obtained compared to the models without interface; therefore, conservatively in this study the interface was not modeled in the SRA. A series of seven ground motions were used for the modeling: AT01, CH70, LIM66, LIM74, MI85, PI07, and TAR05.

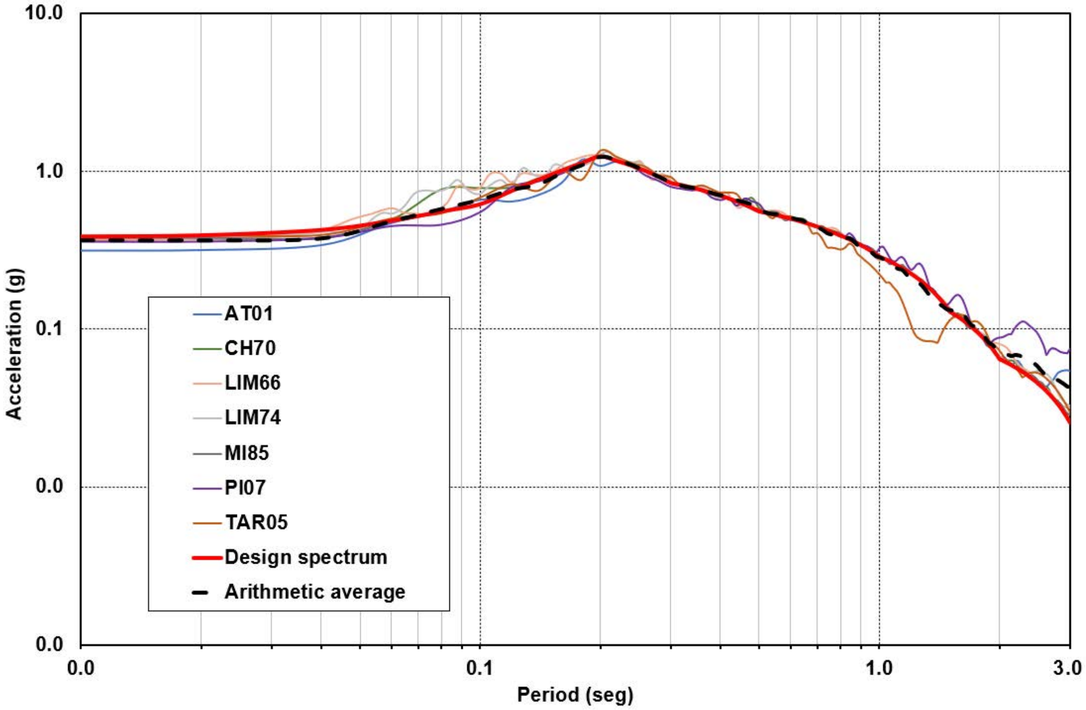

Figure 4: Spectrum adjustment of analysis earthquakes

The seismic demand at the HLP site was estimated from a site-specific seismic hazard analysis. The deaggregation indicates that a M_w 8.8 earthquake and the 475-year Uniform Hazard Spectrum (UHS) are representative for design. To select the suite of ground motions, the arithmetic mean of the spectra of the seven ground motions was fitted to the target UHS. In the fitting procedure, different scale factors were applied to each ground motion until an acceptable fit was achieved. The fitted response spectra of the selected motions are displayed in Figure 4.

Figure 5 shows one-dimensional SRA results for a representative HLP profile at the CPT-8 location where sand-like, transitional, and clay-like ore are shown with different colours. The distribution of horizontal accelerations within the heap of crushed leached ore is presented in Figure 5(a) for the seven ground motions used in this study. The variability due to the ground motion characteristics and crushed leached ore geotechnical properties in the acceleration distribution is highlighted by the lower and upper bounds, which range in the order of 0.1 g. A significant acceleration amplification is observed at a depth of 50 m, which corresponds to a layer of granular ore sandwiched by two relatively thin layers of softer materials. A similar effect is observed at a depth of about 40 m. At the surface of the HLP the overall amplification factor (AF) is 1.25.

The earthquake-induced cyclic shear stress ratio (CSR) at the same CPT location is shown in Figure 5(b). Similarly, the variability in the CSR is highlighted by the lower and upper bounds. It is observed that the variability in the CSR is smaller than the variability in the acceleration in the whole profile. Also, the CSR is significantly higher in the top 20 m of the HLP, and at the surface the overall amplification factor for the CSR (AF_{CSR}) is 2.7.

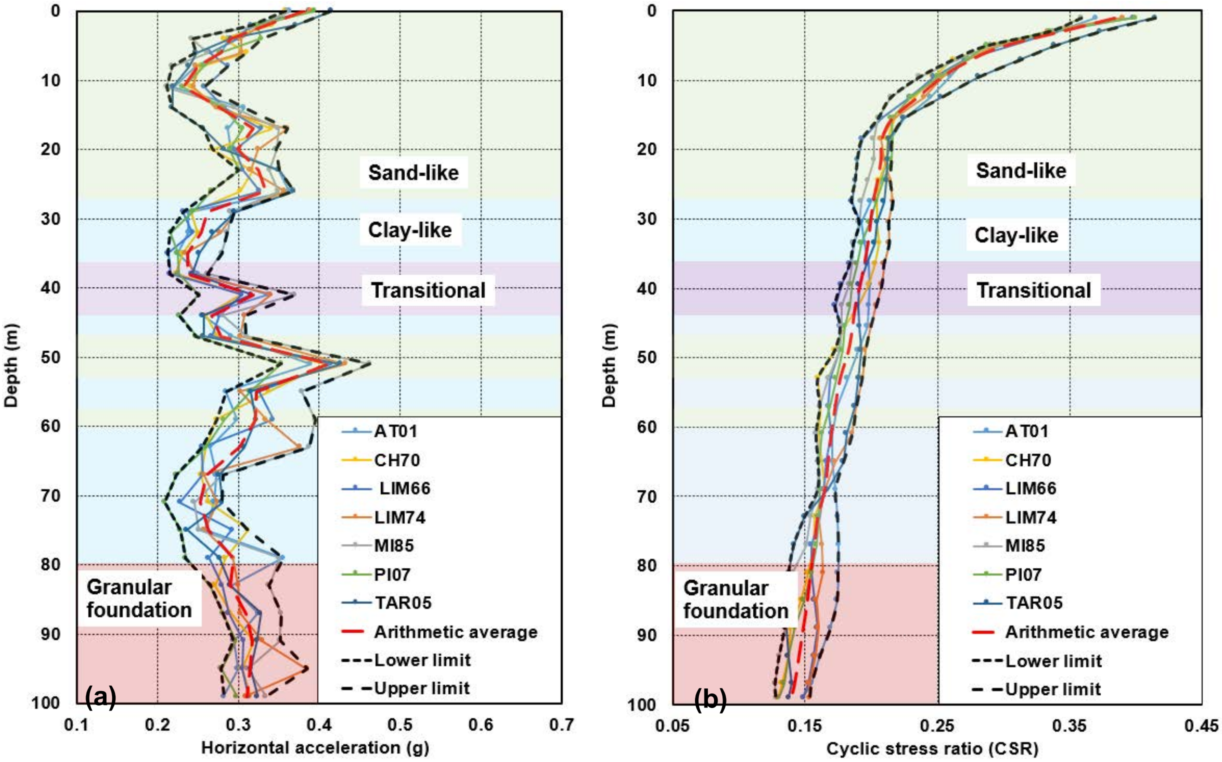

Figure 5: (a) Horizontal acceleration distribution with depth;
(b) Cyclic stress ratio variation with depth

Liquefaction potential

The liquefaction n potential of the crushed leached ore was assessed using the stress-based method proposed by Seed and Idriss (1971) as presented by Youd et al. (2001). The simplified approach compares the cyclic stress ratio (CSR) to the cyclic resistance ratio (CRR) to obtain the factor of safety against liquefaction (FS_L) as shown in Equation 1.

$$FS_L = \frac{CRR_{7.5}}{CSR} \times k_\sigma \times MSF \qquad \text{(Equation 1)}$$

Where:

$CSR_{7.5}$ is the cyclic stress ratio for a 7.5 earthquake magnitude;
k_σ is the correction factor for significant effective confinement stresses; and
MSF is the magnitude scaling factor.

The results of the SRA were used to determine the CSR profiles at 9 representative columns in the analyzed HLP. The SRA was performed using DEEPSOIL. CRR profiles were determined based on empirical relations based on the CPT results. Generally, the CRR was calculated for a base scenario with magnitude 7.5 ($CRR_{7.5}$), then k_σ and MSF factors were applied to correct for depth and magnitude effects. The FS_L for coarse ore materials (sand-like and transition soils) were calculated as per Robertson and Wride (1998). Due to the fact that the first 15 m to 25 m are not saturated and thus are non-liquefiable, the static bias factor (k_α) was not incorporated in the evaluated of FS_L.

Also, ore characterized as clay-like with $I_c \geq 2.7$ was initially assumed to not liquefy, and it is recommended to assess the liquefaction susceptibility for these materials using the procedures of Bray and Sancio (2006) and the strain softening using Idriss and Boulanger (2008). Zones of saturated crushed ore that have a FS_L less than 1.1 may undergo cyclic liquefaction. If unsaturated, the material was considered not susceptible to liquefaction. Figure 6 shows the $(Q_{tn})_{cs}$, state parameter and the liquefaction potential assessment based on FS_L at depth for the coarse ore at the analyzed heap profile.

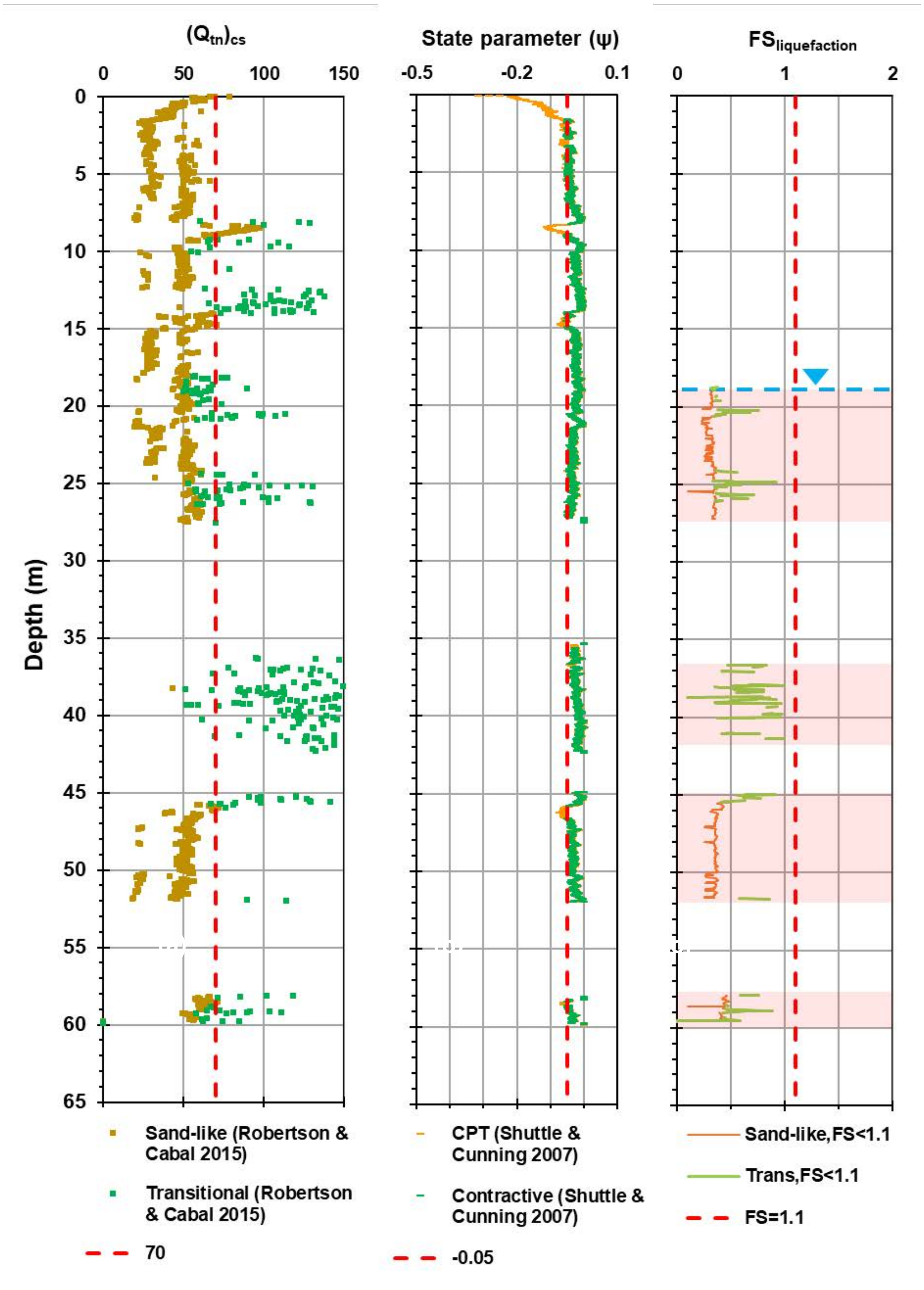

Figure 6: Liquefaction potential assessment results

Based on the results shown in Figure 6, it can be concluded that extensive liquefaction in the HLP profile is expected to occur; therefore final post-earthquake stability analyzed is recommended based on the above and results at other locations in the same main section of the HLP.

Conclusion

This paper presents a practical methodology for the geotechnical characterization of a crushed ore profile of a HLP, analysis of the seismic response and assessment of the liquefaction potential. The methodology is based on the Robertson and Wride (1998) approach, using the I_c parameter to define the ore as sand-like, transitional, or clay-like. The approaches of Robertson (2016) and Jefferies and Been (2016) were used to determine the dilatant or contractive response of the crushed ore. According to Figure 4, both approaches are valid and produce similar results; therefore, it is suggested to use both in a complementary fashion to obtain consistent classifications. SRA suggests that significant acceleration amplification can occur within the HLP and at the surface, depending on the HLP layering. Likewise, an increase of the CSR can be observed in the first 20 m. The analysis of several ground motions compatible with the design spectrum allowed the estimation of the variability in the acceleration and CSR profiles.

To determine the liquefaction potential, a practice-oriented stress-based methodology was used to calculate the CRR and CSR of the crushed ore of the case study. For this paper the CSR was estimated from a series of SRA using the DEEPSOIL program, and the estimation of the CRR for the coarse ore was based on the method of Robertson and Wride (1998). Preliminary, fine ore with $I_c > 2.7$ was assumed to be non-liquefiable. However, it is recommended to assess the liquefaction susceptibility for the fine materials using the procedures of Bray and Sancio (2006) and the strain softening behaviour based on Idriss and Boulanger (2008). Even though the saturation conditions within the HLP allowed a 1D evaluation, the authors are currently performing a series of 2D dynamic analyses for further assessment of 2D effects.

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