

Seismic response analysis and seismic induced permanent displacement calculation on heap leach pads

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Abstract

There are many heap leach pad projects located in highly seismic regions; however, little is known about the seismic response and the calculation of the seismic induced permanent displacements of these facilities. Seismic responses can be analyzed as 1D, 2D, or 3D models; this kind of analysis models the dynamic behavior of the soil when an earthquake strikes, and by applying different approaches the induced displacements on a leach pad can be calculated. The calculation of the seismic induced displacement on a leach pad is a rigorous criteria in comparison to a pseudo-static factor-of-safety calculation, which is routinely used in geotechnical practice for these kind of facilities. This study is focused on the application of 1D seismic response analysis and seismic induced displacements by two different methods in a heap leach pad.

The leach pad liner system is generally composed of geomembrane and low-permeability soil, which generates an interface as a weak zone. This interface constrains the design due to its low shear strength in comparison to other materials involved in the heap stability analysis, such as the ore and foundation. According to research performed by various authors, the maximum displacement induced by an earthquake to be tolerated by a geomembrane varies from 10 to 30 cm, which is a very small displacement compared to other typical geotechnical structures.

The methods to apply for the calculation of the seismic induced permanent displacements of a leach pad are the Newmark (1965) method modified by Houston et al. (1987) and the Bray and Travasarou (2007) method; those methods require a seismic response analysis which was performed with the software Deepsoil (Hashash, 2014) by the equivalent linear method using Yegian et al.'s (1998) recommendations for the dynamic response of geosynthetics. As for the earthquake records, a database of Peruvian recordings was matched to the site's uniform seismic hazard response spectra, degradation curves were used from the existing literature for the materials found at the leach pad, and MASW tests were performed to obtain the shear wave velocity and therefore the maximum shear modulus of these materials.

Finally the Newmark method (1965) modified by Houston et al. (1987) and the Bray and Travasarou method (2007) were compared. These methods represent a quick and economical calculation for determining in a better way the seismic stability of a heap leach pad in comparison to more advanced methods that involve a complex numerical analysis; however, the latter will be always required for complex situations or very critical projects.

Introduction

The following research is focused on the application of advanced methods to determine the physical stability of a heap leach pad under seismic conditions, which has commonly focused on pseudo-static analysis by means of a selected seismic coefficient. In this case, the determination of seismic stability will be based on serviceability, which is determined by the maximum displacement that a heap leach pad liner may stand under seismic loading.

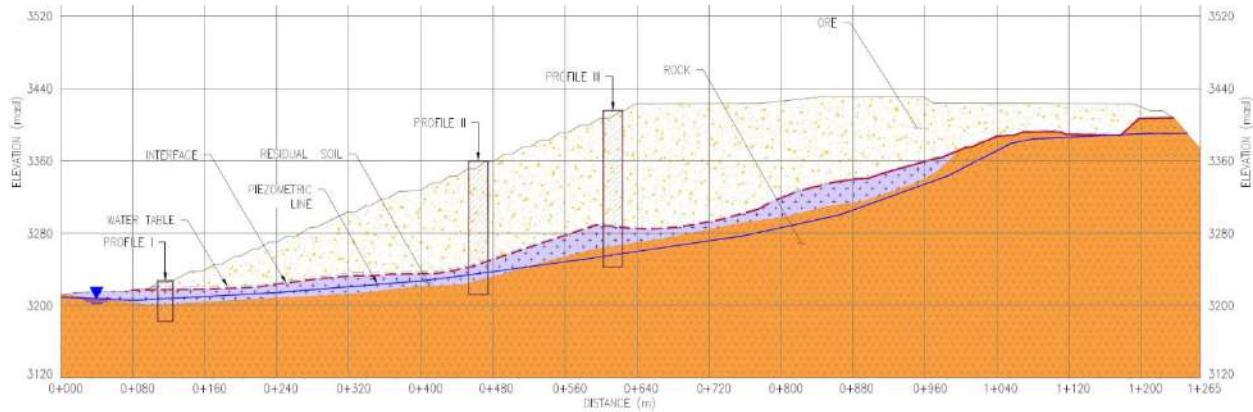
A seismic coefficient that is not related to a serviceability criteria will not actually determine whether a heap leach pad or an earth structure, in general, is stable or not under seismic conditions (Bray and Travasarou, 2009). Therefore, additional analysis should be performed to determine the heap stability under seismic conditions, mainly in high seismicity regions where this condition is most likely to determine the progress of a project in terms of design. As well, it is necessary to be more rigorous in considering risks when finding solutions for the heap stability.

In this study, a current project is taken as an example of the application of this kind of analysis. This project used two different methods to determine the displacements to be developed under seismic conditions for an operational earthquake (100 years return period) and a closure earthquake (475 years return period). The first method is the application of a simplified procedure developed by Bray and Travasarou (2007) that involves the response spectra obtained from a seismic hazard study or obtained by a seismic response analysis, structure period, and yield acceleration. The second method is the modification of the Newmark procedure (1965) by Houston et al. (1987).

The heap leach pad used as example is shown in Figure 1: the global slope is 2.5H:1V, a maximum height of 130 m, and it is founded over a rigid residual soil of 25 to 35 m thickness. This feature makes the heap a very particular earth structure that has a significant local seismic site influence. The project is located 120 km away from the Peruvian coast, and the seismic hazard study determined a high peak acceleration for B and C sites according to the IBC code (2009), as shown in Table 1.

Table 1: Summary of peak ground accelerations (PGA)

Attenuation law	Soil Classification IBC(2009)	T _r (years) to $a_{\text{máx}}(g)$						
		30	50	100	200	475	975	2,475
Youngs et al. Sadigh et al. Rock	B	0.09	0.11	0.14	0.19	0.26	0.32	0.43
Cismid Sadigh et al. Rock	C	0.09	0.12	0.17	0.24	0.35	0.47	0.66
Youngs et al. Sadigh et al. Soil	C – D	0.15	0.19	0.25	0.33	0.44	0.55	0.73

**Figure 1: Heap leach pad 2D section and the three profiles to be analyzed**

Earthquake and spectral matching of the seismic record

For the seismic response analysis, the east-west component of the Lima (Peru) earthquake of 1974 was considered. The earthquake had a moment magnitude (Mw) of 8.1 and a peak ground acceleration of 0.19 g, as shown in Figure 2a; this record was corrected and filtered. Then, the seismic acceleration record was spectral matched to a 100 years return period spectra and a 475 years return period, which correspond to operation and closure conditions, respectively. The spectral matching was performed for the B site spectra of the seismic hazard analysis using the software SeismoMatch (2010), which is based on the pulse wave algorithm proposed by Abrahamson (1992) and Hancock et al. (2006). After the matching the records were corrected again using the base line method. Other aspects to point out are that the peak values, wave shapes, and the strong shock periods should be compatible with the uniform hazard spectra (UHS); as well, the Aria's Intensity should be verified to guarantee that the record final matching has not deviated considerably as to the energy and duration content (Hancock et al., 2006). In Figure 2b that shows the UHS for 100 years and 475 years, the original recording response spectra and the matched ones for a 5% damping are shown.

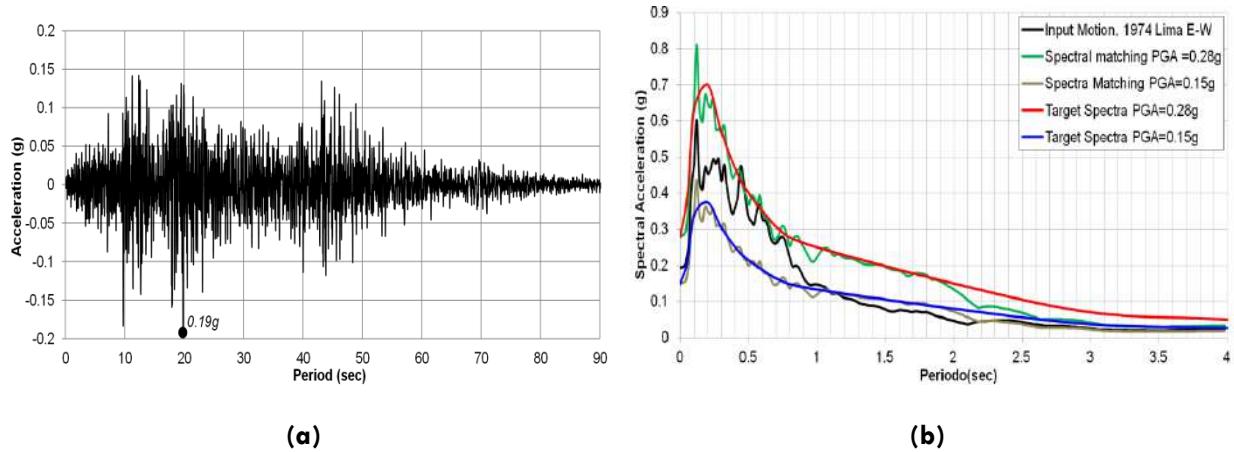


Figure 2: (a) Acceleration record of Lima 1974 earthquake (b) Uniform seismic hazard spectra and spectra matched to 100 and 475 years return period spectra

Seismic response analysis by 1D equivalent linear method

The linear equivalent method enables modeling the non-linear soil response in a simplified way: it considers a linear variation of the soil dynamic properties (shear modulus, G and damping, ξ) for different shear strain levels. This method was developed by Schnabel et al. (1972) in the pioneer program SHAKE. The concept of this method is to assume initial G and ξ values, for which a shear strain calculation is made and the new G and ξ are then compared; these iterative calculations are developed until a tolerable error is obtained for G and ξ , which could be defined by the user. The shear modulus is usually taken as a secant modulus of the hysteretic curve and the damping represents the same energy lost in a unique cycle as a real hysteretic damping (Kramer and Smith, 1997). The linear equivalent method has also been implemented on more updated programs such as D-MOD (Matasovic, 1993), Shake 2000 (Ordoñez, 2000), and Deepsoil (Hashash, 2014); the last-mentioned was used for this study.

The seismic response was performed for three profiles, which are presented in Figures 3a, 3b, and 3c. Houston et al. (1987) recommend using three profiles in order to approach the 2D response, as well as calculate the average displacement at different locations of the model; this was also used to obtain the average response spectra to be input as the spectra for the Bray and Travarasou (2007) method. The ore and residual soil layer were discretized in order to obtain more than 25 Hz frequency for each layer (Hashash, 2010); for the G and ξ the Menq (2003) curves were defined, meanwhile for the residual soil, mostly consolidated clays, the Darendeli (2001) curves were considered. These curves are typically used in practice and were based on laboratory tests such as: cyclic triaxial (CTX), cyclic shear (CSS), cyclic torsional shear (CT), and resonant profile (RC). The initial shear modulus (G_{max}) of the ore and foundation were obtained by means of geophysical tests, MASW (Multi-channel Analysis of Surface Waves). The heap leach interface is a textured geomembrane over low-permeability soil; this was modeled on the recommendations

of Yegian et al. (1998) for linear equivalent response analysis, which considers an equivalent soil layer of 1 m thickness with a specific weight of 0.16 kN/m³. The interface G_{max} was considered for a geomembrane and low-permeability soil proposed by Yegian as 60 σ_n , where σ_n is the normal stress. The average properties of the ore, foundation, and interface are shown in Table 2. An interval is shown for the shear wave velocity, which represents the variation with depth.

Table 2: Summary of materials properties

Material	Thickness (m)	Total unit weight (kN/m ³)	ϕ' average (°)	V_s (m/s)
Ore	8-117	19	36	150-550
Soil/geomembrane (interface)	1	0.16	28.5	750-2,400
Residual soil	25-35	16	15	360-600
Rock	-	24	-	2,400

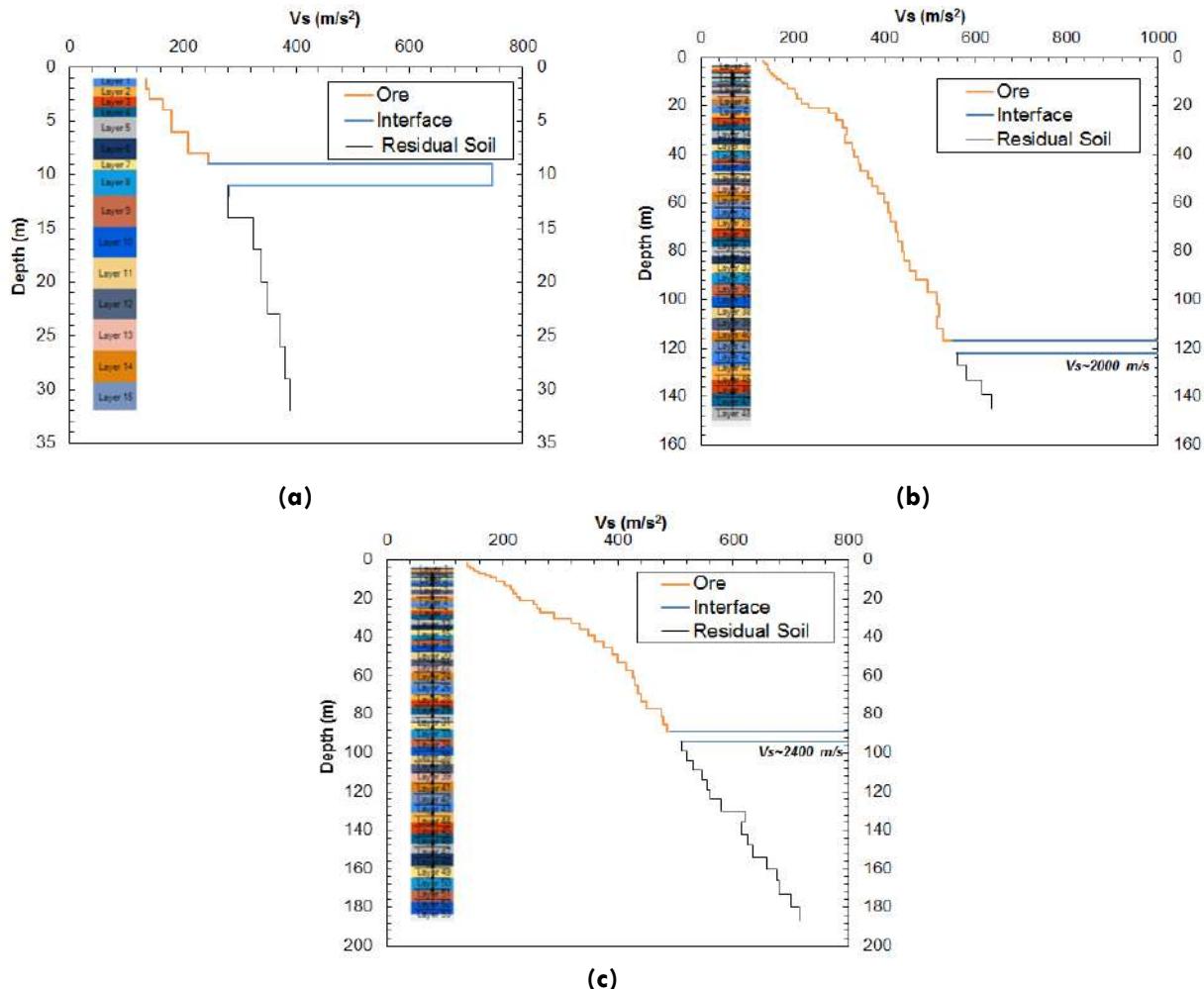


Figure 3: Profiles with V_s (m/s²) to be input on deepsoil (a) Profile I (b) Profile II (c) Profile III

Seismic response spectra

On Figures 4a, 4b, 4c, 4d, 4e, and 4f the response seismic spectra for the 3 1D profiles are shown, which represents three different conditions within the heap. These were analyzed for the operation and closure stages of the heap leach pad, which means 100 years and 475 years return period, respectively. For each of the profiles, the seismic response spectra for the base, foundation (residual soil), interface, ore, and leach pad surface are shown.

Below some comments regarding the seismic response shown in Figure 4:

- Profile I, based on the seismic response shown in Figures 4a and 4b: it is observed that at the interface for short periods (0.1 to 0.3 s), the acceleration deamplifies; for periods above 0.3 s, it amplifies up to 2 to 2.5 times the original one. Above the interface, the acceleration is amplified for all periods reaching up to 1.0 g to 1.5 g for 100 years and 475 years, respectively, at the heap surface.
- Profile II, based on seismic response shown in Figures 4c and 4d: it is observed that at the interface for periods from 0.1 to 1.8 s, the acceleration slightly deamplifies. Above the interface the acceleration is amplified for all periods reaching up to 1.2 g and 1.6 g for 100 years and 475 years, respectively, at the heap surface.
- Profile III, based on seismic response shown in Figures 4e and 4f: it is observed that at the interface for periods from 0.1 to 1.2 s, the acceleration slightly deamplifies; for periods above 1.2 s it is amplified by 1.5 times the original acceleration. Above the interface, the acceleration is amplified for all periods reaching up to 1.1 g and 1.8 g for 100 years and 475 years, respectively, at the heap surface.

According to that described above and the features of profiles I, II and III, it is concluded that for short 1D profiles as high as a 10 m heap height, the liner system deamplifies for short periods, but it greatly amplifies for higher periods. For profiles as high as 90 to 120 m heap height, the liner system slightly deamplifies the original acceleration for almost all periods meaningful in engineering (0.1 to 1.8 s).

Permanent seismic displacements calculation

There are different methods to calculate the permanent displacement to be induced in a geotechnical structure by an earthquake. These enable anticipation of the potential stability problems due to seismic loading by means of a rigorous method based on the displacement magnitude and structure serviceability, instead of a criteria based on a safety factor obtained by limit equilibrium pseudo-static analysis. In order to calculate the magnitude of the induced seismic displacement, the yield acceleration for which the heap leach pad stability is at the limit for failure with a safety factor of 1 was determined.

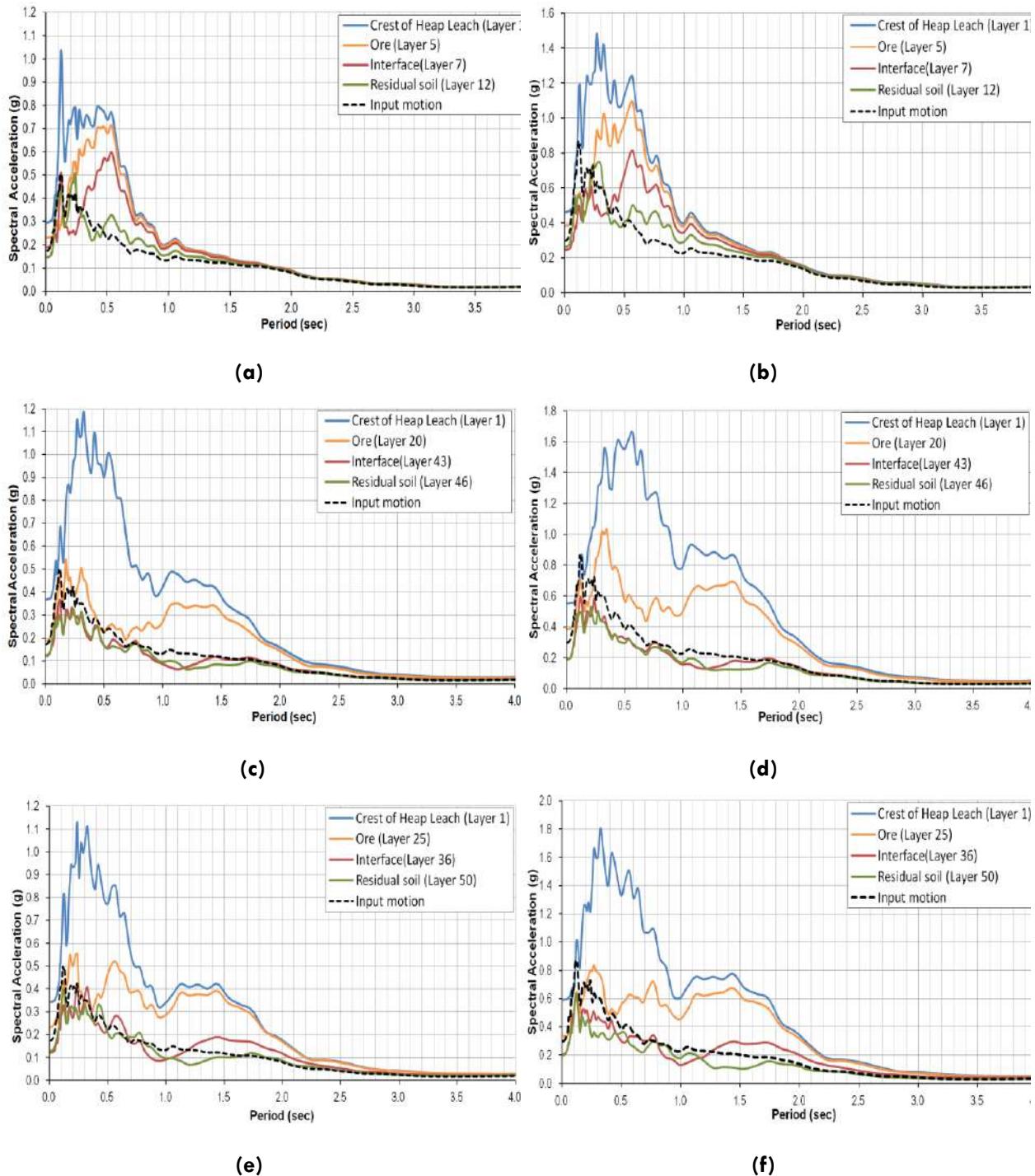


Figure 4: Seismic response spectra of the profiles: (a) 100 years profile I
 (b) 475 years profile I (c) 100 years profile II (d) 475 years Profile II
 (e) 100 years profile III and (f) 475 years profile III

In general, the pseudo-static analysis in leach pads by the limit equilibrium method for block failures considers the nonlinear shear strength envelope of the low-permeability soil and geomembrane interface (Parra et al., 2012), and considers a hyperbolic or square root approach to the normal and shear stresses

(Ayala and Huallanca, 2014) as a way to model the interface behavior under high normal stresses and to avoid overestimation of the interface shear strength, which is usually regarded as a simple liner extrapolation of laboratory results with limited vertical stresses.

For this study, two methods currently used in civil engineering practice are used to calculate the seismic induced displacements: the Bray and Travasarou method (2007) and the Newmark (1965) method modified by Houston et al. (1987).

Simplified permanent seismic displacements calculation, Bray and Travasarou (2007)

Bray and Travasarou (2007) presented a semi-empirical model to estimate the seismic induced permanent displacement based on the Newmark (1965) method and numerical analysis as a way to update the method developed by Makdisi and Seed (1977). This procedure involves a block failure model sliding over a nonlinear coupled surface (Rathje and Bray, 2000), which may represent the dynamic behavior of structures such as: dams, natural slopes, compacted fill dykes, and municipal solid waste fills. The last-mentioned is very similar to a heap leach pad configuration.

Bray and Travasarou (2007) note that the major uncertainty for the evaluation of an earth structure is the seismic event, represented by an acceleration record and the associated response spectra. For the development of the method, the authors used a wide database which involves 688 earthquake records. This method uses the following parameters: yield acceleration (k_y), magnitude of the seismic event (M_w), natural period of the sliding mass (T_s), earthquake spectral acceleration calculated based on the soil degraded period (1.5 T_s) (Travarasou and Bray, 2003), and the stiffness of the sliding material, which is represented by the shear wave velocity (V_s) and the block failure average height. The natural period may be calculated by $4H/V_s$ for a trapezoidal-shaped failure or $2.6H/V_s$ for a triangular-shaped failure.

The model calculates the displacement based on its lower, average, and upper bounds defined by its standard deviation of 0.66. The Bray and Travasarou method was validated by its application to 16 historical cases of dams and municipal solid waste fills, for which information regarding its behavior during and after an earthquake was recorded. Since this method has been widely applied to municipal solid waste fill, which is similar to a heap leach configuration, the authors of this paper chose this application. In order to obtain the response spectra for this method, the average response at the interface for the three profiles analyzed above was used.

Permanent seismic displacements calculation using the Newmark method (1965) modified by Houston et al. (1987)

The Newmark (1965) method was the first method for approaching the calculation of seismic induced displacements for a geotechnical structure. This method considers a rigid block mass that slides on an inclined surface when the acceleration that triggers the movement surpasses the yield acceleration (k_y).

One of the difficulties that arise when applying the Newmark method is considering the sliding mass and the sliding surface as rigid blocks, which is not completely true because the sliding mass takes some small strains during the seismic event. Houston et al. (1987) modified the methodology proposed by Newmark (1965) by introducing a “slip layer,” whose properties induce a shear failure below the sliding mass, as a means to reach an average acceleration of the sliding mass equal to k_y in order to avoid the displacements inside the mass. The seismic record below this layer is taken to apply the Newmark method.

In this research the displacements according to Houston et al. (1987) were calculated using D-MOD 2000 software (Matasovic, 1993). For the analysis, k_y was considered constant and the double integration was applied to the seismic records below the interface surface calculated based on a 1D lineal equivalent method for seismic response, for which the dynamic properties of the ore, residual soil, bedrock, and the interface were considered.

Results

The k_y was determined for the heap leach pad by considering the mechanical properties of the ore, foundation, bedrock, and the nonlinear shear strength envelope of the interface. The properties were obtained by laboratory tests which included triaxial tests and large direct shear test. The minimum k_y determined was 0.043 by the use of 2D slope limit equilibrium analysis software.

In Figures 5a and 5b the response spectra for the interface of each profile for short- and long-term (operation and closure) conditions are shown. In these figures, it can be observed that for short periods, profile I represents an amplification of acceleration for periods between 0.1 s and 1.2 s compared to profile II and III. Between 1.2 s and 2.0 s, the acceleration for profile III is larger than profiles II and III. For periods larger than 2.0 s, the seismic response does not represent major changes from the original acceleration. The amplification for short periods is more meaningful for closure than operational conditions. In these figures the average spectral acceleration used for the calculation of the induced seismic displacements by the Bray and Travasarou method (2007) is also shown.

In Figure 6 the seismic induced permanent displacement estimated by the Houston et al. (1987) method is shown. As observed, for positive and negative acceleration double integration, the calculated displacements are quite similar.

In Table 3, a summary of the calculated displacements is shown for both methods and conditions analyzed. The displacements obtained by these methods agree with each other. Also, we note that the displacements calculated are greater than the maximum tolerable for the liner system of a heap leach pad, which indicates that the facility analyzed in this study is potentially unstable for dynamic conditions.

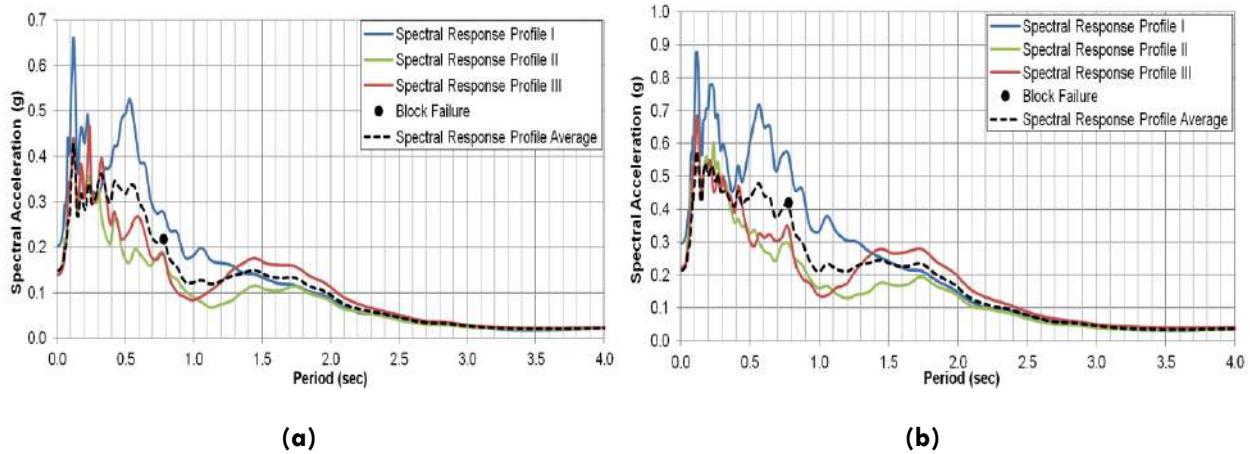


Figure 5: Seismic response spectra at the interface of profiles I, II, III and seismic response spectra average used in the Bray and Travasarou (2007) method to 100 (5a) and 475 (5b) years return period

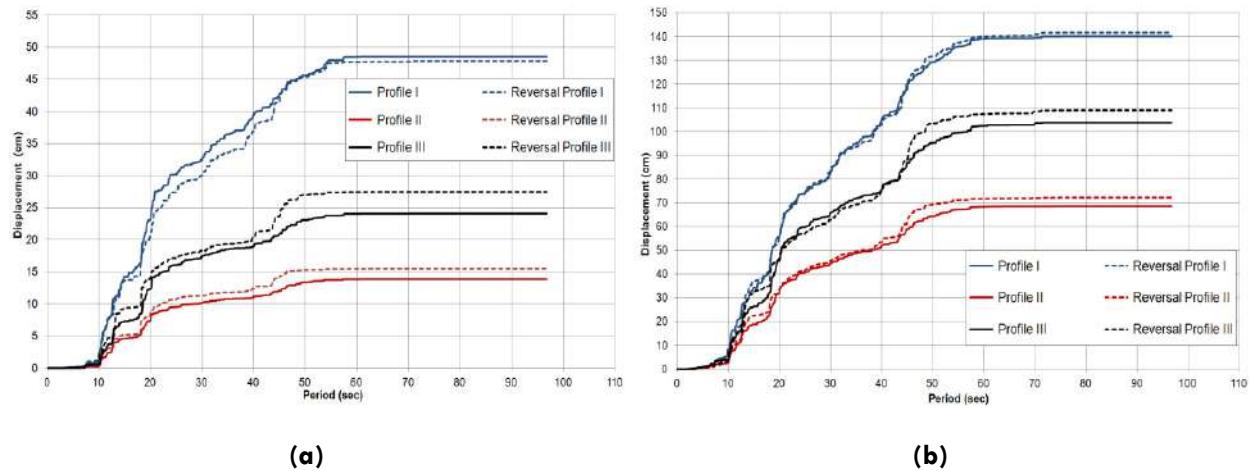


Figure 6: Permanent displacements according to the Houston et al. (1987) method run by D-MOD 2000 of profiles I, II, III at the base of the interface to 100 (6a) and 475 (6b) years return period

Table 3: Summary of displacement results using the Newmark method modified by Houston et al. (1987) and Bray and Travasarou (2007) simplified methods

Profiles	Newmark, Houston Method (1987)		Bray and Travasarou Method (2007)	
	100 years (cm)	475 years (cm)	100 years (cm)	475 years (cm)
Profile I	48.20	140.87	—	—
Profile II	14.67	70.35	—	—
Profile III	25.78	106.29	—	—
Average	29.55	105.84	23.66	1,060

Conclusions

- The seismic induced permanent displacements were determined using two methods, the Bray and Travasarou (2007) and the Newmark (1965) modified by Houston et al. (1987). For both methods a 1D linear equivalent seismic response analysis was needed to determine the acceleration record at the interface.
- A seismic response analysis should be developed for leach pads to understand their true dynamic behavior when facing a seismic loading, focusing mainly at the liner interface since it controls the overall stability. For critical and major projects such analyses are recommended, and cyclic tests are needed to develop accurately the model of the materials involved, especially the ore material. A more complex methodology should be used when the leach pad may trigger liquefaction; however that condition is very unusual for this kind of facility.
- The yield acceleration (k_y) must be calculated for all of the methods above, thus it is a very important index to describe the dynamic resistance of the model. Therefore this value, in the case of heap leach pads, should be calculated based on the post peak shear strength parameters of the interface, in order to estimate accurately the behavior at large strains that will be induced by an earthquake.
- The amplification for short profiles in the heap (around 10 m) is more significant for periods between 0.3 s to 1.2 s for closure conditions (larger earthquake) than operational conditions (smaller earthquake).
- For 1D profile of 90 to 120 m heap height, the liner system seems to slightly deamplify the acceleration for short periods; this agrees with the observations of Kavazanjian et al. (2012). These features may be associated with high normal stresses when applied to the liner system. More research is needed on this matter, since most of the information for the interface characterization is given for low normal stresses.
- The displacements calculated by the Bray and Travasarou (2007) and the Houston et al. (1987) methods are similar. It should be mentioned that based on complexity, the Bray and Travasarou method requires less time and numerical effort compared to the Houston et al. method; therefore, the Bray and Travasarou (2007) method's applicability to heap leach pads is validated by the analysis performed in this research.
- The application of the Bray and Travasarou (2007) method should be a standard for determining the seismic behavior of heap leach pads, since the criteria used are based on the serviceability of the heap leach pad based on the maximum tolerable displacement of the liner system.

- It should be noted that the displacements obtained by these methods are a way to obtain a seismic performance index of a leach pad's stability that is much more accurate than the pseudo-static factor of safety.
- In order to improve the analysis performed in this research, a nonlinear model may be used for the seismic response. Moreover, this analysis could be validated by a 2D dynamical numerical analysis by using current state-of-practice programs in geotechnical numerical analysis, such as FLAC or PLAXIS.

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