Dynamic analysis of a filtered tailings deposit with simplified and numerical methods

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ABSTRACT

This study analyzes the seismic stability and behavior of a filtered tailings storage facility located on the coast of Peru in a zone of high seismicity was analyzed, by using 1D simplified methods and 2D numerical methods subjected to earthquake motions with 475, 1000, 2500 years return periods and to the MCE, and compares the results in terms of response spectrum and seismic induced displacements.

The geotechnical parameters of the filtered tailings and the foundation were estimated based on field geotechnical investigations and a laboratory testing program. Likewise, the seismic conditions were characterized based on the uniform hazard spectrum based on a seismic hazard study. Also a spectral matching was performed with representative earthquake records previously corrected by baseline and filtering.

To evaluate the dynamic response through simplified methods, Newmark (1965), Sarma (1975), Makdisi & Seed (1978), and Bray, Macedo & Travasarou (2018) methods were used, considering the criteria of each one to obtain permanent displacements, such as yield acceleration, degraded period, spectral acceleration, magnitude, etc.

Seismic induced displacements were also estimated based on 2D numerical methods by using finite element Plaxis software. Hardening Soil with Small Strain Stiffness (HS Small) constitutive model was used to characterize the filtered tailings behaviour, while Mohr Coulomb (MC) constitutive model was used to analyze the foundation materials and Linear Elastic model for the bedrock.

Because of the simplified methods are relatively easy to understand and use in a fairly short time and at a relatively low cost, the comparison of the seismic response obtained with these methods and with numerical methods allowed us to conclude about the application and reliability of the simplified methods commonly used in seismic stability analyzes of geotechnical facilities.

INTRODUCTION

For this research a filtered tailing storage facility was analyzed, the geotechnical model included the following materials: filtered tailings A and B with a classification of silt (ML), with 16% moisture content and compacted at 95% and 90% of their standard Proctor maximum density, respectively; alluvial sand deposit classified as silty sand (SM) as a foundation soil; and an andesite bedrock. Figure 1 shows the typical section of the filtered tailing storage facility analyzed.

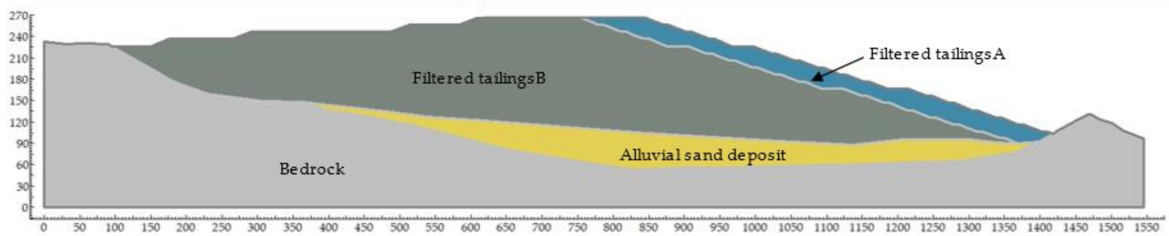

Figure 1 Section of Filtered tailing storage facility

METHODOLOGY

Geotechnical characterization

Characterization for 1D analysis

Shear wave profiles for each of the five columns analyzed and shown in figure 2, also were used, those columns represents the whole section of the filtered tailings deposit. It can be noted that shear wave profile in the foundation soil was obtained based on geophysical surveying, while in the filtered tailings the seismic profile was taken based on similar projects and will need to be verified during operation. The columns were discretized in order to make the wave signal propagated through the column with a maximum frequency of soil layers greater 25 - 30 hz (Hashash, 2010). Also, the sliding mass corresponding to the failure surface shown in figure 2 has a period of Ts = 0.39 s based on recommendation by Bray & Macedo (2021), with a yield coefficient of ky = 0.225. Likewise, the natural period of the filtered tailings deposit is Ts = 0.71 s calculated based on a free vibration analysis numerical modeling following the recommendation in Plaxis (2018). Shear strength parameters of the filtered tailings and foundation soils were obtained based on triaxial test (see table 1). A combination of curves of modulus reduction and damping ratio increase with shear strain proposed by Rojas (2019) (100, 200, 300, 600 y 1000 kPa confining pressure) and those obtained based on resonant column torsional shear (RCTS) test in compacted tailings samples (300, 600 y 1200 kPa confining pressure) were used for dynamic characterization of the filtered tailings A and B (see figure 3), while Menq (2003) curves were used for the alluvial sand deposit and rigid half space for the bedrock.

Characterization for 2D analysis

For the 2D dynamic analysis the followings constitutive models were used: Hardening Soil with Small Strain Stiffness (HS Small) for the filtered tailings A and B, which was calibrated with resonant column torsional shear (RCTS) tests (100, 200, 300, 600, 1000 y 1200 kPa confining pressure) and isotropic consolidated drained triaxial test (ICD Tx) (250 y 500 kPa confining pressure for filtered tailings A and 250, 500, 1000 y 1500 kPa confining pressure for filtered tailings B), as shown in see figures 3 and 4. As can be seen in figure 3, the calibration of the HS Small model produces greater damping than the one used in the characterization for the 1D analysis. Mohr Coulomb model was used for the alluvial sand deposit, calibrated with isotropic consolidated drained triaxial test (ICD Tx) and Lineal Elastic model for the bedrock, calibrated with its shear wave velocity. Finally, the Rayleigh damping parameters was added to model the energy dissipation that occurs in the structure due to its internal and external damping mechanisms (Hudson, Idriss & Beirkae, 1994). The main parameters of the modeled materials are summarized in table 1.

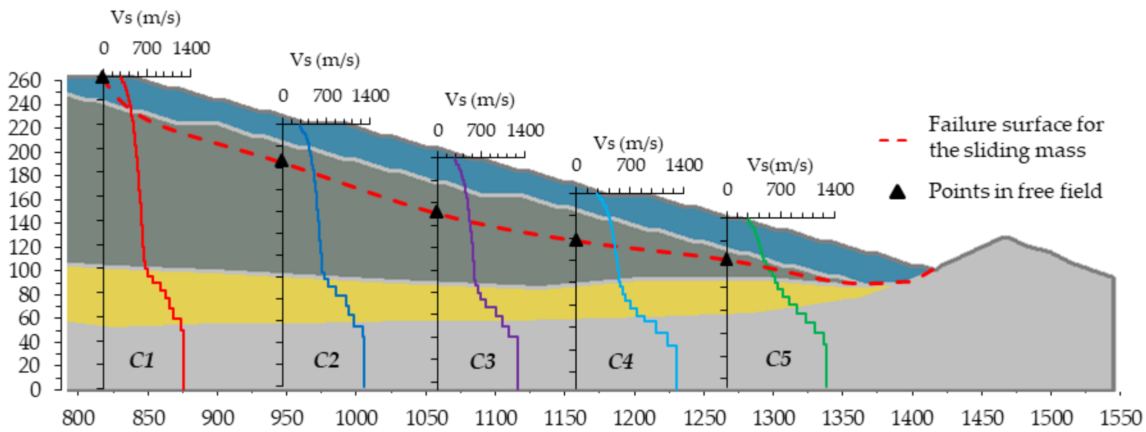

Figure 2 Shear wave profile for the five columns analyzed

Table 1 Material Properties

Material	Constitutive model	γ (kN/m³)	c' (kPa)	Ø'	pref (kPa)	E50 ref (MPa)	m	Go ref (MPa)	$\gamma_{0.7}$ (E-04)	Rayleigh α	Rayleigh β
Filtered tailing A	Hardening soil small	20	0	35	100-300	10-26	0.75	219-377	1.2 – 2.4	0.120	0.72E-3
Filtered tailing B	Hardening soil small	19	0	27	100-1200	10-50	0.73	219-831	1.2 – 4.0	0.120	0.72E-3
Alluvial sand deposit	Mohr Coulomb	20	0	35	-	1480	-	-	-	0.120	0.72E-3
Bedrock	Lineal Elastic	26	-	-	-	-	-	-	-	-	-

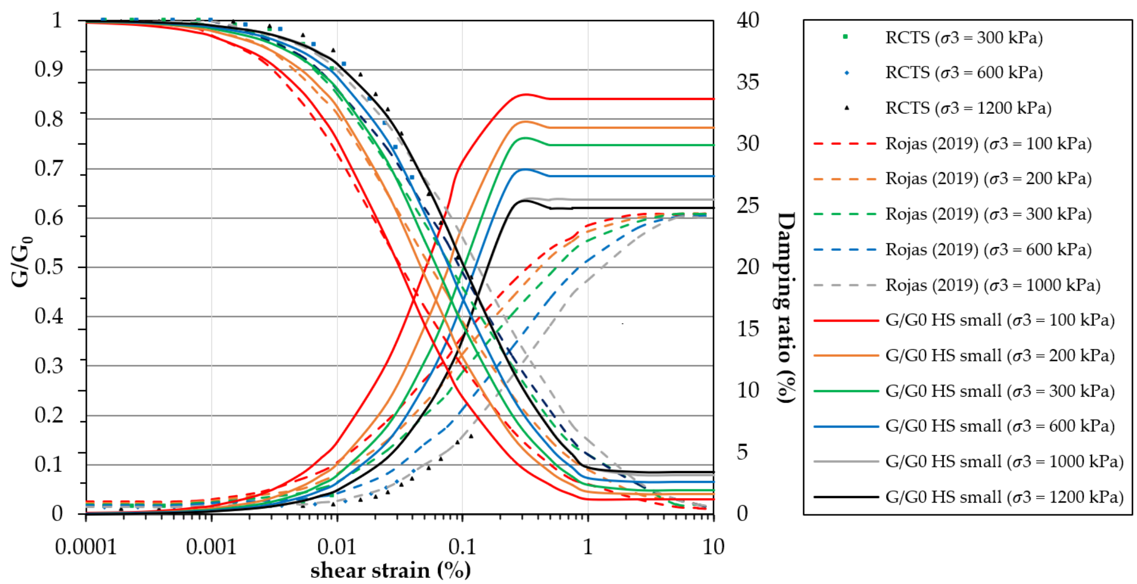

Figure 3 Filtered tailing damping ratio and shear modulus reduction calibration

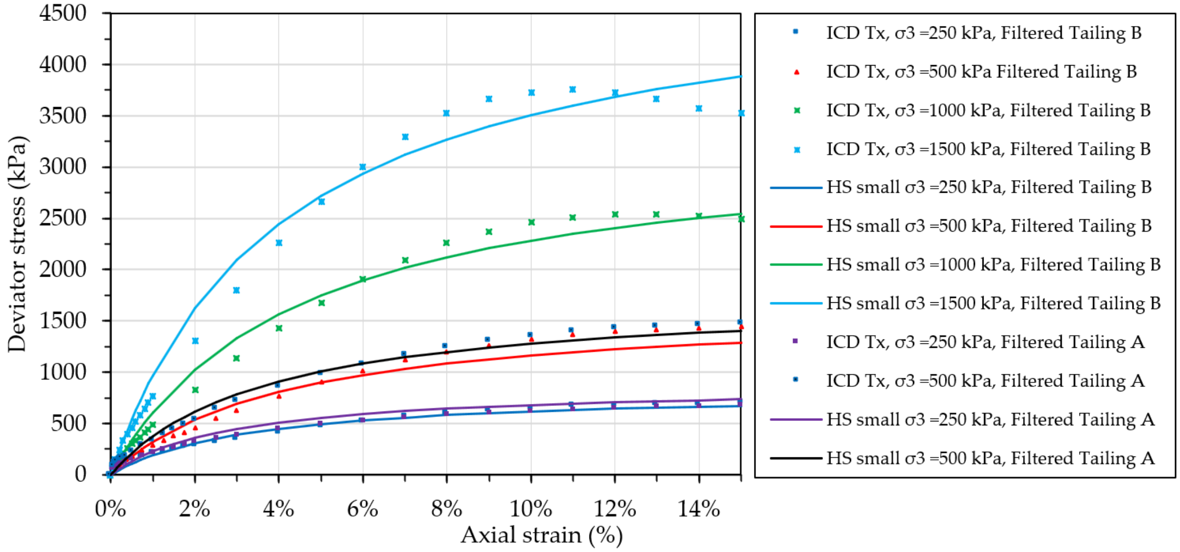

Figure 4 Filtered tailings calibration

Seismic scenario

Two components (EW and NS) of three earthquakes records were selected: Lima 1974, Atico 2001 and Tarapaca 2005, the first two are subduction earthquake and the last one is an intraplate earthquake that represents the seismicity of the study area according to the seismic hazard analysis. The earthquake records were corrected by baseline and a bandpass filtered, after that they were spectral matched to four uniform hazard spectrum UHS corresponding to return periods of 475, 1000, 2475 and the MCE (see figure 5). Table 2 shows the PGA of the original earthquake records used in this work.

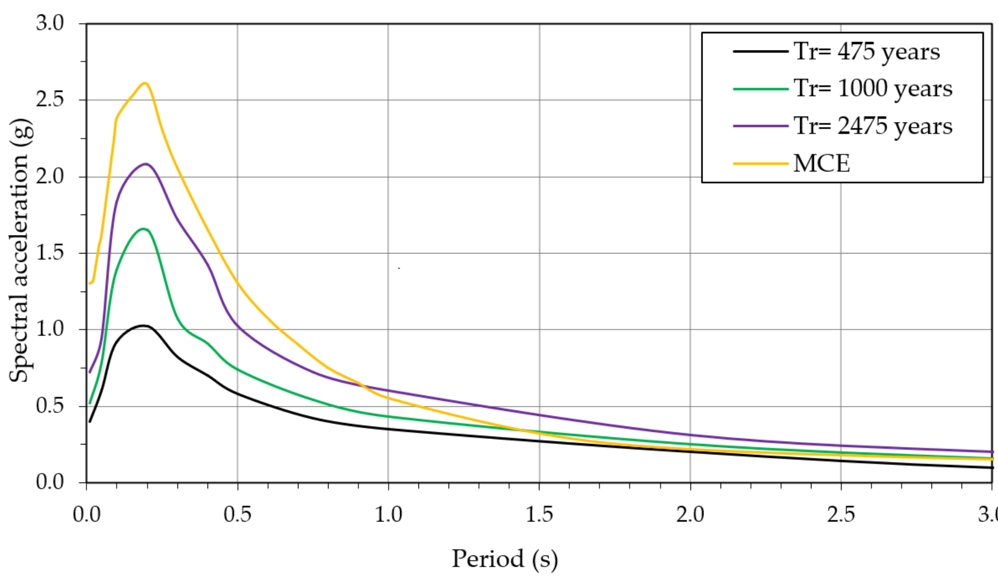

Figure 5 Uniform hazard spectrum for different earthquake scenarios

Table 2 PGA of the original earthquak records

Earthquake	Mw	PGA (g)	Failure Mechanism
LIMA 1974 EW	7.8	0.20	Subduction Interface
LIMA 1974 NS	7.8	0.18	
ATICO 2001 EW	8.4	0.30	
ATICO 2001 NS	8.4	0.22	
TARAPACA 2005 EW	7.9	0.72	Subduction Interplate
TARAPACA 2005 NS	7.9	0.57	

Seismic response assessment

Two methodologies were used for evaluate the seismic response in terms of response spectrum:1D seismic response with the software Deepsoil v7.0, and 2D seismic response with the software Plaxis Connect 2D; the criteria and considerations used are explain below.

1D seismic response

A nonlinear seismic response analysis was performed for each spectral matched earthquake record and for each of the five columns representing the section of the filtered tailings deposit. Two types of seismic response analysis were performed: 1) from the basement rock to the extension of each column at the slope surface to compare the response spectrums obtained based on the 2D analysis; and 2) from the basement rock to the base of the failure surface which correspond to the free field, as shown in the points in free field in figure 2, as stated by some of the 1D simplified approaches which use the response spectrum and acceleration time-history in the free field for seismic induced deformation assessment.

2D seismic response

For computing the 2D seismic response, the dynamic boundaries were set, free-field and the compliant base condition were selected to the lateral and base, respectively; also, interfaces at those boundaries and a plate at the base were added. The mesh was generated to accomplish the equation (1) for the sizing of the elements (Kuhlmeyer & Lysmer, 1973); figure 6 shows the discretization of the filtered tailings deposit. A dynamic multiplier of 0.5 was used in each seismic records to consider a rock outcropping motion at the base of the model.

$$average\ mesh\ size\ of\ the\ elements \leq \frac{\lambda}{8} = \frac{V_{s,min}}{8 f_{max}} \quad (1)$$

Six control points were selected to verify the results, as shown in figure 6. The first one (B1) was located at the base of the model for a validation that the input earthquake is being well applied and the other control points (P1 to P5) were placed at the extension of each column used for the 1D analysis at the slope surface. As can be seen in figure 6, the dynamic lateral boundaries correspond to free field boundaries, which allow to reduce the extension of the dynamic model because the waves are not reflected laterally, otherwise these waves are absorbed according to the recommendation in Plaxis (2023).

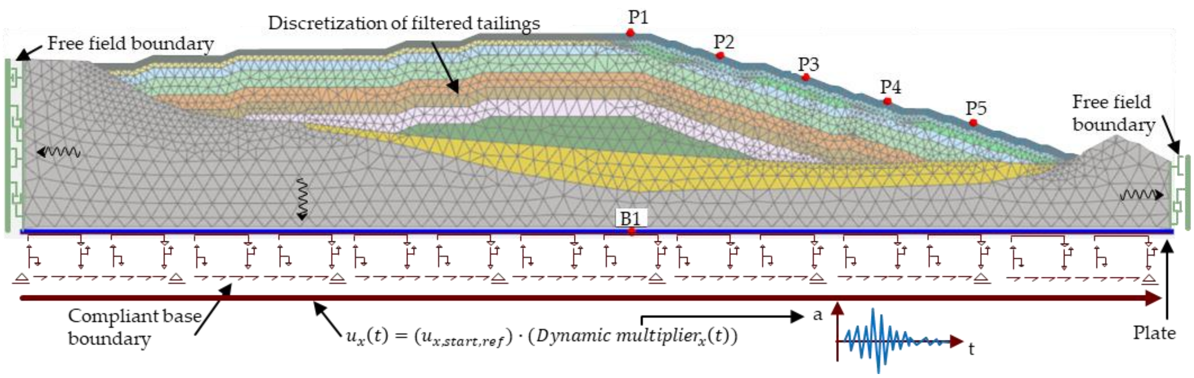

Figure 6 Discretization of filtered tailings and finite element mesh and dynamic boundaries

Dynamic analysis with simplified methods

The dynamic response of the filtered tailings storage facility in terms of induced displacement, was analyzed by simplified methods such as Newmark (1965), Sarma (1975), Makdisi & Seed (1978) and Bray, Macedo & Travasarou (2018) considering each earthquake record and for each column.

Dynamic analysis with numerical analysis

The dynamic displacement response of the filtered tailings storage facility was also analyzed by numerical methods in Plaxis 2D for each seismic record. The permanent displacements were calculated at each control point located at the slope surface.

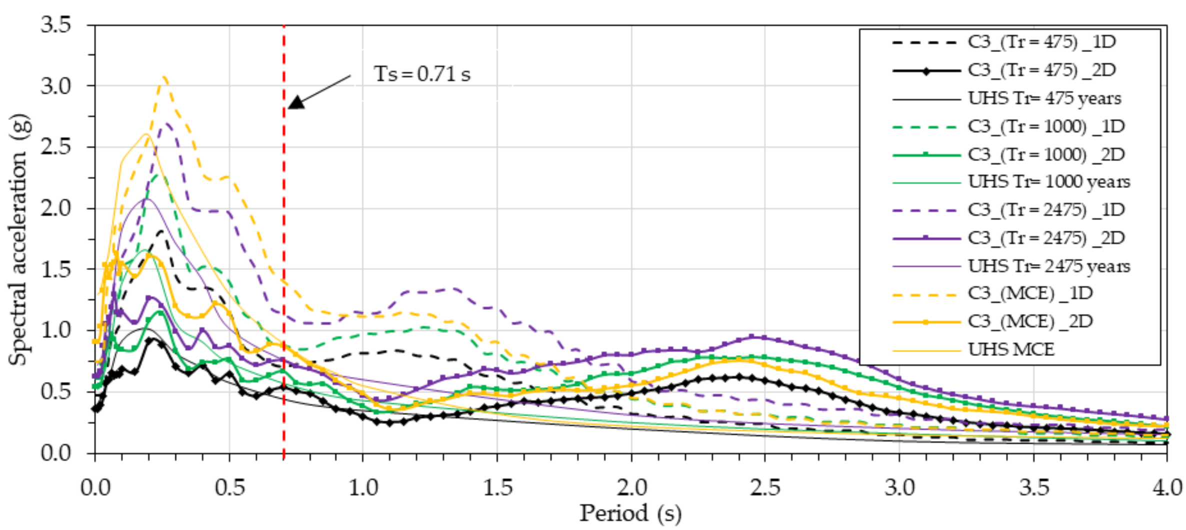

Figure 7 Uniform Hazard Spectrum and response spectrum on the top of column 3 from 1D and 2D analysis

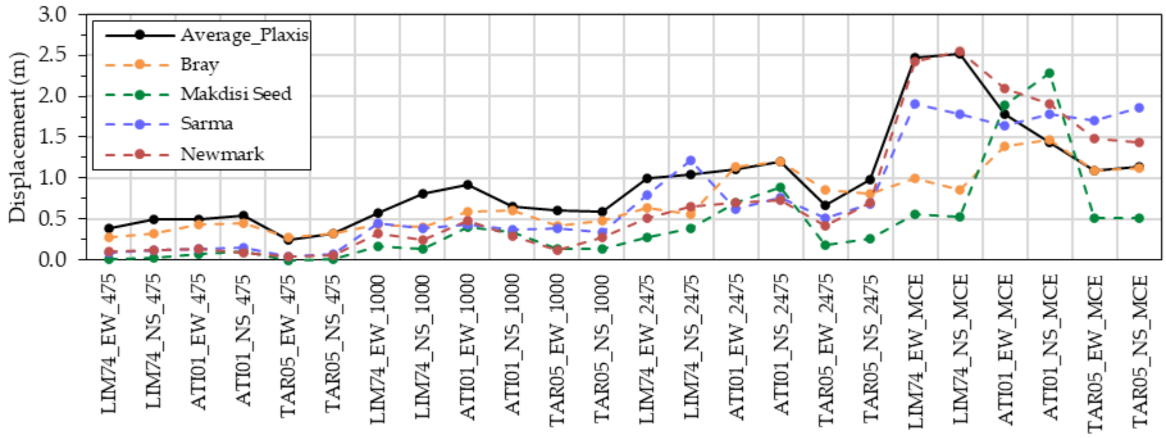

Figure 8 Seismic induced displacements calculated of the filtered tailings storage facility based on different 1D and 2D methods

RESULTS AND DISCUSSION

Figure 7 shows that all the response spectrum from the 1D analysis show greater amplification than the response spectrum from the 2D analysis. The greater damping used in the 2D analysis and shown in figure 3, may be contributing to this effect.

For the structural period of the deposit (Ts = 0.71) the following is observed: the amplification factors of the 1D and 2D response spectrum are 1.57 and 1.19, respectively, for a return period of 1000 years; the ratio of the 2D/1D response spectrum is in the range of 62 to 76% in column 3, similarly it is observed in the remaining columns; the 1D response spectrum amplifies in all the analyzed scenarios, while for the 2D the amplification is observed just for the return periods of 475 and 1000 years.

As can be seen in figure 8, in general, the displacements obtained by simplified methods are smaller than those obtained by numerical analysis, the method of Bray et al. (2018) provides a better approximation to the results obtained by the numerical analysis for return periods of 475, 1000 and 2475, however, for the MCE the results are not conclusive.

The displacements obtained by the simplified methods of Newmark (1965), Sarma (1975) and Makdisi & Seed (1978) do not provide a good fit compared to those obtained by numerical analysis.

The maximum displacements obtained with the 2D analysis for the structure are in the range of 0.24 to 0.54 m for Tr = 475 years, 0.58 to 0.92 m for Tr = 1000 years, 0.67 to 1.20 m for Tr = 2475 years and 1.09 to 2.59 m for the MCE.

CONCLUSIONS

In general, higher amplification is to be expected in a response analysis when analyzing 1D columns compared to a rigorous 2D numerical analysis. The method of Bray et al. (2018) is a reliable simplified method whose results are close to those obtained through rigorous numerical analyses. Estimated displacements of up to 2.59 m (MCE) will not compromise the stability of the filtered tailings facility.

Based on the results of this work and the experience in the analysis of different mining projects of tailings storage facilities, leach pads, waste dumps, water retention dams, etc., we can conclude that the simplified method of Bray et al. (2018) is recommended for a quick calculation of the seismic stability of a facility. Likewise, rigorous numerical methods are applicable in a second stage of the seismic assessment and their application depends on several factors, especially the risk of the facility.

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NOMENCLATURE

Ts	Structural period
ky	yield coefficient
Tr	Return period
UHS	Uniform hazard spectrum
MCE	maximum credible earthquake
PGA	Peak ground acceleration

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