

## Ground motion selection using conditional ground motion models.

Selección de registros sísmicos empleando modelos de movimiento del suelo condicionado.

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**ABSTRACT:** Selection of ground motions is a topic of great interest for nonlinear dynamic analyses (NDAs) of geotechnical structures. Recently, conditional ground motion models (CGMMs) have been developed in subduction earthquakes zones for estimating Arias intensity (AI), cumulative absolute velocity (CAV), and peak ground velocity (PGV). These intensity measures (IMs) are particularly useful for geotechnical earthquake problems. This study analyzes the agreement between the IMs estimated by CGMMs and those obtained from ground motions compatible with a target spectrum (a set or individual records) that can be used in NDAs. The specific case analyzed in this study corresponds to an area located in the central part of Peru. The results show a consistent correlation in estimating the IMs using CGMMs and those obtained from design ground motions. Consequently, it is concluded that, given a specific earthquake scenario and site conditions, CGMMs can be employed to determine and control the characteristics of ground motions to be used in NDAs, allowing for a more accurate assessment of structural performance.

**KEYWORDS:** Ground motion selection, nonlinear dynamic analysis, conditional ground motion models, intensity measures.

### 1 INTRODUCTION

The selection of ground motions is a topic of great interest in NDAs, as these are used in engineering practice to assess the seismic performance of geotechnical structures. NDAs may use a set of ground motions compatible with a target response spectrum, consistent with its median and associated standard deviation, or ground motions obtained through spectral matching methodology. The target spectrum can be defined based on a seismic hazard study (probabilistic or deterministic) or national and international standards. This process involves controlling seismic demand in terms of a spectral accelerations across a certain range of periods of interest, and in certain circumstances, includes the peak ground acceleration (PGA).

Recently, Conditional Ground Motion Models (CGMMs) have been developed for subduction zones, used to estimate AI, CAV, and PGV. These IMs can be considered for applications in seismic geotechnical engineering, serving as indicators of potential damage in structures, addressing issues related to soil liquefaction, and aiding in the development of fragility functions. Since CGMMs have considerably lower standard deviations than traditional unconditional models, the IMs could be estimated with much smaller aleatory variability for a given earthquake scenario and site conditions, as described by Macedo et al. (2019).

This study employs CGMMs to estimate IMs for a site located in the central part of Peru. Additionally, a set of ground motions compatible with the deterministic spectrum (percentile P.50), obtained from a seismic hazard study, is selected. Ground motions, spectrally matched to the deterministic spectrum (percentile P.84) commonly considered for geotechnical structure designs, are also evaluated. The goal is to assess the compatibility of the selected ground motion characteristics with those estimated by the CGMMs.

### 2 BACKGROUNDS

The ground motions used in NDAs are usually obtained using spectral matching methodology developed by Al Atik & Abrahamson (2010). In this methodology, the ground motions

that are spectrally matched do not consider the variability of the target spectrum (i.e., its associated standard deviation). However, it is important that the selected ground motions exhibit variability in the response spectra, accurately representing the distributions and variations of a target spectrum. In this regard, various algorithmic proposals exist for selecting a set of ground motions that take into account the variabilities of the target spectrum (e.g., Kottke & Rathje 2008; Baker & Lee 2018; Arteta & Abrahamson 2019).

The NGA-Sub ground motions database (Kishida et al., 2018; Mazzoni et al., 2022) developed by the Pacific Earthquake Engineering Research (PEER) Center, is used to developed new conditional ground motion models (CGMMs). These CGMMs, along with a design spectrum, can be combined to assess the seismic demand of an earthquake scenario and site conditions. This ensures that the selected ground motions used in NDAs are consistent with the seismic demand of the site in terms of IMs.

The evaluation of seismic performance for a geotechnical structure, involves synthesizing information from tasks regarding: geology, site characterization, property estimation, seismic hazard characterization, analysis models for estimating seismic responses, damage assessment, consequence assessment, and performance objectives. The uncertainties associated with each of these tasks propagate through the evaluation process and are manifested as bias or dispersion in the results (Boulanger & Ziotopoulou, 2018). In addition to these uncertainty factors, the selection of ground motions is crucial. Since the ground motions considered in the evaluation of NDAs have different characteristics (e.g., AI, CAV, PGV) that could significantly affect the response of geotechnical structures.

### 3 METHODOLOGY FOR THE EVALUATION OF GROUND MOTIONS

In this study, a five-step methodology was implemented for the evaluation of ground motions, considering the target spectrum estimated by a deterministic seismic hazard analysis (DSHA). The five-steps are as follows: (1) perform a DSHA for a specific

site; (2) select a set of ground motions according to the procedure of Baker & Lee (2018); (3) generate spectrally matched ground motions according to the methodology of Al Atik & Abrahamson (2010); (4) determine the intensity measures (IMs) for an earthquake scenario and site conditions according to CGMMs developed by Macedo et al. (2019); Liu & Macedo (2022a), and Liu & Macedo (2022b) for subductions zones; and (5) evaluate the ground motions with the IMs determined by the CGMMs.

#### 4 SPECIFIC SITE ANALYSIS - DSHA

A deterministic seismic hazard assessment (DSHA) was carried out to determine the seismic demands at the project site. This approach allows for the creation of design spectra for the Maximum Credible Earthquake (MCE). The analysis incorporates factors such as local fault rupture mechanisms, historical seismic activity, and geological features to model specific ground motion parameters. A critical aspect of the DSHA involves identifying and characterizing the primary seismic sources affecting the area of study. Earthquakes from these sources are evaluated to determine the largest possible events and the most intense seismic motions they could generate at the site. These maximum earthquakes are defined by their magnitude and the distance from the source to the site. For design purposes, it is assumed that these maximum events might occur under the worst-case conditions within the seismic source zone.

A DSHA was conducted for a rock-type material with a time-averaged shear-wave velocity in the top 30 m ( $V_{s30}$ ) equal to 760 m/s, located in Peru (-76.21° longitude; -10.57° latitude). The tectonic and subduction model was based on studies by Bird (2003), Hayes et al. (2018), and DeMets et al. (2010). Ground Motion Prediction Equations (GMPEs) proposed by 1. Montalva et al. (2017), 2. Kuehn et al. (2020), 3. Parker et al. (2022), 4. Abrahamson & Gülerce (2020), 5. Abrahamson et al. (2014), 6. Campbell & Bozorgnia (2014), 7. Chiou & Youngs (2014), and 8. Boore et al. (2014) were employed. Table 1 shows the weights assigned to each GMPEs.

According to the results of this analysis, intraslab subduction earthquakes are dominant when considering a deterministic approach. On the other hand, earthquakes originating from regional geological faults (i.e., shallow crustal) exhibit low intensities at the project site. The median of spectral accelerations (P.50) and the mean plus one standard deviation (P.84) with 5% damping indicate that the seismic scenario with the highest intensity in the analysis area corresponds to an earthquake with a moment magnitude of  $M_w$  8 and a focal distance ( $R_{rup}$ ) of 106.7 km. The obtained spectrum and its associated deviations are presented in Figure 1. Following guidelines from Martinez & Hull (2019), consistent with South American practices, the design earthquake is typically defined as the 84<sup>th</sup> percentile of the deterministic analysis, and this is used to select design ground motions, which, as indicated in a later chapter, is applied.

Table 1. Weighting of Attenuation Laws by Seismic Source.

GMPE s	Weighting		
	Interface Subduction	Intraslab Subduction	Shallow crustal
1	0.30	0.30	-
2	-	0.30	-
3	0.35	0.10	-
4	0.35	0.30	-
5	-	-	0.25
6	-	-	0.25
7	-	-	0.25

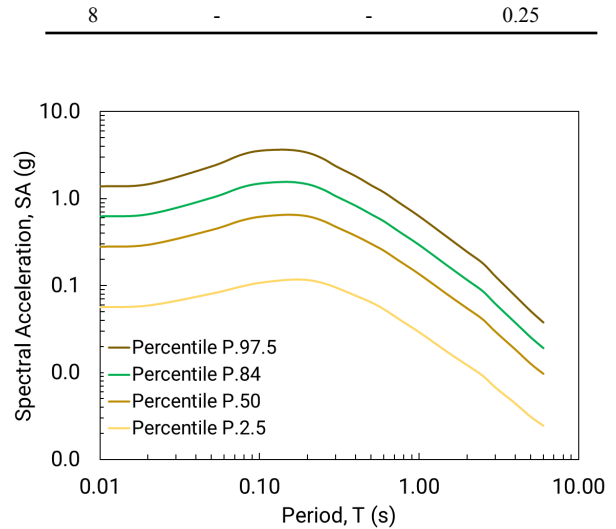


Figure 1. Deterministic seismic response spectrum for a soil with  $V_{s30}=760$  m/s.

#### 5 SELECTION A SET OF GROUND MOTIONS

Baker & Lee (2018) developed an algorithm to efficiently select seismic records from a database that meet target values for mean, variance, and correlations of response spectra over a range of periods. The key steps in the process are described below: (1) Specify a target response spectrum, which can be obtained from a seismic hazard study or from a national or international standard. (2) Statistically simulate the target response spectrum, meaning that through Latin Hypercube Sampling (LHS) methodology, simulated spectra are generated to statistically match the mean and standard deviation of the target spectrum. (3) Create a database of seismic records; in this step, seismic records are collected from various institutions, or alternatively, pre-existing seismic record databases are used. (4) The database should be filtered based on various specific criteria of interest, such as fault mechanism, earthquake magnitude, shear wave velocity, etc. (5) Select seismic records that individually match the statistically simulated spectra. In other words, the goal is to identify real seismic records from step (4) that spectral match the simulated spectra from step (2). This way, the real seismic records would indirectly conform to the target spectrum. For each statistically simulated spectrum and each candidate seismic record, the sum of squared errors (SSE) is calculated (see Eq. 1).

$$SSE = \sum_{j=1}^p \left( \ln S_a(T_j) - \ln S_a^{(s)}(T_j) \right)^2 \quad (1)$$

Where  $\ln S_a(T_j)$  is the logarithm of the spectral acceleration (optionally scaled) of the candidate seismic record,  $\ln S_a^{(s)}(T_j)$  is the  $\ln S_a$  of the statistically simulated response spectrum, and  $T_j$  denotes the period of the spectral acceleration.

The candidate seismic record with the lowest sum of squared errors (SSE) relative to the simulated spectrum is ultimately selected. (6) Estimate the tolerance between the simulated and selected spectra, meaning evaluate the set of selected seismic records to determine if it is sufficiently close to the target distribution. The tolerance is estimated as shown in Eq. 2 and 3.

$$Err_{mean} = \max_j \left( \frac{|m_{lnSa}(T_j) - \mu_{lnSa}(T_j)|}{\mu_{lnSa}(T_j)} \right) \times 100 \quad (2)$$

$$Err_{std} = \max_j \left( \frac{|s_{lnSa}(T_j) - \sigma_{lnSa}(T_j)|}{\sigma_{lnSa}(T_j)} \right) \times 100 \quad (3)$$

Where  $m_{lnSa}(T_j)$  is the sample mean of the  $lnS$  values of the selected seismic records at period  $T_j$ , and  $\mu_{lnSa}(T_j)$  is the target mean. Similarly,  $s_{lnSa}(T_j)$  is the sample standard deviation of the selected seismic records, and  $\sigma_{lnSa}(T_j)$  is the target standard deviation at period  $T_j$ . (7) Finally, the selected seismic records are statistically compatible with the target spectrum and its associated standard deviations. It is important to note that the number of seismic records to be selected is at the user's discretion.

In accordance with the methodology proposed by Baker & Lee (2018), a database of seismic records was compiled from different institutions such as CISMID, CSN, IGP, COSMOS, and RENADIC, generating a total of 251 records obtained from interface and intraslab subduction earthquakes recorded in Peru and Chile. These seismic records were obtained from soils with different shear wave velocities, due to the limited information available for a specific soil type. It was decided to select a set of 15 seismic records that are compatible with the MCE (P.50) spectrum and its associated standard deviations. This quantity was chosen to allow for conclusions based on a broader trend. For the selection of these 15 seismic records, the seismic record database was filtered to include only those recorded in soils with a  $600 \leq V_{s30} \leq 950$  m/s. This was done to ensure consistency with the DSHA evaluated for a soil with  $V_{s30} = 760$  m/s. Given the limited number of historical seismic records identified in Peru and Chile, further filtering of other important characteristics such as fault mechanism, magnitudes, directivity, etc., was not carried out. This was done to ensure the availability of seismic records for applying the described methodology.

The selected ground motions are described in Table 2, and the response spectra with 5% damping corresponding to the selected ground motions are shown in Figure 2. This methodology considers the associated standard deviations of the target spectrum, for which a period of interest between 0.1 - 4 seconds (typical range for geotechnical structures) was considered. As shown in Table 2, a scaling factor was considered to reduce the estimated error in the current methodology.

Table 2. Set of ground motions selected according to the methodology of Baker & Lee (2018).

ID	Seismic event	Station / direction	Scale Factor	$V_{s30}$ (m/s)
1	17/10/1966 (Peru)	Parque de la Reserva / EW	0.8	581
16	09/11/1974 (Peru)	Parque de la Reserva / NS	0.8	581
55		Pichilemu / NS	1.1	623/1135
57	03/03/1985 (Chile)	Quintay / T	1.1	595
60		San Fernando / EW	0.8	543 / 666
69	15/10/1997 (Chile)	Illapel / T	0.8	613
97	13/06/2005 (Chile)	Calama / NS	0.8	745

162	27/02/2010 (Chile)	Santiago La Florida / NS	0.9	598 / 685
171		Talca / T	0.8	537/548
197	01/04/2014 (Chile)	T03A / HNN	0.8	613
207		CO03 / HNN	1.1	704
208		C110 / HNN	1.1	626
214	16/09/2015 (Chile)	C200 / HNE	1.1	737
216		C330 / HNE	0.9	587
239		C230 / HNN	1.0	751

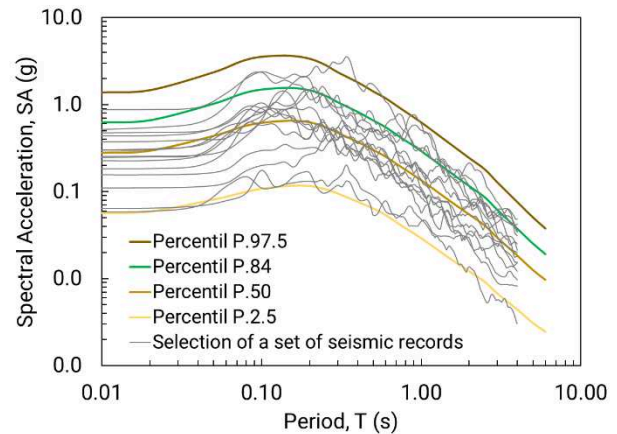


Figure 2. Response spectra with 5% damping of the selected record set according to the methodology of Baker & Lee (2018).

## 6 SPECTRALLY MATCHED GROUND MOTIONS

The spectral matching methodology (Al Atik & Abrahamson, 2010) is based on adding wavelets to the original or candidate seismic record to align its spectrum with a target spectrum. Each wavelet aims to match the spectral ordinate of the target spectrum at each spectral period. The adjustment can be performed either period by period or in groups of periods. Typically, multiple iterations are needed to achieve reasonable convergence between the spectrally adjusted acceleration record and the target spectrum.

The ground motions used for spectral matching correspond to historical earthquakes commonly employed in current engineering practice in Nonlinear Dynamic Analyses (NDAs). For spectral matching, the target spectrum was the MCE (P.84). Ideally, the time-history records selected for generating synthetic seismic records should have tectonic mechanisms, magnitudes, site conditions, and other characteristics similar to those of the design spectra. However, due to the limited number of records in South America with the same parameters as those in the study area, it was necessary to relax these conditions. Earthquakes with an intraslab mechanism, consistent with the MCE, were considered (see Table 3), as they exhibit a spectral shape similar to that of the design spectrum, which can be verified with a lower value of SSD (sum of squared deviations), as expressed in Eq. 4

and 5. Where  $\ln SA(T_i)$  is the target spectrum evaluated at period  $T_i$ ,  $Sa(T_i)$  is the spectrum of the candidate record without any scaling factor; and  $N$  is the number of periods that make up the spectrum. The response spectra of the accelerograms spectrally matched with 5% damping are shown in Figure 3. The earthquakes were selected based on their predominant fault mechanism (intraplate subduction), the SSD, and the  $V_{s30}$  of the soil where they were recorded.

$$SSD = \sqrt{\sum_{i=1}^N (\ln SA(T_i) - \ln(\alpha \cdot Sa(T_i)))^2} \quad (4)$$

$$\alpha = \exp \sum_{i=1}^N \left( \frac{\ln SA(T_i) - \ln Sa(T_i)}{N} \right)^2 \quad (5)$$

Table 3. Ground motions selected for spectral matching.

ID	Seismic event	Station / direction	$V_{s30}$ (m/s)
A	31/05/1970 (Peru)	Parque de la Reserva / NS	608
B	15/10/1997 (Chile)	Illapel / T	613
C	13/01/2001 (El Salvador)	San José de la Montaña / 180	Suelo
D	13/06/2005 (Chile)	San José de la Montaña / 180	1263
E	13/06/2005 (Chile)	Pica / EW	1087
F	08/09/2017 (Mexico)	Escuela Primaria Mugica	Soil
G	19/09/2017 (Mexico)	Raboso	Rock

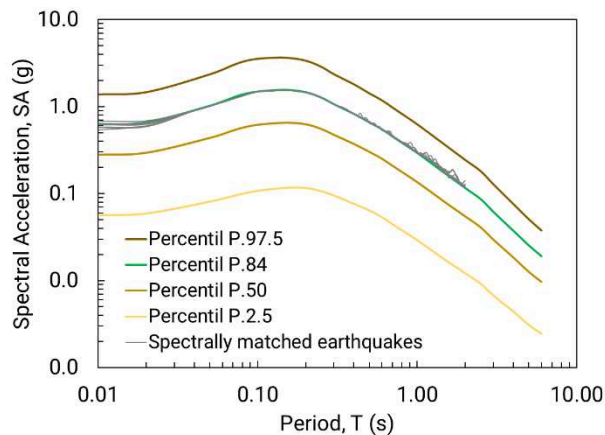


Figure 3. Response spectra with 5% damping of the spectrally matched ground motions.

## 7 ESTIMATION OF INTENSITY MEASURES ACCORDING TO THE CONDITIONAL GROUND MOTION MODELS

For the estimation of the IMs (AI, PGV, and CAV), the characteristics of the deterministic spectrum of the MCE (P.84)

were considered, which has the features described in Table 4. Where  $R_{rup}$  refers to the distance of the site to the earthquake rupture and SA1 to the spectral acceleration for  $T=1.0$  sec.

Table 4. Characteristics of the MCE (P.84).

Characteristics	Unit	Value
$V_{s30}$	m/s	760
Mechanism	-	Intraslab
$M_w$	-	8
PGA	g	0.626
SA1	g	0.294
$R_{rup}$	km	106

According to the parameters described in Table 4 and the formulations proposed by Macedo et al. (2019); Liu & Macedo (2022a), and Liu & Macedo (2022b), the IMs were estimated: AI, CAV, and PGV, respectively, which are presented in Table 5, including their associated standard deviations (in natural logarithmic scale).

Table 5. Estimation of the IMs according to the CGMMs and MCE P.84.

IM	Value	Standard deviation
AI (m/s)	7.59	0.33
CAV (m/s)	31.57	0.30
PGV (cm/s)	24.53	0.37

## 8 RESULTS ANALYSIS

In Figure 4 (logarithmic scale), the IMs estimated by the CGMMs are presented alongside those obtained from the design ground motions, considering the two methodologies described earlier. To enable fair comparisons, the IMs estimated from a set of ground motions obtained using the methodology by Baker & Lee (2018) were evaluated to derive their median and associated standard deviation. This ensured that their mean plus one standard deviation is comparable to those obtained by the spectral matching methodology and those obtained from the CGMMs, all of which utilized the MCE P.84 as their design spectrum.

The results of the IMs from the spectrally matched ground motions (purple points) generally align with those estimated by the CGMMs. Although some records exceed the estimates from the CGMMs, they do not exceed the usual standard deviation of 1 obtained from traditional models. Therefore, these could be analyzed in terms of seismic performance results of structures.

The results of the IMs from a set of ground motions (blue points), in terms of their mean plus one standard deviation, are consistent with those estimated by the CGMMs. Therefore, they would be representative of seismic demand and could be used in the evaluation of structures, such as generating fragility curves given the variability of the IMs in the records.

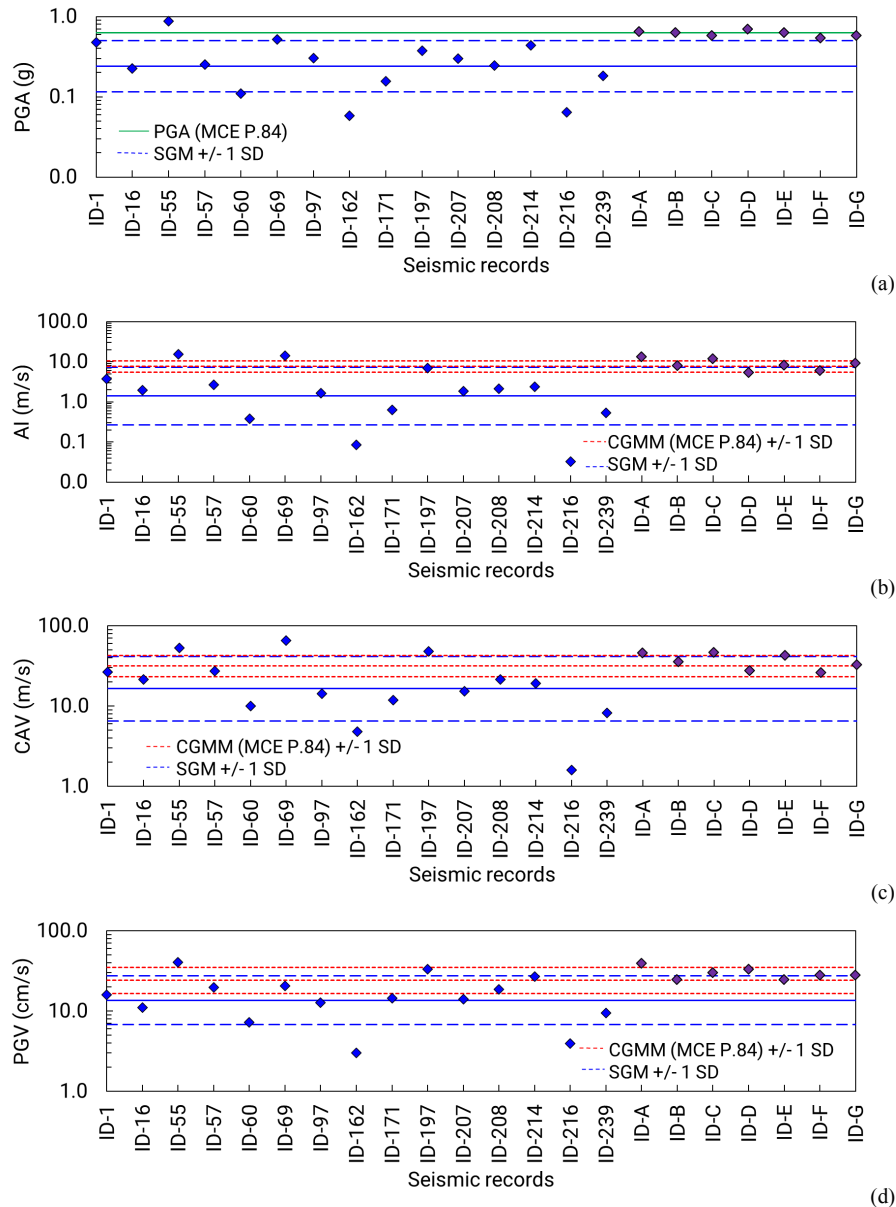


Figure 4. Comparison of the estimated IMs from the CGMMs and those obtained from design ground motions (using 2 methodologies) on a logarithmic scale. Red lines represent estimations according to the CGMMs, with their respective associated standard deviations. Blue lines represent estimations according to a selected set of ground motions by the methodology of Baker & Lee (2018). (SD: Standard Deviation)

## 9 CONCLUSIONS

In current engineering practice, spectral matching methodology is widely employed to generate design ground motions (based on a target spectrum). From the evaluation conducted, it is observed that the estimated IMs from these records generally fall within the estimated range of the CGMMs. Records showing higher IMs than those estimated by the CGMMs could be considered as exceeding the average seismic demand of the structure for the design earthquake. However, they could be used in NDAs to provide comments based on the seismic performance of the structures.

The selection of a seismic record set based on the methodology of Baker & Lee (2018) considers the mean and

associated standard deviation of a target spectrum. Intensity measures (their mean and standard deviation were estimated) were obtained from this record set, resulting in compatibility with the estimated CGMMs. Therefore, they are considered representative of the design spectrum and seismic demand in terms of IMs. Hence, this set of seismic records can be used to evaluate the seismic performance of structures, develop fragility curves, etc.

It should be noted that if a seismic record has a higher IM than another record, it does not necessarily imply that all other IMs in that same record are also higher.

The CGMMs developed for subduction zones can be used to control the seismic demand of seismic records based on a design

spectrum in order to not overestimate or underestimate the mean demand.

It is fundamental for NDAs of geotechnical structures to consider a significant number of ground motions to have a wider range of structure response for different IMs.

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