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Subduction versus shallow crustal earthquakes: Intensities versus amplitude

Subduction versus séismes crustaux peu profonds : intensités versus amplitude

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ABSTRACT: The practice of earthquake engineering is based principally on estimate amplitude (i.e. PGA) and accelerations spectra (PSa). However tectonic environment across the world shows significant differences of amplitude and intensities of ground motion (e.g., frequency content and duration) which explain the differences between observed structural/geotechnical behavior. In general, hazardous earthquakes, due to highest recurrence and maximum magnitude credible, are associated to subduction environments. In this century, a lot of >8.0Mw occurs on subductions zones, this is evidence of high seismic activity on these zones. This investigation explored and compiled significant distinctions between cortical and subduction (interplate and inslab earthquakes) zones. Particularly used the Perú-Chile subduction zone and shallow crustal strong ground motions (e.g., NGA-West2 project) models developed to various seismic intensities. Attenuation decay, amplitude response (PGA and PGV), seismic spectral response, numbers of equivalent cycles, energy content (e.g., Arias Intensity and CAV) and significant duration are contrasted. The last two parameters show the most relevant differences between seismotectonic sources studied. Finally, discuss about implications on seismic hazards and the need to develop a set of ground motion prediction models to describe better expected behavior.

RÉSUMÉ : La pratique du génie parasismique est basée principalement sur l'estimation des amplitudes (i.e. PGA) et des spectres d'accélération (PSa). Cependant, l'environnement tectonique à travers le monde montre des différences significatives d'amplitude et d'intensité des mouvements du sol (par exemple, le contenu fréquentiel et la durée) qui expliquent les différences entre le comportement structurel/géotechnique observé. En général, les séismes dangereux, en raison de la récurrence la plus élevée et de la magnitude maximale crédible, sont associés à des environnements de subduction. Au cours de ce siècle, beaucoup de >8,0Mw se produisent sur les zones de subduction, c'est la preuve d'une activité sismique élevée sur ces zones. Cette enquête a exploré et compilé des distinctions significatives entre les zones corticales et de subduction (séismes interplaques et inslab). Particulièrement utilisé la zone de subduction Pérou-Chili et les modèles de forts mouvements du sol crustaux peu profonds (par exemple, projet NGA-West2) développés à diverses intensités sismiques. La décroissance de l'atténuation, la réponse en amplitude (PGA et PGV), la réponse spectrale sismique, le nombre de cycles équivalents, le contenu énergétique (par exemple, l'intensité Arias et le CAV) et la durée significative sont contrastés. Les deux derniers paramètres montrent les différences les plus pertinentes entre les sources sismotectoniques étudiées. Enfin, discutez des implications sur les risques sismiques et de la nécessité de développer un ensemble de modèles de prédiction des mouvements du sol pour décrire un meilleur comportement attendu..

KEYWORDS: seismic, hazard, subduction, intensity, amplitude

1 INTRODUCTION

Earthquake engineering has developed around the amplitude (e.g., Peak Ground Acceleration, PGA; and Peak Ground Velocity, PGV) or frequency content (i.e., Spectral Acceleration) of seismic record. However, a necessary understanding of system dynamic behavior must complement using non-spectral intensity measures, based on, for example, accumulated energy or duration of strong ground motion.

The main scope of the selection of seismic parameters to describe seismic demand is their theoretic background and the ability to correctly predict the seismic behavior on the structural or geotechnical system under evaluation. Performance-Based Earthquake Engineering (PBEE) requires a quantitative assessment of the seismic effects that affecting engineering systems for different levels of demand (Kramer and Mitchell, 2006). In this line, is highly necessary an accurate estimation and characterization of seismic intensities that control the performance of different structures.

On engineering systems, the performance under seismic load could be measured using amplitude (e.g., Montalva et al., 2017), spectral intensities (e.g., Housner Intensity; Montalva et al., 2021), or non-spectral parameters. A ground motion parameter is essentially a quantitative form to describe relevant characteristics of strong ground motion. However, Housner and Jennings (1982) established that is inherently impossible to describe a complex phenomenon, like earthquakes, with a unique parameter (or

number), and in this attempt are unavoidable miss important information.

In general, predict the accumulated damage of engineering systems is the main objective of the estimations of these parameters. Consequently, the significant duration must be used as a relevant performance predictor, in addition to energy, frequency content, and amplitude parameters. Also, non-spectral parameters associated with energy content (i.e., CAV and Arias Intensity) have shown a high correlation with observed damage (Campbell and Bozorgnia, 2019).

The Chile-Perú subduction zone is characterized by a high seismic activity ratio due to the subduction of the Nazca plate beneath the South America plate. In the last two decades, four earthquakes higher than 8.0 have been produced: 2001 Perú (Mw8.4), Maule 2010 (Mw8.8), Iquique 2014 (Mw8.1) and, Illapel 2015 (Mw8.3).

This investigation quantifies the differences between shallow crustal earthquakes and subduction tectonic environments. Chilean subduction flatfile (Bastías and Montalva, 2015) is used as a reference database for the evaluation of ground motion predictions models developed on shallow crustal tectonics.

2 SEISMIC INTENSITIES AND STRONG GROUND MOTION EVALUATION

Two categories of seismic parameters are defined to evaluate the differences between two tectonic environments: spectral (e.g., frequency content and amplitude of signal parameters) and non-

spectral (e.g., durations, energy, and equivalent cycles) strong ground motion parameters. In the last years, the last one is grown in number, due to extra-information that provides to describe the earthquake strong ground motion.

Amplitude parameters consist in the easiest way to describe the strong ground motion. PGA is the absolute maximum value on acceleration time history, and PGV is the respective value on velocity traces. Due to the dynamic response of structures are sensitive to frequency content, spectrum describes how systems respond to different frequencies modeling by an oscillator of a single degree of freedom. In consequence, SA shows the acceleration response in a specific frequency under seismic load.

Spectral parameters used for the evaluation in this investigation are SA 0.1 and 1 seconds, in addition to amplitude measures: PGA and PGV. Also, will be grouped in bins to describe magnitude-, and distance-dependency. In past, vertical components of time histories received less attention than horizontal, but at short site-to-source distance vertical component of motion could be larger than the horizontal component (Bozorgnia and Campbell, 2016). Therefore, both directions of strong ground motion are evaluated.

On other hand, non-spectral intensities evaluated are Arias Intensity (I_a ; Arias, 1970), Cumulative Absolute Velocity (CAV; EPRI, 1988), significant duration between 5-75% and 5-95% of Arias Intensity, Number of equivalent cycles (N_{eq}; Seed et al., 1975), and the Mean Period (T_{mean} ; Rathje et al., 1998).

Arias Intensity is a description of the energy content of an earthquake and it is computed by the integral of the square acceleration time history between the zero and the duration of the signal. In physics terms, is the representation of the sum of dissipated energy per mass unit. Cumulative Absolute Velocity is an alternative form of Arias Intensity to describe energy content, in this case, the normalization scheme used is the absolute value of acceleration trace, integrated between zero and end time of the signal. Significant duration intends to characterize the strong ground motion segment that contains the destructive energy (Trifunac and Brady, 1975). Despite that exists multiple definitions of strong ground motion duration, the normally used are the significant duration. This duration is defined on the interval between a portion of Arias Intensity are developed on seismic record. Two intervals are commonly used, between 5-75% ($D_{s,5-75\%}$) and between 5-95% ($D_{s,5-95\%}$) the Arias Intensity time history. Theoretically, the first is the representation of body waves of ground motion, and the second one is the duration of the complete train waves (Bommer et al., 2009).

In some cases, is necessary to represent the irregular and non-periodic signal of the strong ground like a harmonic and periodic wave. In these situations, the strong ground motion need represented by an amplitude parameter (e.g., PGA) and an equivalent number of cycles (N_{eq}). The aim is compatibilized the damage-induced from the earthquake through uniform stress cycles. The counting technique most used is the developed by Seed et al. (1975), which used a weighting curve that converts all peaks of stress time history to cycles concerning a reference stress value (typically, $0.65 \tau_{max}$). Finally, the Mean Period is a unique and weighted representation of frequency content of the strong ground motion, based on amplitude associated with each frequency strong ground motion and computed between frequencies of structural interest (i.e., 0.25 and 20 Hz).

Ground Motion Prediction Models (GMPMs) used in this investigation are as follows: Campbell and Bozorgnia (2014; CB14) for horizontal spectral acceleration, Stewart et al. (2019; SEA19) for vertical spectral acceleration, Campbell and Bozorgnia (2019; CB19) for CAV and Arias Intensity, Sandikkaya and Akkar (2017; SA17) for CAV, significant duration and Arias Intensity, Du and Wang (2017, DW17) for a significant duration, Liu et al. (2001; L01), Kishida y Tsai (2014; K14) and, Cetin et al. (2021, C21) for the equivalent number of

cycles and, finally, Du (2017; D17) for the mean period. All models are developed based on the NGA-West2 database (Ancheta et al., 2014), with exception of SA17 development on European tectonic context for shallow crustal earthquakes. For more details about functional forms, extension of database (range of validity), and regression techniques are recommended the revision of each reference. In general, few models on subduction environments about non-spectral intensities have been developed (Bahrapouri, 2017).

The evaluation of ground motion models is based on the strong ground motion database from Chilean subduction zone developed by Bastias and Montalva (2015). Geometric mean is used to combine both components, less the case of the Mean Period models that Euclidean norm is the combination preferred for these models.

Goodness-of-fit of models are computed using the normalized residuals (Z_t). Normalized residuals (see Eq. 1) are obtained from the difference between observed intensity measured and predicted intensity, normalized by the total standard deviation of the model (Scherbaum et al., 2004).

$$Z_t = \frac{\ln(IM_{obs}) - \ln(IM_{pred})}{\sigma_T} \quad (1)$$

This technique is usually used to ranked GMPM based on spectral response (e.g., Bastias et al., 2015), but could be extended to evaluated other types of seismic parameters. To define the distribution, the normalized residuals are fitted with a normal distribution described by a mean value and a standard deviation. Also, the subduction database is segregated between the subduction interface and inslab earthquakes.

3 RESULTS

3.1 Spectral and amplitude parameters

Results of spectra and amplitude parameters are grouped in bins to study distance and magnitude dependence. Figure 1 and Figure 2 shows the results of residuals for the subduction interface of horizontal and vertical components, evaluated using CB14 and SEA19 models, respectively.

Subduction interfaces events are homologated to an earthquake with a reverse faulting in an active tectonic environment. Note that positive residuals mean underprediction of the model ($y_{pred} < y_{obs}$) and vice versa.

In general, extreme events ($M_w > 8$) underpredict spectral intensities in comparison to subduction earthquakes (for horizontal and vertical components). It is important to note, that shallow crustal models have data until $M_w \sim 8.0-8.5$, and in the bin of extreme events, the strong ground motion parameters predicted are extrapolations of models.

In addition, the signal attenuation of subduction interface earthquakes is slower than shallow crustal events (i.e., residuals are negative in short distances and converted to positive in large distances). Also, in short distance ($< 50\text{km}$) shallow crustal models have higher intensities than subduction interface in all spectral periods of analysis, except for extreme events.

In the case of subduction inslab (Figure 3 and Figure 4), the source is modeled like normal faulting.

Bias in the prediction of ground motion parameters is clear in high frequency (i.e., PGA and SA at 0.1 seconds) because in all cases subduction inslab shows higher values than homologate fault in shallow crustal context. This is replicated on vertical and horizontal components. Larger periods (i.e., 1 second) show negative residuals (i.e., shallow crustal scenarios expected higher values than subduction inslab) for intermediate magnitudes ($M_w < 7$).

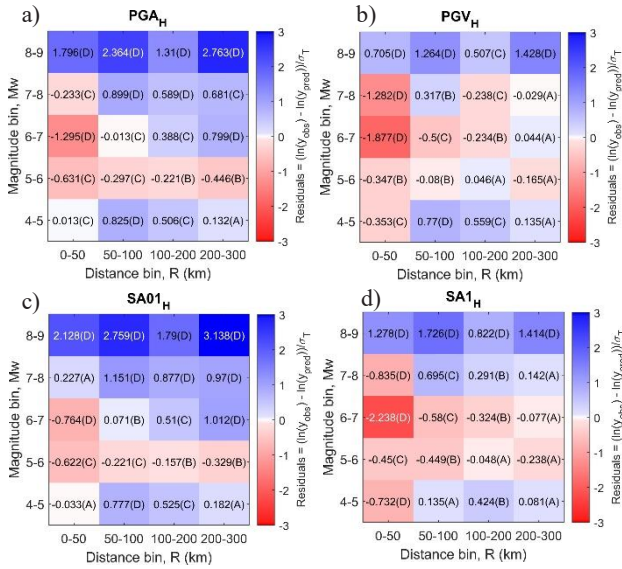


Figure 1. Residuals distribution for spectral and amplitude parameters of horizontal component in subduction interface. In parentheses class of rank based on Scherbaum et al. (2004) scheme. Panel a) is for PGA, b) is for PGV, c) is for spectral acceleration (SA) at 0.1 seconds and, d) is for SA for 1 second.

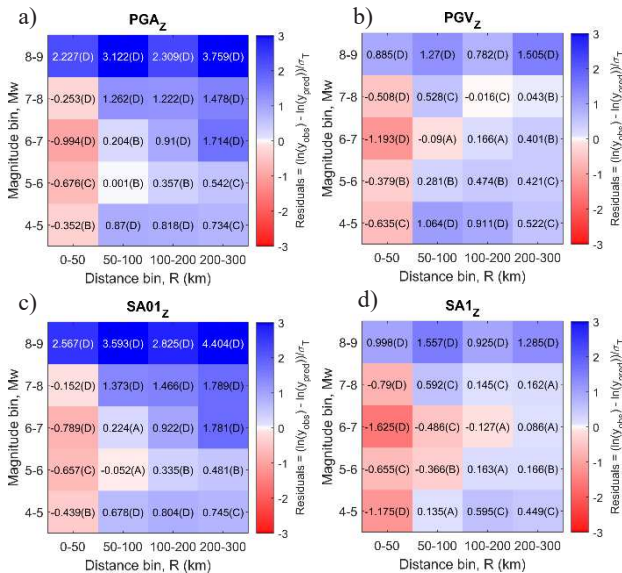


Figure 2. Residuals distribution for spectral and amplitude parameters of vertical component in subduction interface. In parentheses class of rank based on Scherbaum et al. (2004) scheme. Panel a) is for PGA, b) is for PGV, c) is for spectral acceleration (SA) at 0.1 seconds and, d) is for SA for 1 second.

However, in a similar way of subduction interface, extreme events of this tectonic environment developed higher values in all situations in comparison with shallow crustal earthquakes. Besides, horizontal and vertical components following the same tendency.

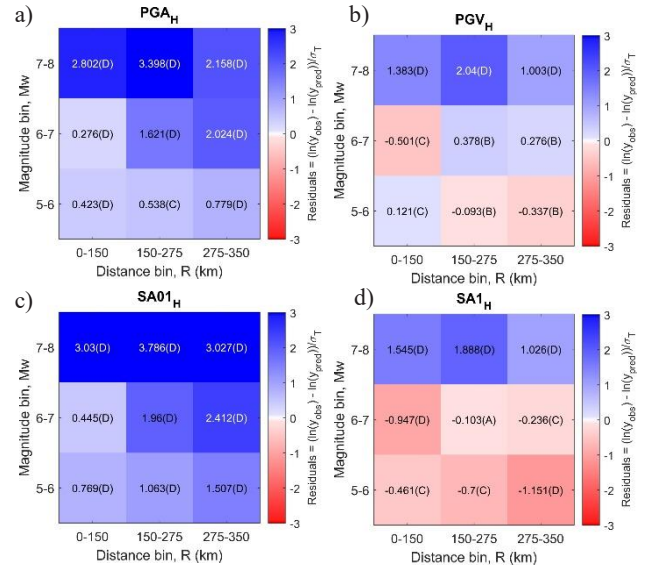


Figure 3. Residuals distribution for spectral and amplitude parameters of horizontal component in subduction inslab. In parentheses class of rank based on Scherbaum et al. (2004) scheme. Panel a) is for PGA, b) is for PGV, c) is for spectral acceleration (SA) at 0.1 seconds and, d) is for SA for 1 second.

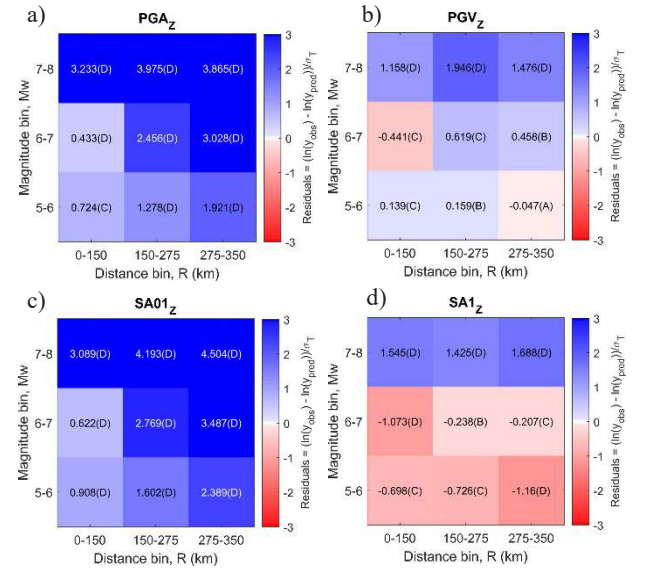


Figure 4. Residuals distribution for spectral and amplitude parameters of vertical component in subduction inslab. In parentheses class of rank based on Scherbaum et al. (2004) scheme. Panel a) is for PGA, b) is for PGV, c) is for spectral acceleration (SA) at 0.1 seconds and, d) is for SA for 1 second.

3.2 Non-Spectral intensities

Multiples non-spectral intensities are evaluated. Arias Intensity (Figure 5) shows a poor fit to the observed data of the Chilean subduction zone.

A high standard deviation on prediction (>1 log-unit in residual distribution) is observed. Also, are distributed with positive residual, except for CB19 on the subduction interface. In consequence, in comparison, Arias Intensity parameter on subduction environment shows higher values than shallow crustal earthquakes.

For CAV analysis (Figure 6) the models also present a poor capacity of prediction, under the scheme of Scherbaum et al. (2004) is classified at C and D class for subduction interface and

inslab earthquakes. Again, consistently both models (CB19 and SA16), based on active tectonic, underpredicted the intensities observed (i.e., positive residual) and with high uncertainty (>1) on prediction. CB19 is more accurate in the mean prediction of values in the case of the subduction interface.

The tendency is replicated in the significant duration analysis (Figure 7), both models in evaluation (SA16 and DW16) underpredicted the duration of strong ground motion on subduction interface context. For subduction in slab, SA16 estimated higher durations than observed in the Chilean subduction zone, and DW16 model underpredict the intensities. These tendencies occur to $D_{s,5-75\%}$ and $D_{s,5-95\%}$ parameters.

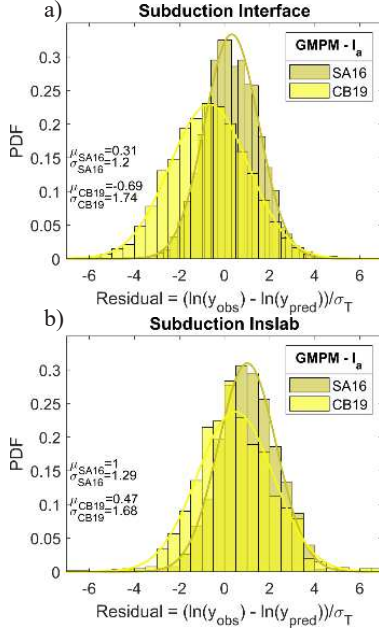


Figure 5. Residual distribution for Arias Intensity. Panel a) is for subduction interface and, panel b) is for subduction inslab

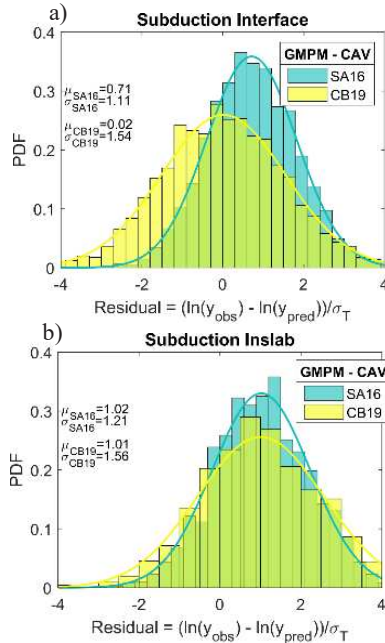


Figure 6. Residual distribution for CAV. Panel a) is for subduction interface and, panel b) is for subduction inslab

The equivalent number of cycles (N_{eq} , Figure 8) have in general a good fit to observed data. To compute N_{eq} has been assumed a unique b-exponent equal to 0.41 and a stress reference

equal to $0.65\tau_{max}$. C21 model has the better performance of evaluated models on subduction interface, but L01 is the best for subduction inslab events.

Finally, the Mean Period (Figure 9) is evaluated for subduction data. For both tectonics scenarios, shallow crustal earthquakes have lower values mean period of subduction events. An unusual and extremely large underestimation is observed for inslab earthquakes.

To evaluate the models for most severe and dangerous earthquakes to structures, the database has been filtered and the analysis replicated only for strong ground motion records with the Moment Magnitude (M_w) greater than 8.

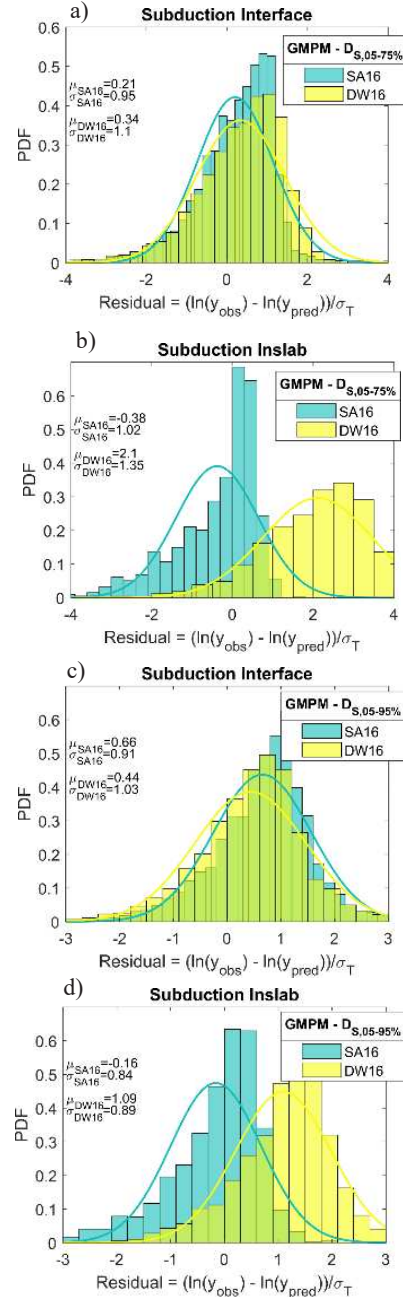


Figure 7. Residual distribution for significant duration. Panel a) is for $D_{s,05-75\%}$ in subduction interface, panel b) is for $D_{s,05-75\%}$ in subduction inslab, c) is for $D_{s,05-95\%}$ in subduction interface, and d) for $D_{s,05-95\%}$ in subduction inslab

This selection, consequently, only uses the largest interplate events (i.e., Maule, 2010; Illapel, 2015; Iquique, 2014). The compilation of the goodness-of-fit parameters is summarized in Table 1, where it can be seen that, except for T_{mean} , the models maintain or worsen their predictive capacity for extreme earthquakes. On the other hand, the tendency that the models in cortical environment deepen their positive bias is reaffirmed, underpredicting intensities than those observed in large events.

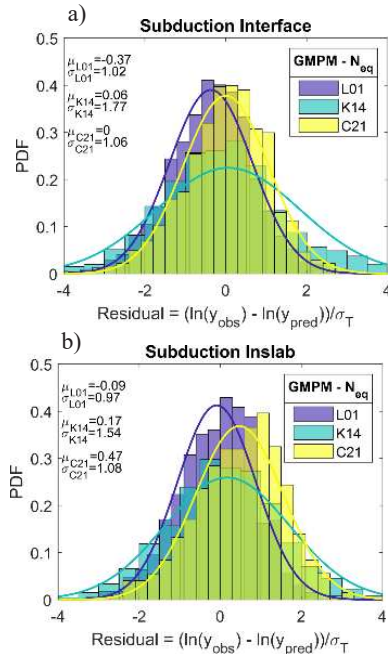


Figure 8. Residual distribution for number of equivalent cycles. Panel a) is for subduction interface and, panel b) is for subduction inslab

Table 1. Goodness-of-fit values for different models and non-spectral parameters for all and a subset of the database

Parameter	Model	All database (subduction)		Only $M_w > 8.0$ earthquakes	
		μ_{z_i}	LH/ Class	μ_{z_i}	LH/ Class
Arias Intensity	SA16	0.55	0.35/C	0.81	0.28/D
	CB19	-0.28	0.23/D	0.23	0.21/D
CAV	SA16	0.82	0.33/D	1.43	0.13/D
	CB19	0.36	0.29/D	0.55	0.34/C
$D_{s,05-75\%}$	SA16	0.00	0.54/A	0.32	0.51/B
	DW16	0.96	0.27/D	0.25	0.54/D
$D_{s,05-95\%}$	SA16	0.37	0.48/B	0.81	0.30/D
	DW16	0.66	0.36/D	0.62	0.20/D
N_{eq}	L01	-0.27	0.51/B	-0.29	0.37/C
	K14	0.10	0.34/D	0.25	0.29/D
	C21	0.17	0.46/A	0.35	0.37/B
T_{mean}	DU17	3.41	0.01/D	0.29	0.42/B

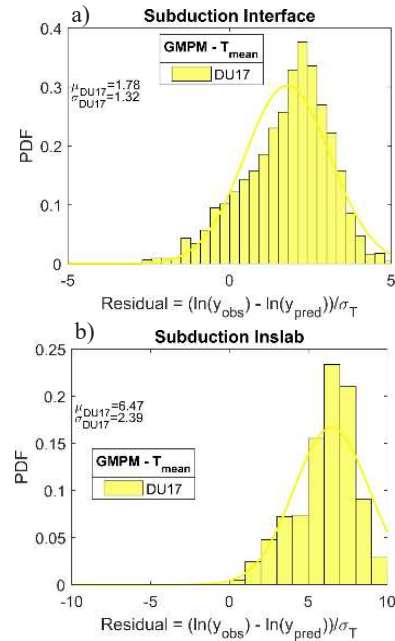


Figure 9. Residual distribution for mean period. Panel a) is for subduction interface and, panel b) is for subduction inslab

4 CONCLUSIONS

Recently, with the increase in the amount of data available of Chilean seismic records, the possibility of exploring the use of new seismic parameters of those already used. All with the scope of improving the description and understanding of a complex phenomenon as earthquakes.

In line with the development and massification of methodologies to study seismic demand at specific-project or -site, a complete and descriptive set of seismic parameters must be used to engineering design. In consequence, the observed tectonics differences are relevant and must be considered in earthquake engineering.

Typically, design codes include a unique seismic source to describe the demand, however, the substantial differences proposed in this study must be reflected on seismic design process. For example, the Seismic Building Code of Chile (NCh433) is based only on subduction interface, and ATC-63 provisions only on shallow crustal earthquakes (Tehrani and Denis, 2013). In both cases, there is a possibility occur an earthquake of different tectonic environments that must be considered.

The results obtained show that the parameter of significant duration and energy content is the most relevant bias in the prediction, underestimating the seismic intensities (i.e., positive residuals) in most of the cases.

In engineering systems that have the potential to degrade under cyclical load (e.g., liquefiable soils), the characterization of seismic demand must necessarily include the amplitude and duration of the strong movement correctly. Due to scarce correlation between both parameters (Kramer, 1996), their independent estimation become even more relevant in design methodologies. For example, co-seismic landslide (Rauch and Martin, 2000) or lateral spreading tends to increase with the duration of the strong ground motion.

Evaluation of energy-content intensities (Ia and CAV) shows a large standard deviation in prediction, this situation under probabilistic schemes for estimation seismic demand (PSHA) causes an unnecessary overestimation at longer analysis return periods (e.g., Strasser et al., 2009). For prediction of the number of equivalent cycles, acceptable predictive behavior is observed,

however, it contains two strong hypotheses: first, the assumption that reference amplitude corresponds to the 65% of maximum amplitude of shear stress, and secondly, the equivalent cycle counting scheme (Hancock and Bommer, 2005) what can be controversial for subduction tectonics and would produce different results.

In general, intensities observed on subduction are higher than evaluated models on the shallow crustal environment (SA16, CB19, and DW16) for non-spectral intensities. On other hand, amplitude parameters (PGA, PGV, and SA) do not have a clear tendency and have a distance and magnitude dependency for the good prediction capacity. The main differences are shown in severe earthquakes scenarios that control the engineering design.

In specific, some design methodologies could be rethought to include intrinsic differences between tectonics environments. Former studies of predictive equations of various intensities were developed for shallow crustal earthquakes, but are not replicated in subduction zone. For example, soil improvement for liquefied soils under design based on drainage, need define duration of strong ground motion that typically are based on shallow crustal earthquakes (Seed and Booker, 1976).

Finally, due to the sparse development of non-spectral intensities of strong ground motion, this investigation allows finding the best candidates to functional forms and explanatory variables to new ground-motion prediction models.

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