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COSTA RICAN STRONG MOTION DATABASE: 1998-2019, DESCRIPTION AND PRELIMINARY ANALYSIS

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Abstract

The Earthquake Engineering Laboratory of the University of Costa Rica (LIS-UCR) operates the Costa Rican Strong Motion Database (CRSMDB) and the Costa Rican Accelerographic Network (CRAN). The CRAN started in 1983, and ever since, it has recorded several hundreds of strong motion records that integrate the CRSMDB. The CRSMDB is thus made up of both analog and digital records. Here, we will analyze the digital period that runs from 1998 until 2019. From that period, there are more than 2400 3-axial records with a PGA greater than 2cm/s^2, which include a large variety of focal mechanisms, magnitudes, depths, and intensity measures on the surface. The largest event recorded is the 7.6Mw earthquake that occurred on September 5, 2012, in Samara with a maximum as-recorded PGA of 1580 gals. That earthquake occurred in the subduction zone between the Cocos and the Caribbean plates. In this article, we make a brief description of the CRAN, a general description of the CRSMDB, and a characterization of the available records according to common seismological parameters. An engineering-focused signal processing is carried out, estimating different Intensity Measures (IM) like PGA, PGV, 5% damped acceleration response spectrum at different periods, and orientation independent measures like the RotD100 and RotI100. Additionally, the Effective Peak Ground Acceleration (EPGA) and its ratio with the PGA are obtained. This is relevant because the Costa Rican Seismic Code makes use of the EPGA as an IM for designing purposes by transforming the results from a PSHA (where the PGA is the dependent variable) into EPGA with a constant correction factor. Finally, an updated correction factor is also proposed. In this respect, several ratios are calculated in order to compare the variability between different IM's.

Keywords: Strong Motion, Database, Intensity Measures, Orientation Independent.

1. Introduction

The subduction of the Cocos and Caribbean plates along the Pacific coast of Costa Rica is the country's major source of seismic activity [1, 2]. Consequently, many earthquakes occur along the subduction zone, and the continental part has active volcanism as well. The outer slope side of the place generates normal faulting, while reverse faulting takes place at depths between 15 and 50 km [3]. At depths between 50 and 280 km, intraplate or intra-slab earthquakes (deep subduction) occur, and Normal-type mechanisms are predominant [4].

The Benioff zone gets shallower in the southern part of Costa Rica, where the Cocos mountain range subducts. The Panama Fracture Zone is a dextral fault system that separates the Cocos plate from the Nazca plate [5]. At the southern end of the Burica Peninsula, lies the triple point where the Cocos, Caribbean, and Panama blocks meet. Also, a large number of temblors take place along the Northern Panama Deformed Belt (NPDB) and the Central Costa Rica Deformed Belt (CRDB) [6]. These are a series of cortical deformation zones with a high density of active faults [7]. This complex tectonic framework has resulted in numerous destructive earthquakes (i.e., 1991 Limon Mw 7.7; 2012 Nicoya Mw 7.6), supporting the interest of having a dense network of instruments that capture surface acceleration levels in different parts of the country.

The Earthquake Engineering Laboratory at the University of Costa Rica (LIS-UCR for its acronym in Spanish) started working in 1983 with a donation of the United States Agency for International Development (USAID). Several SMA-1 Kinemetrics strong-motion accelerographs were deployed along the Pacific Coast and the highly populated Central Valley. At that moment, it was called the Faculty of Engineering's Accelerographic Network. It was an analog network, which made it difficult to get the information and the right processing.

In 1989 the lab's name was changed to LIS-UCR and it was moved to the Engineering Research Institute of the same University. New digital instruments were acquired, and the geographic coverage of the stations increased. Nowadays, LIS-UCR has more than 160 digital, 24-bit strong-motion units located in free-field conditions, boreholes, and inside buildings.

This paper used a database with a time span that ranges from March 1998 to July 2019. The objective of this article is to give a description and the first overview of its content in order to expand its use on research.

2. Costa Rican Accelerographic Network

In 1983, the LIS-UCR analogic network started working. In June 1991, the digital network began operations with SSA-2 Kinemetrics type sensors. For 2010, most of the analog instruments were replaced by Ref Tek technology, and in 2012, Güralp and Nanometrics sensors were also added. At the time of writing this document, more than 130 free-field stations (most of them with FBA sensors but MEMS as well) are working (see Fig. 1).

The site soil classification of each station is related to the dynamic properties of the upper soil layer. For this classification, the Costa Rican Seismic Code [8] defines four types of soils. This classification is similar to the one proposed in the ASCE 7-16 [9] (and originally based on UBC97[10]), grouping types A and B in S1 (rock), soils B, C, and D of ASCE 7-16 are equivalent to S2 (hard soil), S3 (soft soil), and S4 (very soft soil), respectively.

The soil classification uses a layered protocol with a bottom base that applies the geological available information and experts' opinions. The second level of classification uses the method proposed by Zhao et al., [11] based on spectral ratios and applied by Schmidt-Díaz [12]. This method makes use of the horizontal-to-vertical (H/V) spectral ratios in order to define a site predominant period using earthquakes recorded at each station. The third level for soil classification adds MASW measurement to define the VS30, improving the soil classification in each site. This work is underway, and at the time, we have more than 30 stations analyzed with this level of information.

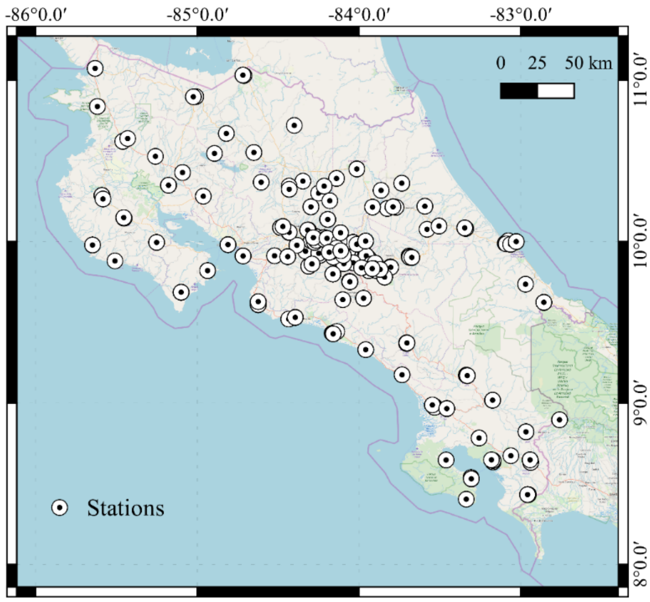

Fig. 1 – Location of accelerometric stations of the Costa Rican Strong-motion Network

Most of the stations are classified as S3 soil (42%), 33.1% as S2 soil, 17.2% as S4, and 7.7% as rock sites (S1). Fig. 2 shows the soil classification of each station and its distribution over the country.

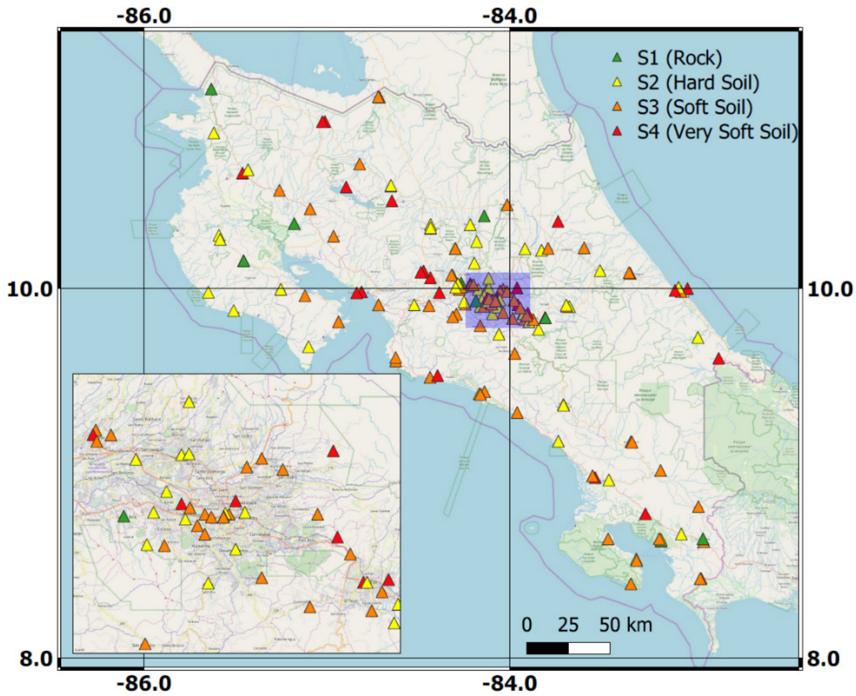

Fig. 2 – Map of Costa Rica showing the distribution of stations with their site classification.

3. Costa Rican Strong Motion Database

The Costa Rican Strong Motion Database (CRSMDB) is constantly growing due to the high seismicity of Costa Rica and a large number of stations available. For the preliminary exploration of the CRSMDB, a total of 2471 three-component accelerograms are used, related to 155 earthquakes recorded between 1998 and 2019 with a minimum horizontal Peak Ground Acceleration (PGA) of 2 cm/s^2. Fig. 3 shows the distribution of ground motions per year. As it can be seen, since 2010, on average, a significant increase in recorded events can be observed, which is related to the increase in the number of stations. 2016 presented a reduction of earthquakes recorded by the accelographic network. This reduction is due to a natural phenomenon.

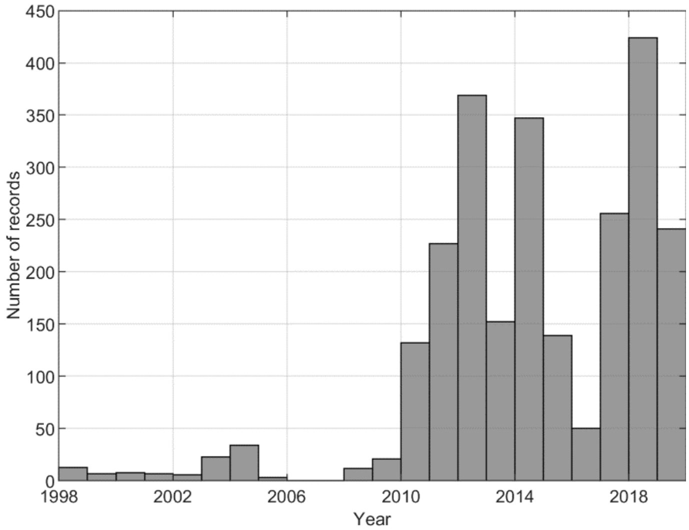

Fig. 3 – Number of ground motions recorded per year.

LIS-UCR has an automatic system that determines some seismological properties like magnitude (M_w), event location (coordinates in WGS84 system), and depth. This information combined with the station characteristics and maximum PGA's is then printed in the header of the records, according to Moya-Fernández [13, 14], in a "*lis-format*". This is a special ASCII format file with 34 header lines and 3 columns with acceleration data in north-south (N00E), vertical (UPDO), and east-west (N90E) components.

This automatic system receives data in a miniSEED format. Data is processed in SAC2000 [15], which makes a transformation to consistent units (cm/s^2). After that, using the mean value of the complete signal, a baseline correction is made. To avoid rippling, a taper is applied to both extremes of the signal, and finally, a second-order Butterworth bandpass filter is applied with corner frequencies of f_L = 0.05 Hz and f_H = 25 Hz. Table 1 shows an interval analysis of magnitude, epicentral distance, depth, horizontal PGA, and vertical PGA for the CRSMDB.

Table 1– Magnitude, Depth, Epicentral Distance, Horizontal PGA, and Vertical PGA statistics for the entire database. Number of three-components records per interval.

Magnitude (*Mw*)		**Depth (km)**		**Epicentral distance(km)**		**PGA$_h$ (cm/s^2)**		**PGA$_v$ (cm/s^2)**	
Range	**# of records**	**Range**	**# of records**	**Range**	**# of records**	**Range**	**# of records**	**Range**	**# of records**
<3,0	0	<10	183	<10	71	2-25	1925	<25	2295
3,0-4,0	65	10-25	1137	10-25	231	25-50	325	25-50	107
4,0-5,0	897	25-50	834	25-50	525	50-100	134	50-100	52
5,0-6,0	930	50-100	259	50-100	762	100-150	39	100-150	11
6,0-7,0	508	100-150	30	100-150	327	150-500	46	150-500	5
>7,0	71	>150	28	>150	555	>500	2	>500	1

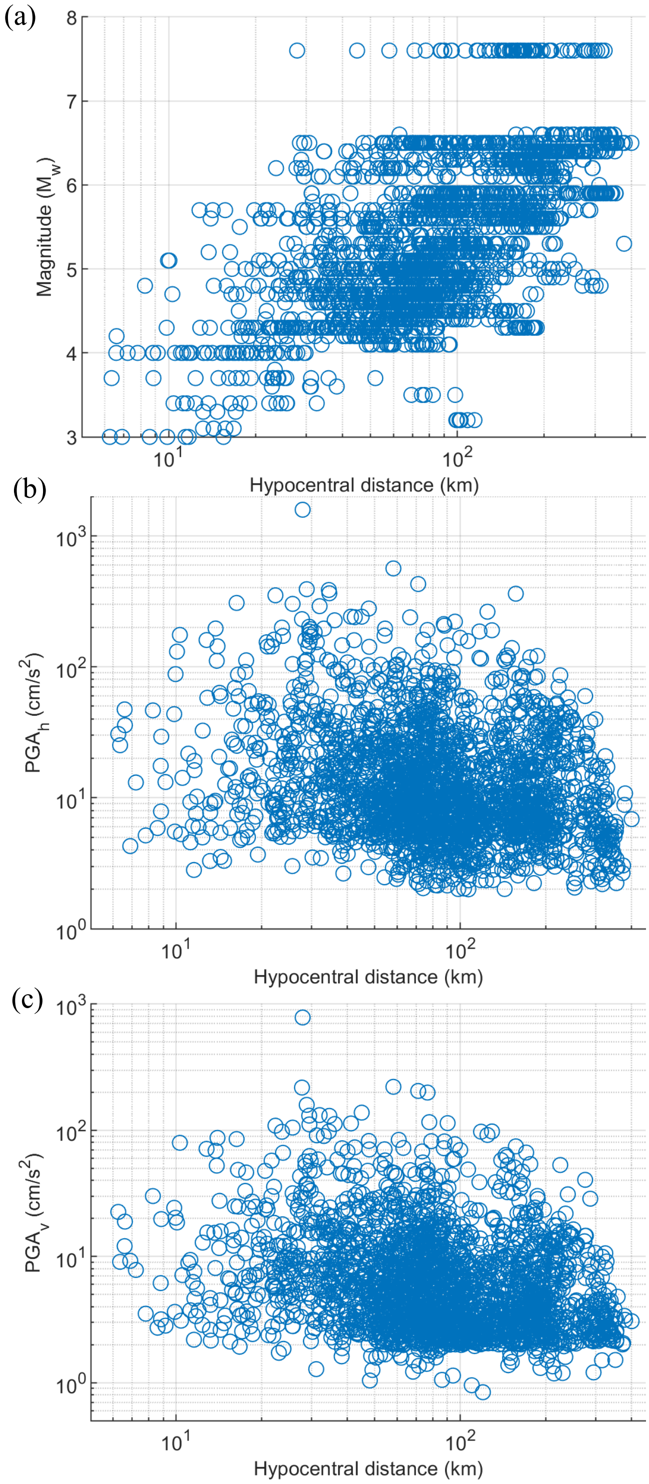

Fig. 4 – (a) Magnitude as a function of the hypocentral distance for the 2471 records, (b) Horizontal PGA as a function of the hypocentral distance and (c) Vertical PGA as a function of the hypocentral distance of earthquakes recorded with the Accelerometric Network

The vast majority of the records come from earthquakes with magnitudes between 4.0 and 7.0 (95%). From those, 61.1% are equal or higher than M_w 5.0, and only one earthquake has a magnitude above 7.0 — the 7.6 M_w Nicoya earthquake of 2012 [16]. This temblor was felt in the whole country, and 71 stations were activated. On the other hand, 22% of the records have a horizontal PGA greater than 25 cm/s^2.

Fig. 4 shows the relationship between magnitude, horizontal PGA, and vertical PGA with respect to the hypocentral distance. There is a lack of coverage of small earthquakes at large distances and big earthquakes at small distances, which is typical in this kind of database.

4. Intensity Measures

As a complementary study of the CRSMDB, a set of intensity measures (IMs) based on ground motion time-histories (Table 2) and on peak responses (Table 3) was estimated. The IMs based on peak responses are calculated with 5% of critical damping using several single-degree of freedom oscillators from PGA to 8 seconds.

IMs described in Table 2 are obtained directly from the as-recorded motion and have been used for ground-motion prediction models (GMPM) [5, 17, 18] as well as damage predictors [19, 20]. Fig. 5 shows the relationship between each IM as a function of the hypocentral distance.

Table 2– Intensity Measures based on time histories, applied to records in CRSMDB

Intensity measure	Acronym	Formulation	Units
Peak ground acceleration	PGA_{N00E} PGA_{N90E} PGA_Z	$\max\lvert a_{N00E}(t)\rvert$ $\max\lvert a_{N90E}(t)\rvert$ $\max\lvert a_Z(t)\rvert$	cm/s^2
Peak ground velocity	PGV	$\max\lvert v(t)\rvert$	cm/s
Arias intensity [21]	I_A	$\frac{\pi}{2\,g}\int_{t_i}^{t_f} a(t)^2\,dt$	cm/s
Significant duration [22–25]	Δ	5-95% of Arias intensity	s

- *a(t)* and *v(t)* represent the acceleration and velocity time histories of an earthquake.
- t_i is the beginning of the record, and t_f is the total duration of the record.
- 5% and 95% of the Arias intensity mark the beginning ($t_{5\%}$) and end ($t_{95\%}$) of the strong phase.

Table 3– Intensity Measures based on peak responses, applied to records in CRSMDB

Intensity measure	Definition
SA_{GM}	Geometric mean of the response spectra of the two as-recorded horizontal components [26–29]
$SA_{GMRotDpp}$	Percentile (pp) value of the geometric mean of the response spectra of the two as-recorded horizontal components rotated onto all non-redundant azimuths [27, 30]
$SA_{GMRotIpp}$	Percentile (pp) value of the geometric mean of the response spectra of the two as-recorded horizontal components rotated onto all non-redundant period- independent azimuths [27, 30]
SA_{RotDpp}	Percentile (pp) values of the response spectra of the two as-recorded horizontal components rotated onto all non-redundant azimuths [31, 32]
$EPGA$	Mean response spectra ordinates between 0.1 and 0.5 seconds divided by 2.5 [33, 34]

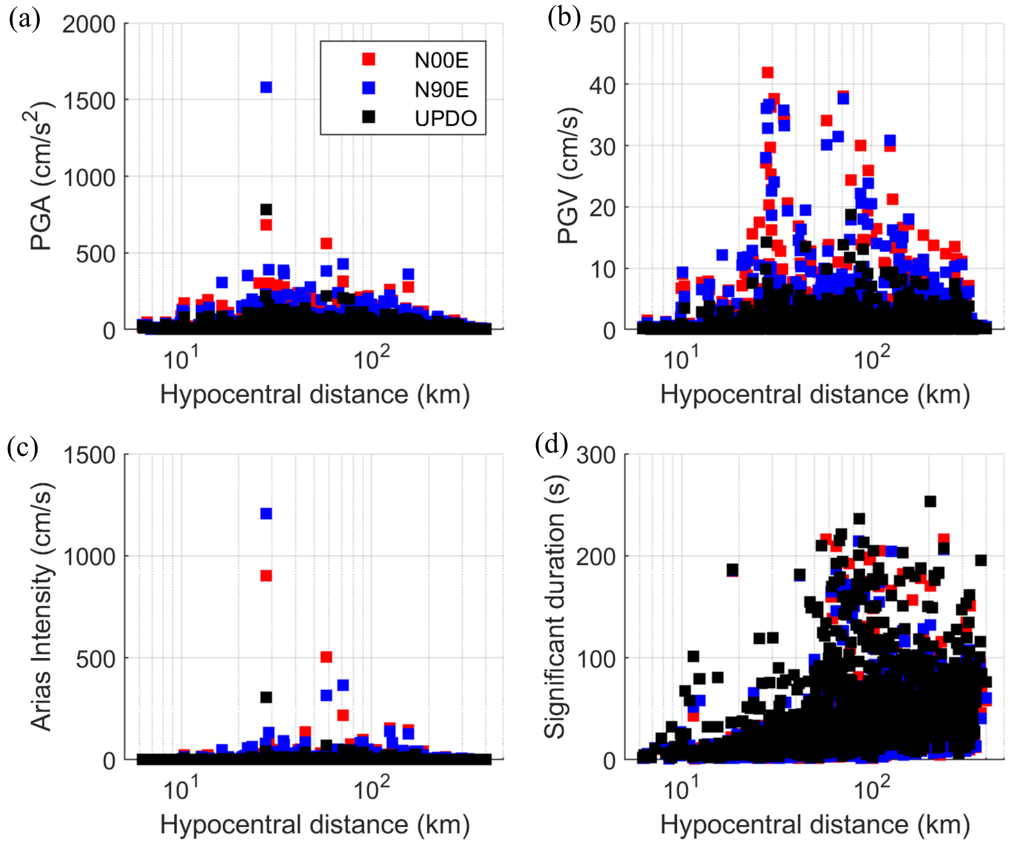

Fig. 5 – IMs as a function of the hypocentral distance: (a) PGA, (b) PGV, (c) Arias intensity, (d) Significant duration

Table 3 presents a group of IMs with dependency on the response spectra. The SA_{GM} (GM stands for Geometric Mean) is one of the most common IMs used in GMPM in recent years [35], mainly because the dispersion in the averaging procedure in GMPE is reduced significantly [18, 36, 37]. Nonetheless, this IM has an orientation dependence on the sensor orientation (normally N00E-N90E) and can be affected by the polarization of the signal. Boore et al. [30] have proposed an IM that used the GM of the response spectra with orientation independence ($SA_{GMRotDpp}$ and $SA_{GMRotDpp}$), which can be dependent (D) or independent (I) of the oscillator period and can be defined for any desired percentile (pp). The Next Generation Attenuation (NGA) project adopts the $SA_{GMRotI50}$ as IM [38].

In addition, Boore [39] proposed a second group of IMs that makes use of the maximum spectral response in one direction of an oscillator with orientation independence (SA_{RotDpp}). This IM was used on the second part of the NGA project, called NGA-West2, considering the 50th percentile [40]. A regular form to represent the variation of the different IMs is the ratio with respect to the SA_{GM} [26, 28, 41, 42]. Fig. 6 shows the ratios between the peak intensity measures with respect to SA_{GM}. The IMs with rotation independency that use the 50th percentile are close to the reference measure (ratio approximately 1.0), while $SA_{GMRotD100}$ presents variations between 1.21 and 1.29. This last ratio has a higher standard deviation.

A comparison of the ratio $SA_{GMRotD100}/SA_{GMRotI50}$ obtained with the CRSMDB and the ones founded by other researches [18, 26, 42–45] is presented in Fig. 7. The results obtained with CRSMDB are in good agreement with other investigations but with a narrower variation between the low and high period range, showing a variation range from 1.21 to 1.28. Similar behavior was reported by Hidalgo et al. [41] for a Central American database.

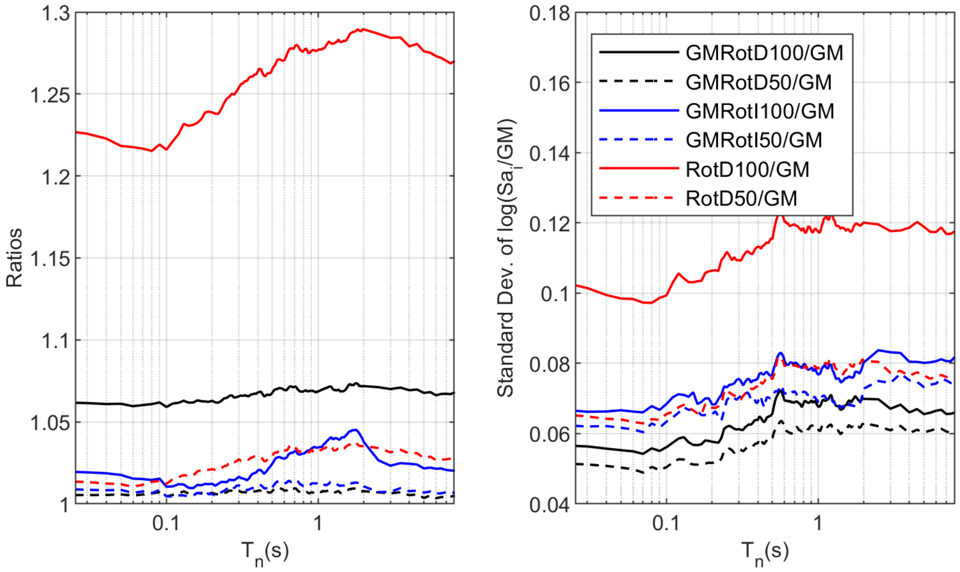

Fig. 6 – Ratios for IMs and standard deviation of $SA_{GMRotD100}/SA_{GM}$, $SA_{GMRotD50}/SA_{GM}$, $SA_{GMRotI100}/SA_{GM}$, $SA_{GMRotI50}/SA_{GM}$, $SA_{RotD100}/SA_{GM}$ and SA_{RotD50}/SA_{GM}.

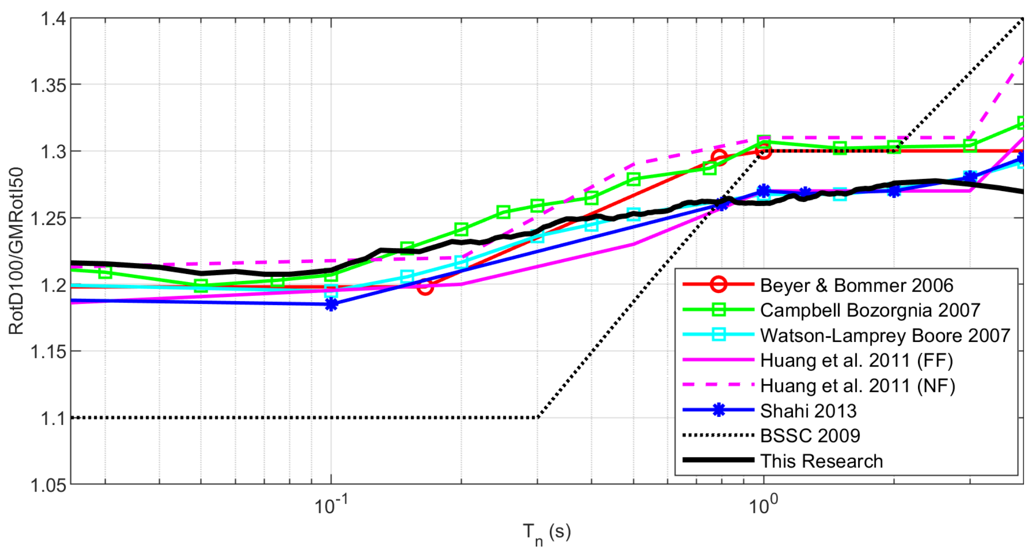

Fig. 7 – Geometric mean value of the ratio $SA_{GMRotD100}/SA_{GMRotI50}$ found in this study and comparison with the obtained by other researchers.

Finally, we present the mean and median ratios between EPGA and PGA in Fig. 8. A previous study that makes use of an analogic database of Central America reported a mean ratio of 0.80 [34]. The Costa Rican Seismic Code uses this value in order to transform the PGA obtained from a PSHA for design purposes to EPGA [8]. Results from CRSMDB showed a small variation in the mean ratio with a mean value over the complete orientation range of 0.866. Meanwhile, the median value has a variation with respect to the orientation angle with a maximum of 0.894, a minimum of 0.874, and a median value of 0.882. Compared with the previous value, this new study has a significant increment in the ratio, which can affect the acceleration values used for the design of structures in Costa Rica. The standard deviation varies from [±0.207] and [±0.212], depending on the selected orientation.

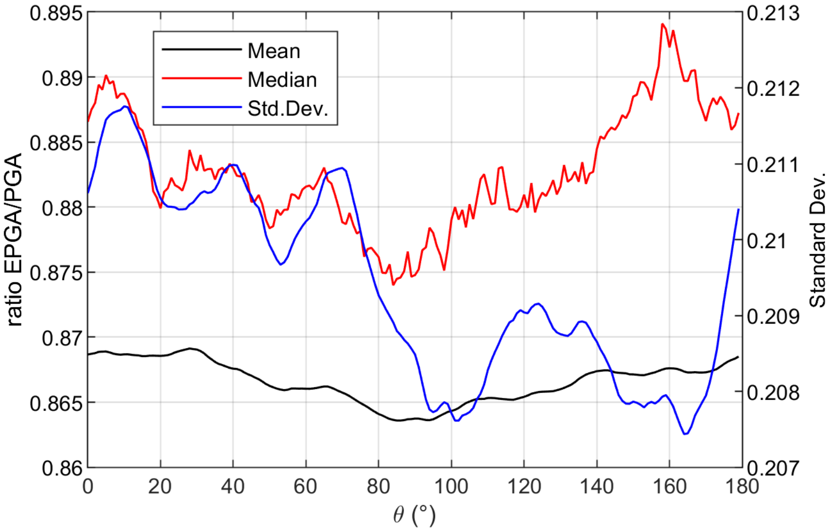

Fig. 8 – Median ratio of EPGA/PGA and the standard deviation as a function of the orientation angle.

The EPGA has not been commonly used as an intensity measure in other countries. The Colombian Seismic Code NSR-10 [46] uses this parameter in the same way the Costa Rican code does. These presented results could be used as a decision tool to define the IM for future design codes, especially in Costa Rica but also in Colombia.

4.1. Use of the CRSMDB for Seismic Hazard Analysis

Currently at the University of Costa Rica, new researches led by the LIS-UCR are using the CRSMDB to define the most suitable GMPM for Costa Rica according to the available information. At the time this article is presented, there is work in progress in order to define the set of earthquakes with a full seismological characterization. This project includes the National Seismological Network of the same University to combine the seismological and the strong motion catalogs. Further publications will be available with the results from the GMPM selection and the hazard analysis for Costa Rica.

5. Conclusions

We present a preliminary study of the Costa Rican Strong Motion Data Base (CRSMDB) with more than 2400 records obtained from digital accelerometers from 1998 to 2019. An exploratory evaluation of the database was made using seismological variables like magnitude, epicentral distance to the stations, and depth. This database can be consulted at the LIS-UCR web page (www.lis.ucr.ac.cr).

Intensity measures (IMs) were evaluated in two categories: based on time histories and peak responses. The first group of IMs was plotted as a function of the hypocentral distance. PGA and Arias Intensity present a concentration of cases for small values of the IM. PGV and significant duration have more cases with similar values and less skewed distribution. The second group of IMs is presented in a particular form where they are divided by the spectral acceleration of the Geometric Mean of the as-recorded components (SA_{GM}). This ratio has particular relevance due to the extended use of this particular IM on attenuation models. In general, IMs calculated with the 50th percentile have similar values, being the $SA_{GMRotD50}$ the one with less standard deviation and closer to 1.0 ratios. On the other hand, $SA_{RotD100}$ has ratios between 1.21 and 1.28 with respect to the reference IM.

Finally, effective peak ground acceleration (EPGA) is presented as a ratio of the PGA. Mean and median values of 0.866 and 0.882 are obtained. The standard deviation is high and should be considered in the transformation of IMs from a PSHA in order to use the EPGA on seismic design codes.

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