A Strong-Motion Database of Costa Rica: 20 Years of Digital Records


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Abstract

In this paper, we present a strong-motion database from earthquakes recorded by the Earthquake Engineering Laboratory at the University of Costa Rica. The database consists of 2471 three-component accelerograms from 155 digitally recorded events. It covers the last 20 years of measurements, including records from the Nicoya earthquake of Mw 7.6 on 2012 September 05. The engineering and seismological communities can use this data either to conduct new research or to improve seismic or hazard studies in the region. A catalog is also available with metadata of each record containing several intensity measures from the ground-motion time-histories.

Introduction

The convergence of the Cocos and Caribbean plates along the Pacific coast of Costa Rica is the major source of seismic activity for the country (Alvarado et al., 2017; Arroyo et al., 2017). As a result, many earthquakes occur along the subduction zone as well as active volcanism in the continental part. The outer slope side of the place generates normal faulting while reverse faulting takes place at depths between 15 and 50 km (Quintero and Güendel, 2000; DeShon et al., 2003; Norabuena et al., 2004). At depths between 50 and 280 km, intraplate or intra-slab earthquakes (deep subduction) occur and in general normal type mechanisms predominate (Guendel and Protti, 1998).

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 (Schmidt-Díaz, 2014). At the southern end of the Burica Peninsula lies the triple junction where the Cocos, Caribbean and Panama block meet. There is also a high number of seismic events that take place along the Northern Panama Deformed Belt (NPDB) and Central Costa Rica Deformed Belt (CRDB). These are a series of cortical deformation zones with a high density of active faults (Goes et al., 1993; Guangwei Fan et al., 1993; Montero, 2001). This complex tectonic framework has resulted in numerous destructive earthquakes (i.e., 1991 Limon $M_w$ 7.7; 2012 Nicoya $M_w$ 7.6), and, consequently, a concern to develop and improve the seismic hazard and risk studies of the country.
The Earthquake Engineering Laboratory at the University of Costa Rica (LIS-UCR for its acronym in Spanish) started operations in 1983. That year, the United States Agency for International Development (USAID), donated several SMA-1 Kinemetrics strong-motion accelerographs to Costa Rica. They were located along the Pacific coast and the highly populated Central Valley. That was known as the Faculty of Engineering’s Accelerographic Network. It was an analog network, which meant that after a strong earthquake took place, the collection and processing of the information took several days to weeks to get ready for analysis.

In 1989 the name was changed to LIS-UCR. New digital instruments were acquired, and the geographic coverage of the stations increased. At the time of writing this document, the LIS-UCR has more than 160 digital, 24-bit strong-motion units located in free-field conditions, boreholes, and inside buildings. The LIS-UCR is in charge of recording, processing and storing all acceleration records for academic and research purposes. The accelerograms used in this document were recorded only by sensors in free-field conditions.

The time span for the database provided in this paper ranges from 1998 to the present. The objective of this article is to give an overview and provide easy access to this database, and therefore, expanding its use on research.

**Strong-Motion Network**

The strong-motion network of the LIS-UCR began operating in 1983 with the installation of SMA-1 Kinemetrics analog sensors. In June 1991, digital processing started with the installation of several SSA-2 Kinemetrics type sensors. In 2010 many analog instruments were replaced by Ref Tek technology, and in 2012 Güralp and Nanometrics sensors were also added to the network. Nowadays, there are a total of 130 free-field stations [most of them with FBA (force-balanced-accelerograph) sensors, but MEMS (Micro-Electro-Mechanical Systems) as well] as shown in figure 1.

There are four soil types according to the Costa Rican Seismic Code (CRSC) (CFIA, 2016). This classification is similar to that proposed in the ASCE 7-16 (ASCE, 2017) with some differences. Soil types
A and B are called S1 (rock). Soil types C, D, and E of ASCE 7-16 are equivalent to S2 (stiff soil), S3 (soft soil) and S4 (very soft soil). There is no F type of soil in the CRSC classification.

Due to the complexity of data acquisition and the cost of the geotechnical studies, we used the classification method proposed by Zhao et al. (2006). The results can be found in Schmidt-Díaz (2011). The method is based on the horizontal-to-vertical (H/V) 5% damped response spectral ratio. From that, the fundamental period can also be obtained. We then used a classification index for each station. When available, geological and geotechnical information was also used as a reference.

A total of 42.0% stations are classified as soft soil (S3), 33.1% as stiff soil (S2), 17.2% are classified as very soft soil (S4), and 7.7% as rock sites (S1). In order to get a better site characterization, we are also conducting MASW measurements to define the Vs30 parameter. Currently, 35 stations have Vs30 and we are conducting measurements in 30 more stations (data available upon request via email). Figure 2 shows the site classification described above. There is also a table with a summary of the site conditions available at the LIS-UCR website (see Data and Resources).

**Strong-Motion Database**

The strong-motion database we present here has a total of 2471 three-component accelerograms. They correspond to 155 earthquakes recorded from 1998 to the present. The database is being updated automatically with new events as they trigger the Accelerographic Monitoring System (SMA in Spanish, Moya-Fernández, 2018). Figure 3 shows the distribution of ground motion recordings per year. The number has increased in recent years because at present there are more stations.

The SMA threshold requires that 30 stations surpass a value of 10 defined as follows: Every 15 seconds the SMA computes the PGA at every station for the last 60 seconds and stores its value. Only the NS component is used. It compares the PGA from the current minute \((PGA_C)\) and the previous one \((PGA_P)\). If the ratio \((PGA_C/PGA_P)\) is larger than 10 in 30 sites, the SMA processing begins. PGA is computed for the three components of every station once the SMA gets activated using the whole waveform. Once the SMA closes
the event, we select the records that have at least one horizontal PGA greater than 2 gals in order to include them in the final database.

The earthquake’s location (coordinates in WGS84 system), depth, and magnitude are calculated automatically by the SMA (Moya-Fernández, 2018). The magnitude used to characterize the database is the moment magnitude ($M_w$). Table 1 shows a statistical summary of the number of records per different ranges of magnitude, depth, and epicentral distance. Figure 4a shows the relation magnitude vs hypocentral distance. The hypocentral distance for the events in the database ranges from 5 to 400 km. There are 1509 records from earthquakes with $M_w \geq 5$ (61.1 %) (see Figure 4b). Figure 5 shows the location of the events in the database. Only one of the recorded earthquakes has an $M_w > 7$, the 7.6 $M_w$ Nicoya earthquake of 2012. A total of 71 stations recorded that event which shook the whole country. The largest peak ground acceleration was 1.6 g at GNSR station, which was the closest to the epicenter (Schmidt-Díaz et al., 2014).

The LIS-UCR stores strong-motion data in an ASCII format called “lis-format” (Moya-Fernández, 2006). This is a special type of format developed for researchers and students to have access to time-series data. The files contain a header of 34 lines with relevant station and earthquake information of each record, after which there are the three independent columns corresponding to the north-south (N00E), vertical (UPDO), and east-west (N90E) component. Metadata from the header includes the earthquake source (subduction or local), site to event distance [epicentral ($R_{ep}$), hypocentral ($R_{hypo}$), Joyner-Boore ($R_{jb}$) and the closest distance to rupture ($R_{rup}$)], site condition, soil classification, among others. The $R_{jb}$ and the $R_{rup}$ were computed following the methodology proposed by Thompson and Worden (2018). Earthquake source information is given in the database as local (LOCAL) or subduction (SUBDU) type events. This classification is a general one, and it is based on the epicenter location and depth. Earthquakes located place along the Pacific coast are usually classified as subduction type events. Earthquakes further inland in the rest of the country at shallow depths (less than 30 km) are classified as local ones. Deeper earthquakes (more than 30 km) along the subducted Cocos plate are classified as intraslab (INSLB) events. We use “UNDEF” for those earthquakes happening in complex tectonic settings or where a simple classification
cannot be made. The slab model for Central America from USGS was used to help define which events happened along the subducted slab in Costa Rica (Hayes et al., 2012). This metadata is available in a catalog on the LIS-UCR website (see Data and Resources).

Data Processing

Each station transmits real-time data to the LIS-UCR servers in miniSEED format. When an earthquake is strong enough to trigger 30 stations, the SMA extracts a pre-defined time-window and converts waveform data to SAC format (Goldstein et al., 2003) in cm/s$^2$. A baseline correction is applied by removing the mean value. After tapering on both ends, a second-order Butterworth bandpass filter is used. The SMA then processes the source parameters, calculate peak values, and gathers station information and soil type to save data into lis-format. Notice that the entire process is automatic, for that reason, the data is later inspected by eye in order to identify events with a low signal-to-noise ratio or with processing issues. Records that are not suitable are removed from the database.

Data processing is proposed to satisfy the requirements of an Engineering Strong Motion (ESM) database. Frequency bandpass is set to include and overcomes the frequency range for civil structures. Over the years, corner frequencies have change according with technology, equipment brands and internal requirements on LIS. For example, before 1998, the LIS's network was made of Kinemetrics type instrumentation only. The default filtering from the K2 and ETNA strong motion records from Vol2 format was 0.12 to 47 Hz. When Reftek was introduced in 2010, the range was set at 0.1 to 40 Hz. After 2017, when the SMA took care of the automatic signal processing, it was decided that the range 0.05 to 25 Hz best fitted the needs for most engineering purposes in Costa Rica. In this way, new technologies such as Guralp and Nanometrics that were later introduced could be used with common values. It is recommendable for the reader to take care when this parameter is sensitive and read the corner frequencies for each record.
Intensity Measures

In addition to the database and the catalog, we computed a series of intensity measures (IMs) based on ground motion time-histories (Table 2) and peak responses (Table 3). The IMs for each record are also available in the LIS-UCR website (see Data and Resources). The IMs based on time histories are available in a single table where each column represents a single IM. In the case of the IMs based on peak responses, they were calculated with absolute spectral acceleration (SA) and a 5\% damping. Despite the most commonly used IM in Ground Motion Prediction Equations (GMPE) is the pseudo-spectral acceleration (PSA), we estimate the SA with the Nigam and Jennings (1969) exact solution of the differential equation governing the response. For small damping, these two IMs are equivalent (Chopra, 2007). They are presented in single tables as a function of several oscillator periods.

We used the acceleration time-histories to calculate the IMs in Table 2. They have been widely used in the development of ground-motion prediction equations and seismic hazard studies (Boore et al., 1997; Watson-Lamprey and Boore, 2007; Mezcua et al., 2008; Schmidt-Díaz, 2014; Douglas, 2017), as well as in the evaluation of expected damage (Park et al., 1987; Kostinakis et al., 2015; Muin and Mosalam, 2017). Figure 6 shows the relation between PGA (PGA_{N00E}, PGA_{N90E} and PGA_{Z} from Table 2) and hypocentral distance in the database. There are 7413 individual time-histories corresponding to the 2471 records. Of them, 39.5\% have a PGA larger than 10 cm/s^2. Comparing the mean values of several PGA definitions, we got differences of 1.45\% between PGA_{Larger(3)} and PGA_{Larger(2)}, and 12.5\%, 15.6\% and 14.0\% between PGA_{Larger(2)} and PGA_{N00E}, PGA_{N90E}, and PGA_{GM} respectively. Figure 7 shows the relation for the rest of the IMs with hypocentral distance.

The IMs from peak responses in Table 3 are commonly used in the development of GMPE and hazard maps (Douglas, 2017). The SA_{GM} (where GM means geometric mean) has gained popularity in the development of GMPEs in recent years (Douglas, 2003; Campbell and Bozorgnia, 2008; Bindi et al., 2011) because the dispersion in the averaging procedure in GMPE is significantly reduced (Baker and Cornell, 2006; Watson-Lamprey and Boore, 2007; Stewart et al., 2011). However, this IM has a dependence on the recording
sensor orientation (this means that if the recording sensor is oriented along the polarization direction, the GM of the response spectra of the as-recorded ground motion tends to zero, Boore et al. 2006). The \( \text{SA}_{\text{GMRotDpp}} \) and the \( \text{SA}_{\text{GMRotIpp}} \) developed by Boore et al. (2006) (where GM means geometric mean, Rot: rotation, D and I: period-dependent and independent rotations, and pp is the percentile) were proposed in order to eliminate the sensor orientation dependency of the \( \text{SA}_{\text{GM}} \). The IM \( \text{SA}_{\text{GMRotDpp}} \), for the 50th percentile (\( \text{SA}_{\text{GMRI50}} \)), was used as an intensity parameter in the Next Generation Attenuation (NGA) project (Chiou et al., 2008; Power et al., 2008). Later on, Boore (2010) proposed the usage of the orientation-independent \( \text{SA}_{\text{RotDpp}} \) and \( \text{SA}_{\text{RotIpp}} \) IMs without computing the geometric mean. Finally, the \( \text{SA}_{\text{RotD50}} \) IM was used to develop the NGA-West2 (Boore et al., 2013; Bozorgnia et al., 2014) and NGA-East (PEER, 2015) GMPEs models.

Figure 8 shows a comparison between the rotated spectra and the \( \text{SA}_{\text{RotD100}} \) IM (following Boore (2010)) for the 2012 Nicoya earthquake at GNSR station. It is clear from the figure that the \( \text{SA}_{\text{RotD100}} \) is the envelope of the rotated spectra. Because this IM represents the maximum value of the vector composition, it could be used for the design (or risk assessment) of structures of special importance such as historical-cultural heritage buildings or other high-risk constructions (Pinzón, Pujades, Hidalgo-Leiva, et al., 2018). Figure 9 shows the rest of IMs: \( \text{SA}_{\text{RotD100}}, \text{SA}_{\text{Larger}}, \text{SA}_{\text{GMRotD50}}, \text{SA}_{\text{GMRotI50}}, \text{SA}_{\text{RotD50}}, \) and \( \text{SA}_{\text{GM}} \) calculated in the in the range of 0.10s to 0.25s. \( \text{SA}_{\text{GMRotD50}}, \text{SA}_{\text{GMRotI50}} \) and \( \text{SA}_{\text{RotD50}} \) correspond to the median values of the rotated spectra and have similar values compared to \( \text{SA}_{\text{GM}} \). \( \text{SA}_{\text{RotD100}} \) and \( \text{SA}_{\text{Larger}} \) represent the maximum spectral values. \( \text{SA}_{\text{RotD100}} \) is 9% larger than \( \text{SA}_{\text{Larger}} \) on average for the entire database. A statistical summary for all the IMs can be found on the LIS-UCR website (see Data and Resources).

Conclusions

The database presented in this paper contains 2471 three-component digitally recorded strong-motion records from the last 20 years in Costa Rica. They correspond to 155 earthquakes with maximum hypocentral distances of 400 km. Data will continue to be added as new earthquakes get recorded by the LIS-UCR network. In addition, a catalog with earthquake and station metadata is also available. Several
time-history IMs and peak responses were also calculated for each component. The IMs will be useful for developing new seismic hazard studies for the region or for updating the current GMPEs established for Costa Rica (Schmidt-Díaz, 2014). The database, the catalog with the metadata, and the estimated IMs are available at the LIS-UCR website (see Data and Resources).

Data and Resources

The link to the LIS-UCR website is http://www.lis.ucr.ac.cr/. A table with the site conditions of each station is available in the following link: http://www.crsmd.lis.ucr.ac.cr/?id=Estaciones. To request the database of accelerograms please access the following link: http://www.crsmd.lis.ucr.ac.cr/?id=BD, and fill out the form or send an e-mail to lis.inii@ucr.ac.cr.

The catalog is available at http://www.crsmd.lis.ucr.ac.cr/?id=BD. The IMs and statistical summary can be found in the following link: http://crsmd.lis.ucr.ac.cr/crsmdb.zip.

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Table 1 Magnitude, depth and epicentral distance statistics for the entire database. Number and percentage of three-components records per interval.

<table>
<thead>
<tr>
<th>Magnitude ($M_w$)</th>
<th>Depth (km)</th>
<th>&lt; 10</th>
<th>10—25</th>
<th>25—50</th>
<th>50—100</th>
<th>100—150</th>
<th>≥ 150</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 - 4.0</td>
<td>&gt; 100</td>
<td>-</td>
<td>38 (1.5%)</td>
<td>27 (1.1%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4.0 - 5.0</td>
<td>10—100</td>
<td>-</td>
<td>76 (3.1%)</td>
<td>348 (14.1%)</td>
<td>365 (14.8%)</td>
<td>108 (4.4%)</td>
<td>-</td>
</tr>
<tr>
<td>5.0 - 6.0</td>
<td>50—100</td>
<td>-</td>
<td>57 (2.3%)</td>
<td>472 (19.1%)</td>
<td>229 (9.3%)</td>
<td>144 (5.8%)</td>
<td>-</td>
</tr>
<tr>
<td>6.0 - 7.0</td>
<td>100—150</td>
<td>-</td>
<td>12 (0.5%)</td>
<td>232 (9.4%)</td>
<td>227 (9.2%)</td>
<td>7 (0.2%)</td>
<td>30 (1.2%)</td>
</tr>
<tr>
<td>≥ 7.0</td>
<td>≥ 150</td>
<td>-</td>
<td>71 (2.9%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnitude ($M_w$)</th>
<th>Epicentral distance (km)</th>
<th>&lt; 10</th>
<th>10—25</th>
<th>25—50</th>
<th>50—100</th>
<th>100—150</th>
<th>≥ 150</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 - 4.0</td>
<td>&gt; 100</td>
<td>17 (0.7%)</td>
<td>31 (1.3%)</td>
<td>5 (0.2%)</td>
<td>8 (0.3%)</td>
<td>4 (0.2%)</td>
<td>-</td>
</tr>
<tr>
<td>4.0 - 5.0</td>
<td>10—100</td>
<td>30 (1.2%)</td>
<td>130 (5.3%)</td>
<td>325 (13.1%)</td>
<td>326 (13.2%)</td>
<td>53 (2.1%)</td>
<td>33 (1.3%)</td>
</tr>
<tr>
<td>5.0 - 6.0</td>
<td>50—100</td>
<td>18 (0.7%)</td>
<td>58 (2.3%)</td>
<td>170 (6.9%)</td>
<td>316 (12.8%)</td>
<td>182 (7.4%)</td>
<td>186 (7.5%)</td>
</tr>
<tr>
<td>6.0 - 7.0</td>
<td>100—150</td>
<td>3 (0.1%)</td>
<td>12 (0.5%)</td>
<td>26 (1.0%)</td>
<td>104 (4.2%)</td>
<td>75 (3.0%)</td>
<td>288 (11.7%)</td>
</tr>
<tr>
<td>≥ 7.0</td>
<td>≥ 150</td>
<td>-</td>
<td>1 (0.1%)</td>
<td>1 (0.1%)</td>
<td>8 (0.3%)</td>
<td>13 (0.5%)</td>
<td>48 (2.0%)</td>
</tr>
</tbody>
</table>
Table 2 List of intensity measures based on ground motion time histories

<table>
<thead>
<tr>
<th>Intensity measure</th>
<th>Acronym</th>
<th>Formulation</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak ground acceleration</td>
<td>$PGA_{N00E}$</td>
<td>$\max</td>
<td>a_{N00E}(t)</td>
</tr>
<tr>
<td></td>
<td>$PGA_{N90E}$</td>
<td>$\max</td>
<td>a_{N90E}(t)</td>
</tr>
<tr>
<td></td>
<td>$PGA_z$</td>
<td>$\max</td>
<td>a_z(t)</td>
</tr>
<tr>
<td>Larger value of the two horizontal components of</td>
<td>$PGA_{Larger(2)}$</td>
<td>$\max\left[\max</td>
<td>a_{N00E}(t)</td>
</tr>
<tr>
<td>acceleration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\max\left[\max</td>
<td>a_{N00E}(t)</td>
</tr>
<tr>
<td>Larger value of the three components of acceleration</td>
<td>$PGA_{Larger(3)}$</td>
<td>$\max\left[\max</td>
<td>a_{N00E}(t)</td>
</tr>
<tr>
<td>Geometric mean of the PGA of the two horizontal</td>
<td>$PGA_{GM}$</td>
<td>$\sqrt{PGA_{N00E} * PGA_{N90E}}$</td>
<td>cm/s²</td>
</tr>
<tr>
<td>components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak ground velocity</td>
<td>$PGV$</td>
<td>$\max</td>
<td>v(t)</td>
</tr>
<tr>
<td>PGV-to-PGA ratio</td>
<td>$PGV/PGA$</td>
<td>$\frac{\max</td>
<td>v(t)</td>
</tr>
<tr>
<td>Arias intensity</td>
<td>$I_A$</td>
<td>$\frac{\pi}{2g} \int_{t_i}^{t_f} a(t)^2 , dt$</td>
<td>cm/s</td>
</tr>
<tr>
<td>Root-mean-square (RMS) of acceleration</td>
<td>$acc_{RMS}$</td>
<td>$\sqrt{\frac{1}{\Delta} \int_{t_{5%}}^{t_{95%}} a(t)^2 , dt}$</td>
<td>g</td>
</tr>
<tr>
<td>Root-mean-square (RMS) of velocity</td>
<td>$vel_{RMS}$</td>
<td>$\sqrt{\frac{1}{\Delta} \int_{t_{5%}}^{t_{95%}} v(t)^2 , dt}$</td>
<td>cm/s</td>
</tr>
<tr>
<td>Specific energy density</td>
<td>$SED$</td>
<td>$\int_{t_i}^{t_f} v(t)^2 , dt$</td>
<td>cm²/s</td>
</tr>
<tr>
<td>Characteristic intensity</td>
<td>$I_C$</td>
<td>$acc_{RMS}^{1.5} \sqrt{I_f}$</td>
<td>-</td>
</tr>
<tr>
<td>Cumulative absolute velocity</td>
<td>$CAV$</td>
<td>$\int_{t_i}^{t_f}</td>
<td>a(t)</td>
</tr>
<tr>
<td>Significant duration</td>
<td>$\Delta$</td>
<td>5-95% of Arias intensity</td>
<td>s</td>
</tr>
<tr>
<td>Duration-PGV intensity</td>
<td>$I_{A-PGV}$</td>
<td>$PGV^\alpha \Delta^\beta$</td>
<td>-</td>
</tr>
</tbody>
</table>

- $a(t)$ and $v(t)$ represents the acceleration and velocity time histories of an earthquake.
- $t_i$ is the beginning of the record, $t_f$ is the total duration of the record.
- 5% and 95% of the Arias intensity marks the beginning ($t_{5\%}$) and end ($t_{95\%}$) of the strong phase.
Table 3 List of intensity measures based on peak responses

<table>
<thead>
<tr>
<th>Intensity measure</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SA_{NOE}$ and $SA_{N0E}$</td>
<td>Response spectra of the as-recorded horizontal orthogonal components</td>
</tr>
<tr>
<td>$SA_{Larger}$</td>
<td>The larger of the two horizontal components (Douglas, 2003; Beyer and Bommer, 2006; Bradley and Baker, 2015; Boore and Kishida, 2016; Pinzón, Pujades, Hidalgo-Leiva, et al., 2018)</td>
</tr>
<tr>
<td>$SA_{GM}$</td>
<td>Geometric mean of the response spectra of the two as-recorded horizontal components (Beyer and Bommer, 2006; Bradley and Baker, 2015; Boore and Kishida, 2016; Pinzón, Pujades, Hidalgo-Leiva, et al., 2018)</td>
</tr>
<tr>
<td>$SA_{GMRotDpp}$</td>
<td>Percentile (pp) value of the geometric mean of the response spectra of the two as-recorded horizontal components rotated onto all non-redundant azimuths (Boore et al., 2006; Boore and Kishida, 2016)</td>
</tr>
<tr>
<td>$SA_{GMRotIpp}$</td>
<td>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 (Boore et al., 2006; Boore and Kishida, 2016)</td>
</tr>
<tr>
<td>$SA_{RotDpp}$</td>
<td>Percentile (pp) values of the response spectra of the two as-recorded horizontal components rotated onto all non-redundant azimuths (Boore, 2010; Pinzón, Pujades, Diaz, et al., 2018)</td>
</tr>
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Figure 2

Soil type
- S1 (Rock)
- S2 (Stiff soil)
- S3 (Soft soil)
- S4 (Very soft soil)
Figure 7

- (a) PGV vs. PGV90A
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