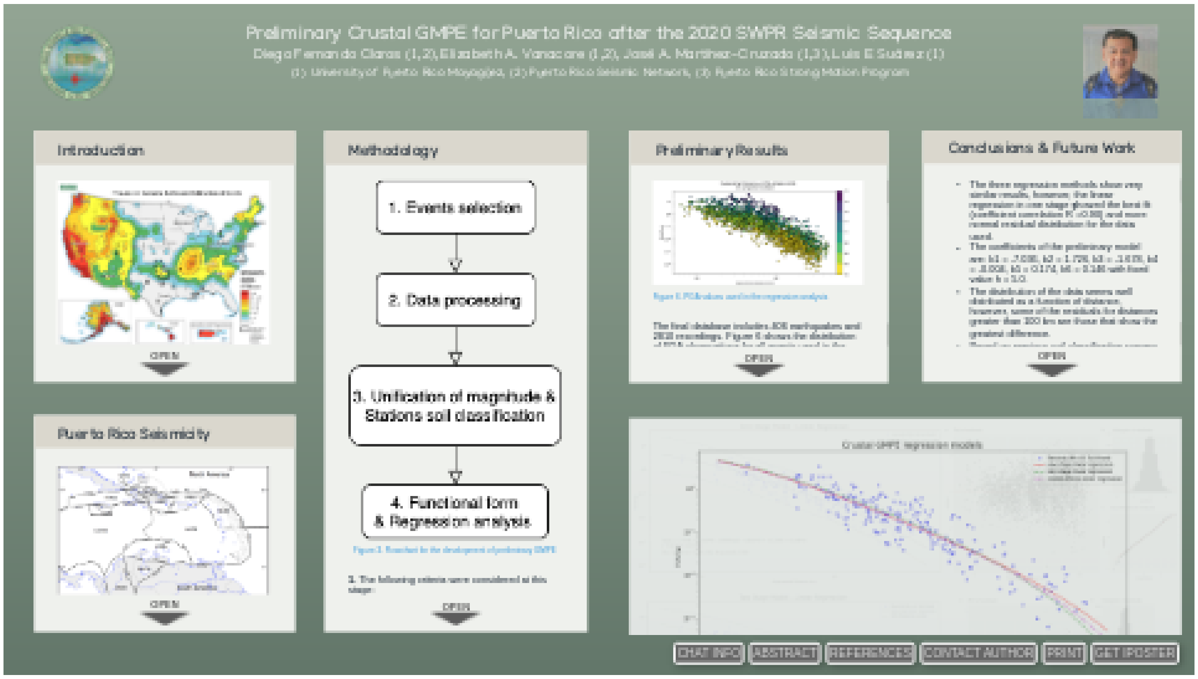
Preliminary Crustal GMPE for Puerto Rico after the 2020 SWPR Seismic Sequence



Diego Fernando Claros (1,2), Elizabeth A. Vanacore (1,2), José A. Martínez-Cruzado (1,3), Luis E Suárez (1)

(1) University of Puerto Rico Mayagüez, (2) Puerto Rico Seismic Network, (3) Puerto Rico Strong Motion Program

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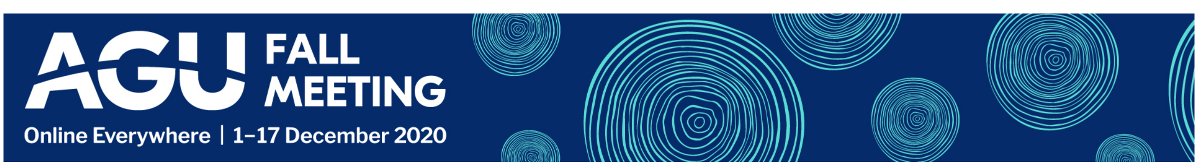


INTRODUCTION

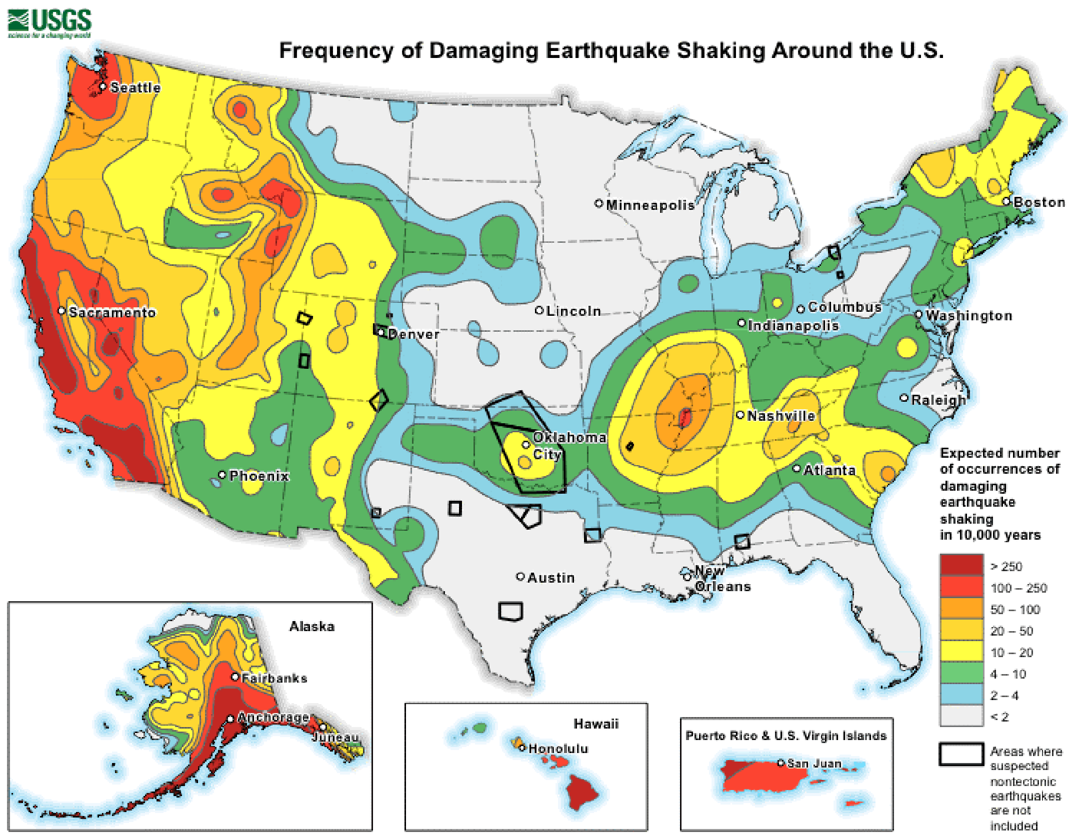


Figure 1. Map of the frequency of damaging earthquakes shaking for the United States (FEMA, 2020).

Puerto Rico and Virgin Islands are located in a high risk region for earthquake damage (FEMA, 2020, Figure 1). In the last year (05-jul-2019 to 05-jul 2020) the Puerto Rico Seismic Network (PRSN) recorded 136 earthquakes greater than M4.0 of which 2 earthquakes are ≧ M6.0. The last update of the Puerto Rico and Virgin Islands seismic hazard maps was performed in 2003. According to Mueller et al 2010, the Bunce fault, Muertos Trough and related fault structures weren't included in the map. Additionally, offshore faults in southern Puerto Rico were not considered, because their rates of activity were poorly known and assumed to be most likely small. However, starting in December 2019 the Southwestern Puerto Rico (SWPR) Seismic Sequence has been active and continues to be active in these southern offshore faults. According to the technical report of StEER (Miranda et al., 2020) between December 2019 to January 2020, there was damage to approximately 10,000 structures and more than 8,000 people were displaced.

One of the main parameters necessary to perform seismic hazard maps are the Ground Motion Prediction Equations (GMPEs or attenuation relationships) (Reiter, 1991). GMPEs are analytical expressions that relate a measure of intensity that can be the acceleration of soil particles and the independent variables associated for this purpose, mainly the magnitude, distance of origin and condition of the site (Sarria, 2008).

$$Y = f(M, R, P_i)$$

Y is the intensity measure, **M** the magnitude of the earthquake, **R** is the distance from the source to the interest site, and the $\mathbf{P_i}$ are other parameters (which may be used to characterize the earthquake source, wave propagation path, and/or local site conditions) (Kramer, 1996).

PUERTO RICO SEISMICITY

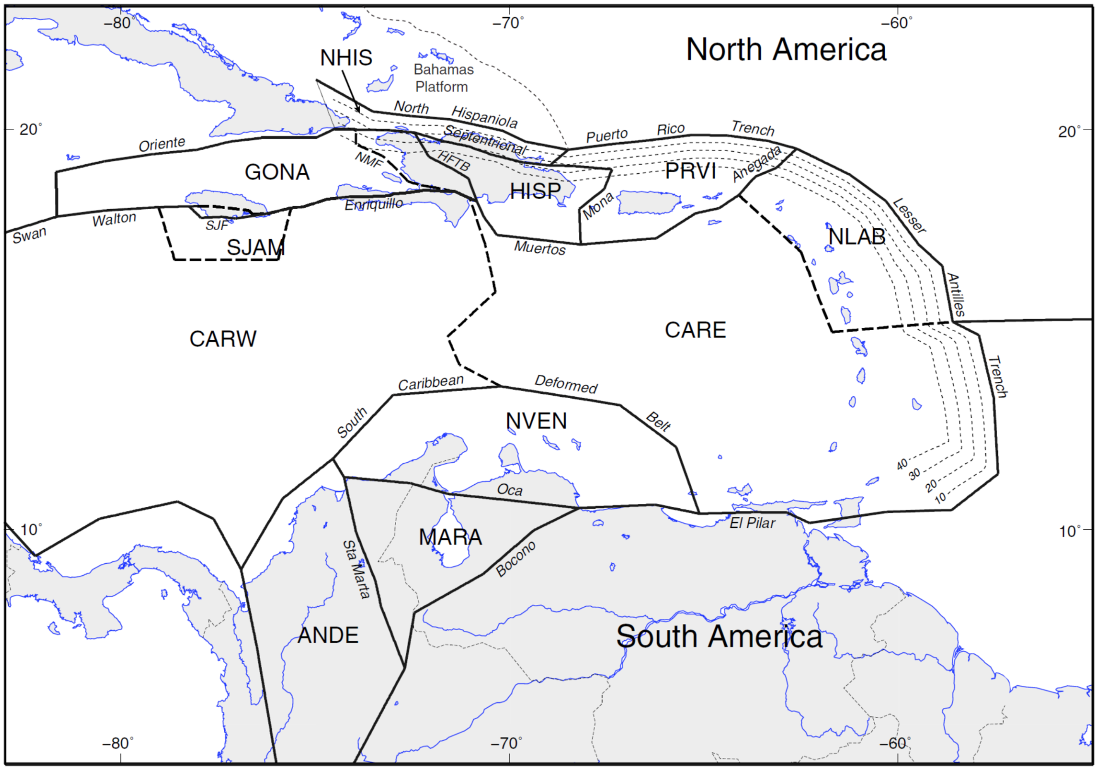


Figure 2. Block geometry for Caribbean (Symithe et al., 2015)

According to the general tectonic configuration (see the Figure 2), Puerto Rico is located in a microplate, Puerto Rico - Virgin Islands (PRVI), between the obliquely subducting plates of North America and the Caribbean (Clinton et al., 2006). To the north in the trench of Puerto Rico, North America plate subducts beneath the Caribbean plate at depths greater than 100 km, this same process occurs to the south in the Muertos trench where the Caribbean plate lithosphere subducts beneath Puerto Rico (Mann et al. 2005).

Recently, according to the catalog of the Puerto Rico Seismic Network (PRSN, 2020), in the last 5 years, 3 events of magnitude greater than 6.0 Mw have occurred. The most recent of these occurred on January 7, 2020 with magnitude 6.4 Mw, this mainshock, has generated a seismic trigger for the southern area in which more than 1500 aftershocks with a magnitude greater than or equal to 3.0 have already been recorded in the first 6 months 2020 (PRSN, 2020)

[VIDEO] https://www.youtube.com/embed/gnapvxONTw0?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

METHODOLOGY

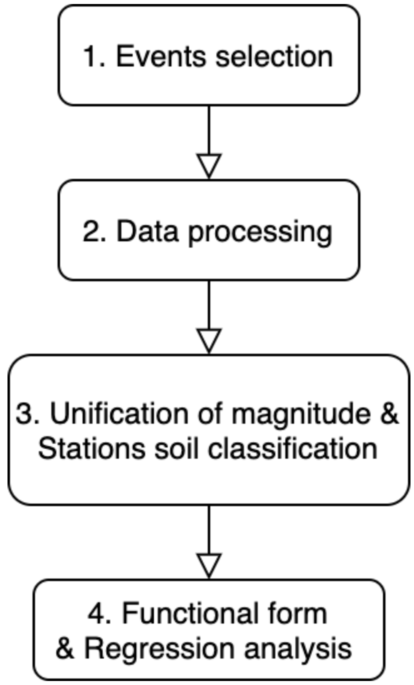


Figure 3. Flowchart for the development of preliminary GMPE

1. The following criteria were considered at this stage:

- Source: ANSS Comprehensive Earthquake Catalog (ComCat): includes PRSN Catalog Events
- Magnitude Range: 3.5 - 6.5
- Search rank: 2003/01/01 - 2020/09/30
- Maximum depth: 25 km (Crustal)
- RMS of the travel time residuals < 1.5
- Standard errors in the depth (ERZ) <10
- Only events with M>4 of SWPR Seismic Sequence were conderered

In this step: Total events: 429,Total records: 5008

2. The data were processing with the USGS code gmprocess (https://github.com/usgs/groundmotion-processing) for the Intensity Measurements (IM) of Peak Ground Acceleration (PGA) and combination of horizontal components RotD50.

Final data for regression: Total events: 406,Total records: 2810

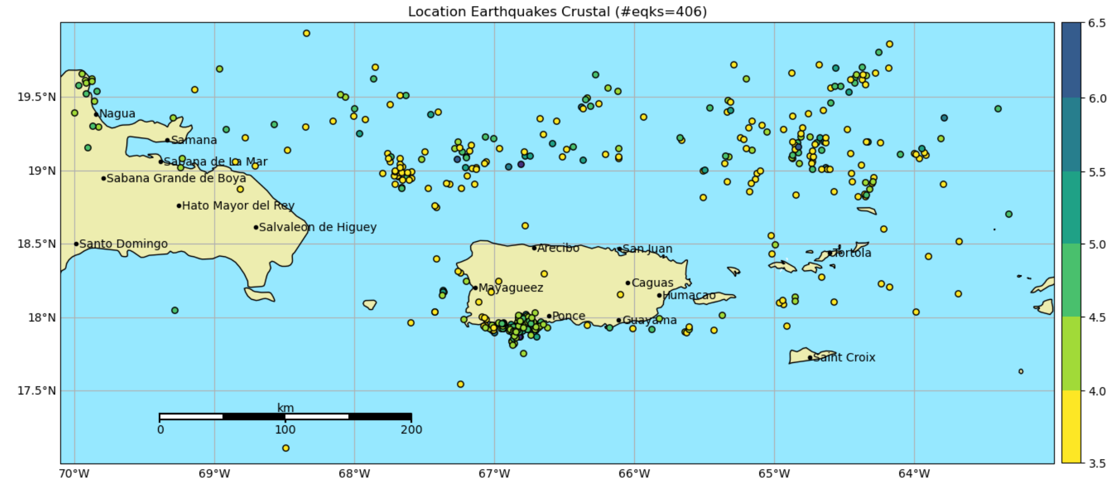


Figure 4. Location of events used in preliminary GMPE

3. To complete the parameters required for the regression, a unification of catalog magnitudes (md, ml) to moment magnitudes is performed from a local empirical relationship and a soil classification is assigned for the stations according to the Global model Vs30 based on topographic slope of Wald and Allen (2007, 2009)

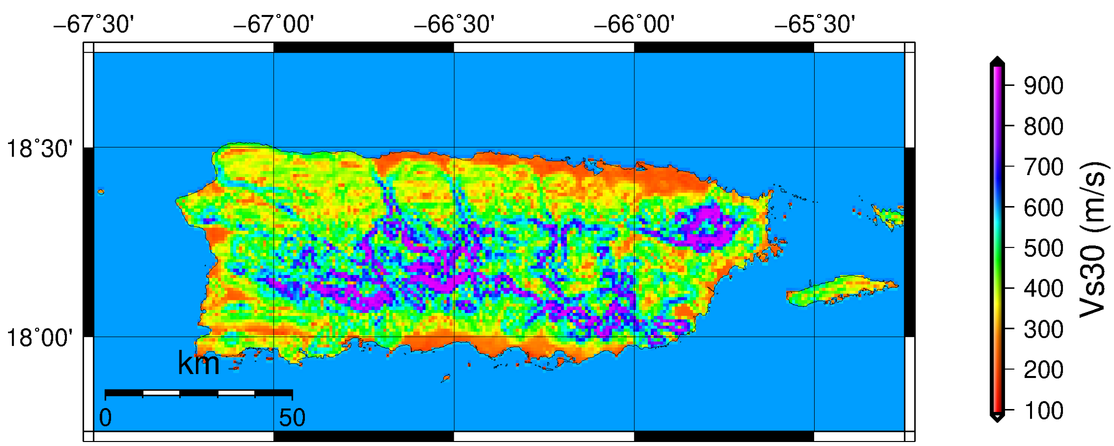


Figure 5. Puerto Rico Slope-Based Vs30 based on Wald and Allen (2007, 2009)

4. The following functional form proposed by Boore & Joyner, (1982), was selected to find the best fit by three regression methods (one stage OLS, two stage OLS and linear mixed-effect)

$$log(Y) = b_1 + b_2 M - b_3 log(\sqrt{d^2 + h^2}) - b_4 \sqrt{d^2 + h^2} + b_5 S + b_6 H$$

Where, *Y* is the dependent variable associated with the IM, *M* is the magnitude of the earthquake, *d* is the distance, for this investigation the hypocentral distance will be considered, *S and H* represents the site effect and b_1, b_2, b_3, b_4, b_5 and b_6 are the parameters to be determined in the regression. The term $b_3 log\ (d^2+h^2)^{0.5}$ is associated with geometric attenuation of the medium and $b_4\ (d^2+h^2)^{0.5}$ represents anelastic attenuation.

PRELIMINARY RESULTS

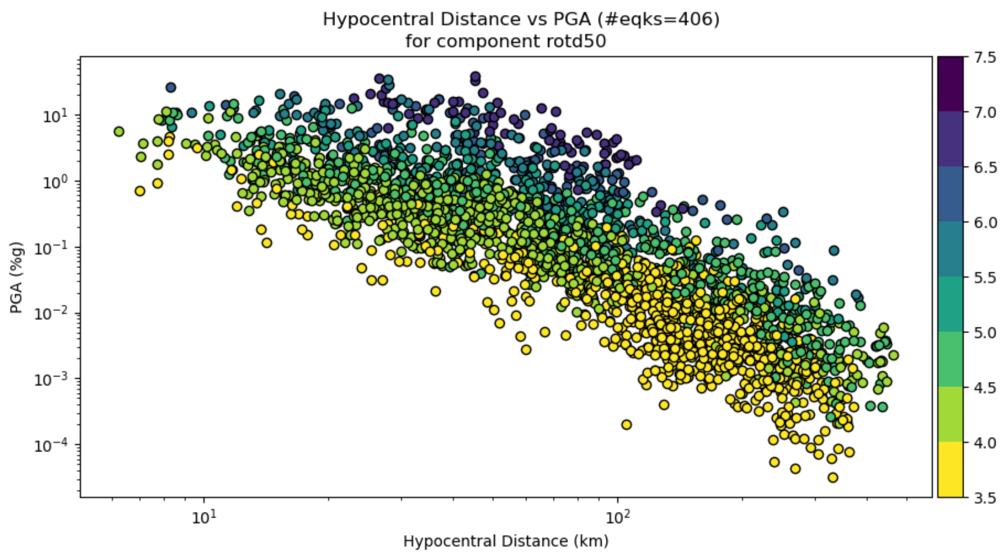


Figure 6. PGA values used in the regression analysis

The final database includes 406 earthquakes and 2810 recordings. Figure 6 shows the distribution of PGA observations for all events used in the regression. The distribution of recordings reached values close to 500 km (see Figure 7)

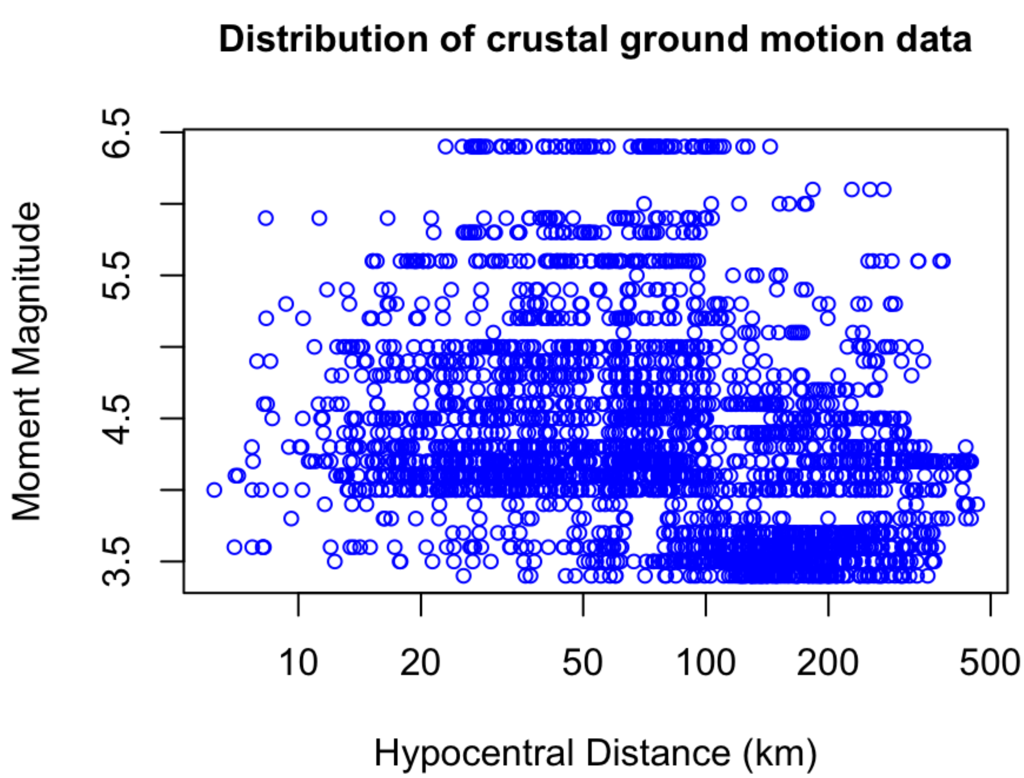


Figure 7. Distribution of database in moment magnitude and hypocentral distance

Figure 8 summarizes the results obtained for the three proposed regression methodologies. To plot the models as a function of distance, the magnitude was fixed at 4.0 and the soil conditions were fixed to hard soil. Blue dots show observed PGA values for 4.0 magnitude earthquakes in hard soil

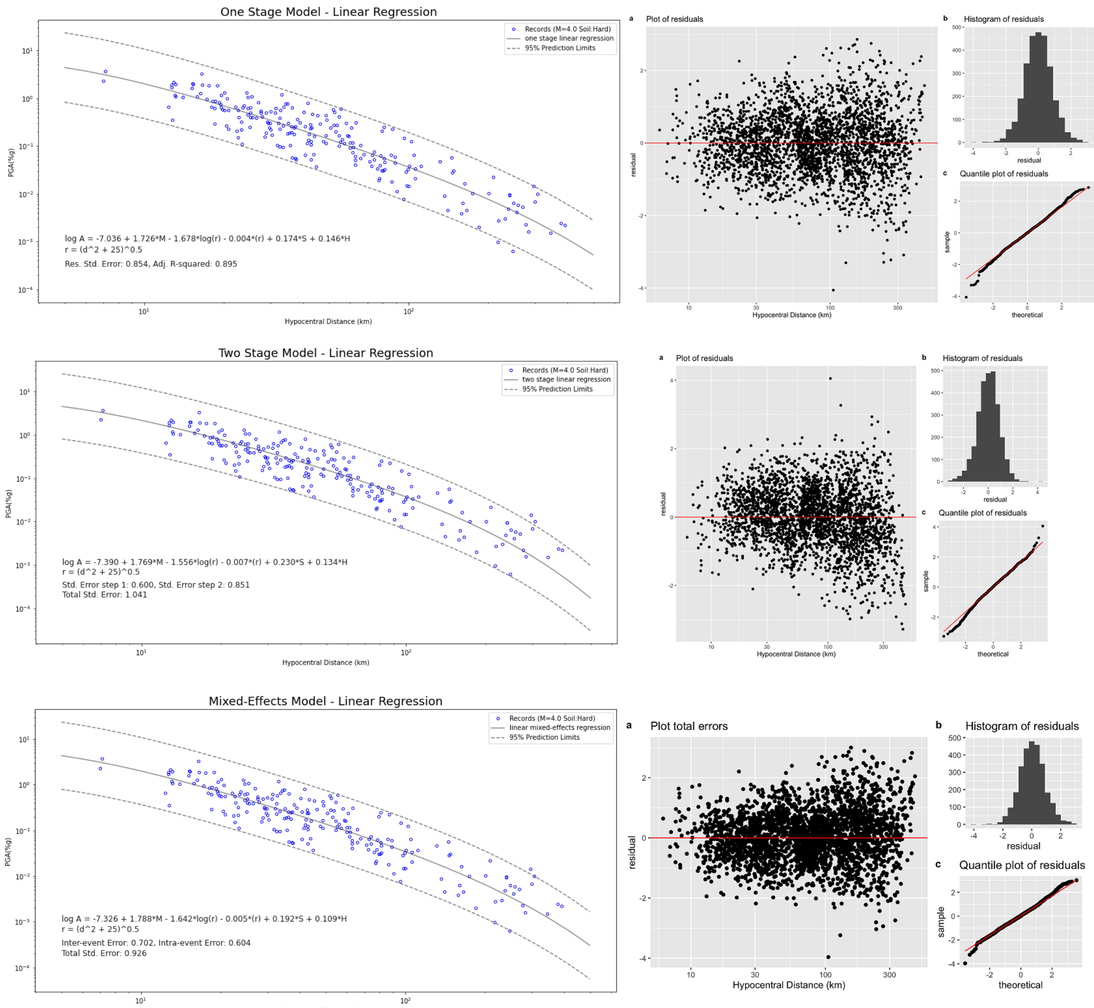


Figure 8. Comparison of PGA observations for events of M = 4.0 and hard soil with three regression methods and their respective residuals

To select the best fit model, the residual distribution shown in Figure 8 and the results of the regression coefficients were considered (see Figure 9)

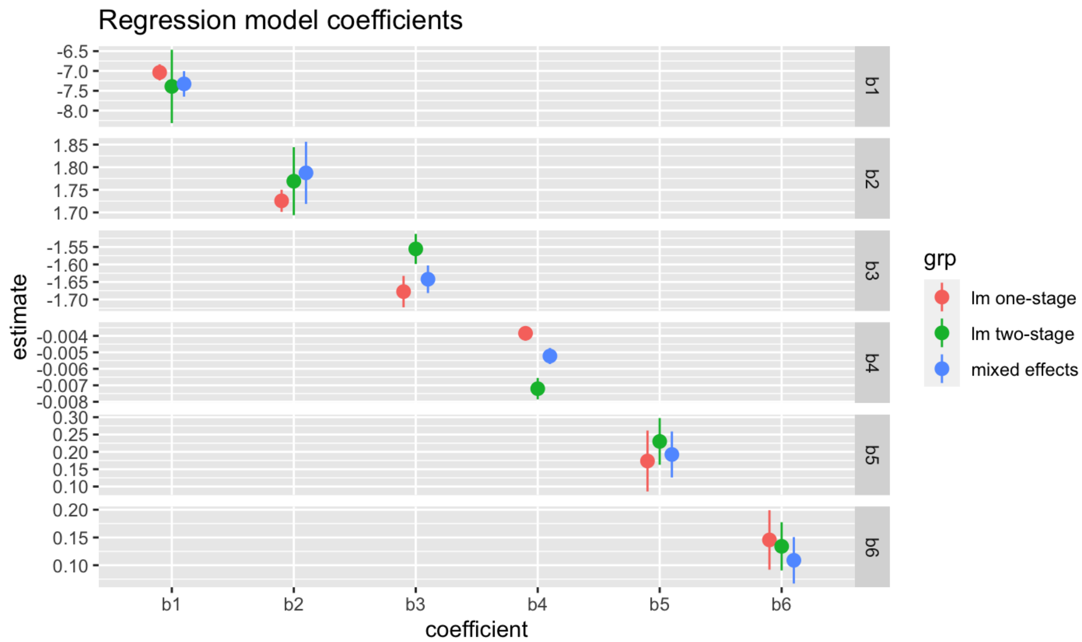


Figure 9. Regression coefficients with their respective standard deviations for the three methods

Figure 10 shows the three regression models compared with the PGA values observed for events with magnitude 4.0 in hard soil.

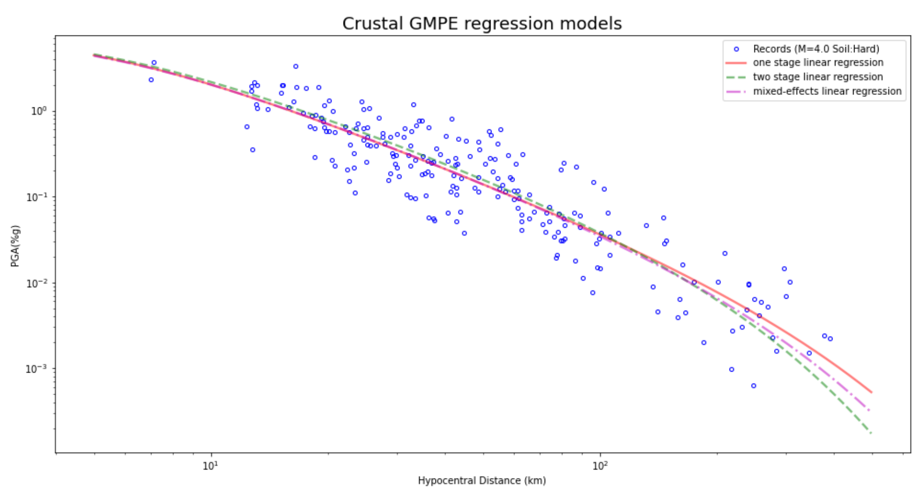


Figure 10. Comparison between the three regression methods

Finally, a comparison is made of the best fit model (one stage - OLS regression) with three crustal models, MA05 - Motazedian & Atkinson (2005), which corresponds to the first regional model developed for Puerto Rico derived from a stochastic method, AB10 - Akkar & Bommer (2010) correspond a crustal model developed for the areas of Europe, the Mediterranean region, and the Middle East and ZEA06 - Zhao et al. (2006) which corresponds to the Japanese model. These last two used in the development of the global seismic hazard map for active crustal regions by the GEM Foundation (https://www.globalquakemodel.org/) (see Figure 11)

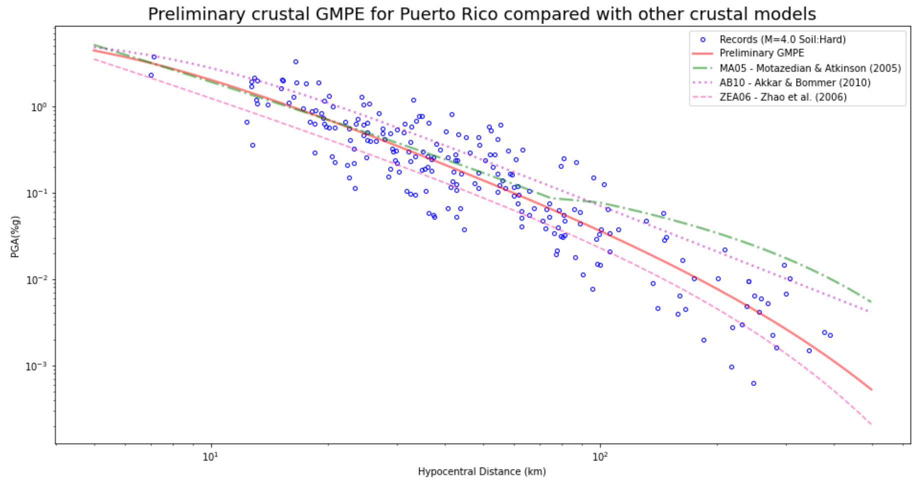
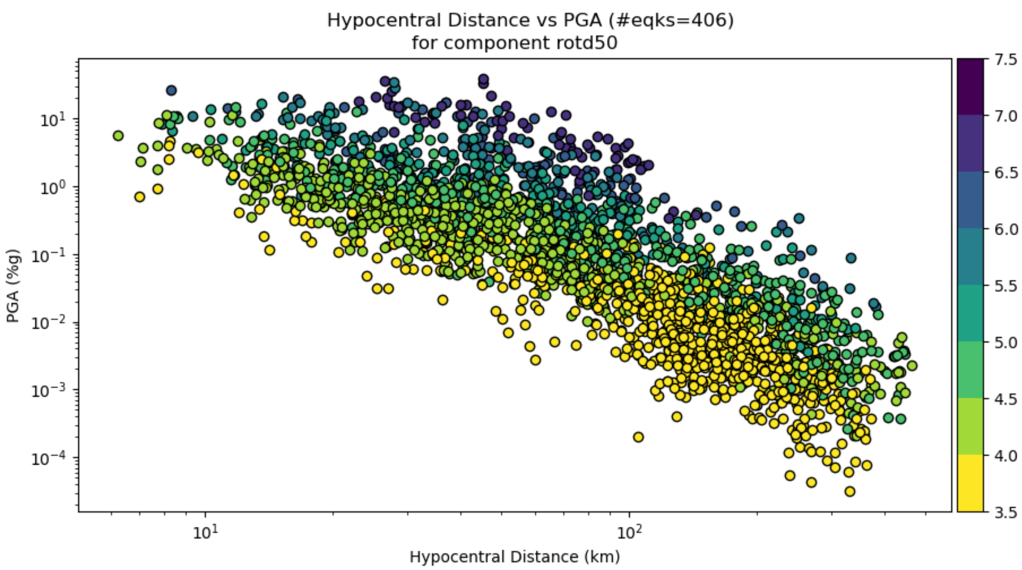
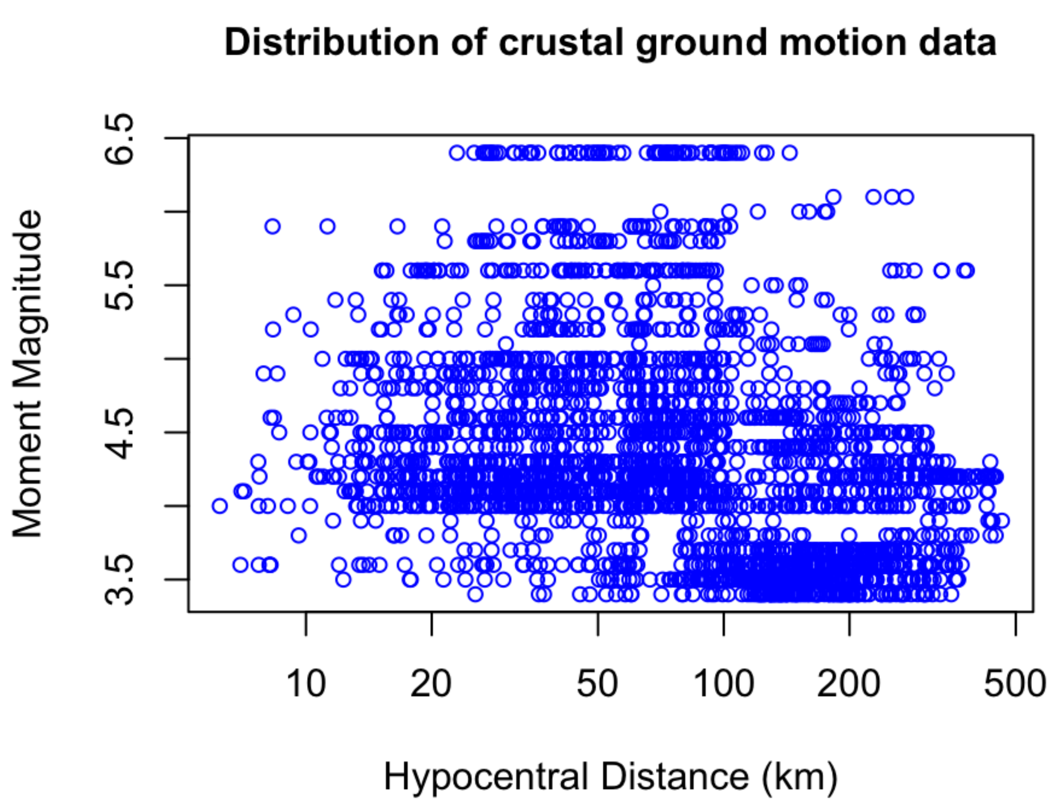


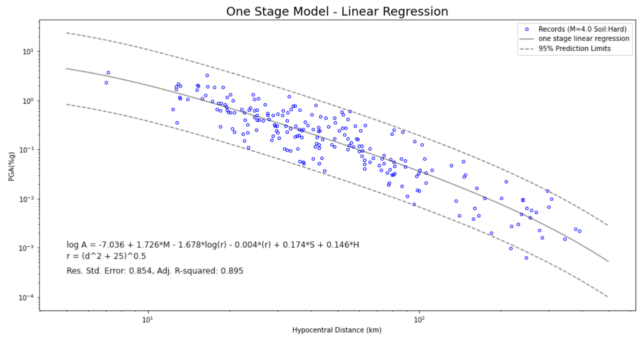
Figure 11. Comparison between best fit (one stage - linear regression) with others crustal models

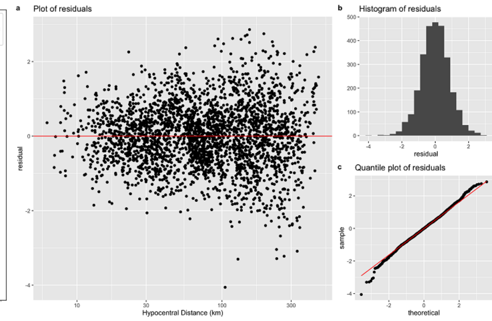
CONCLUSIONS & FUTURE WORK

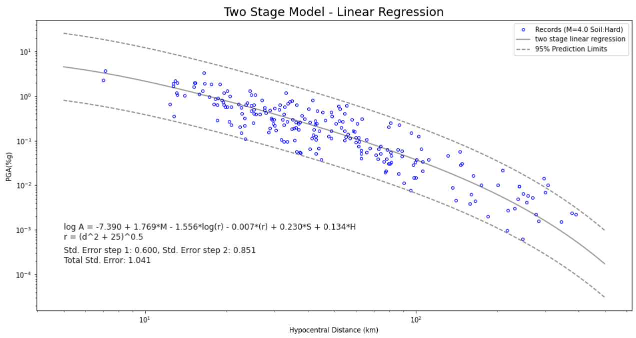
- The three regression methods show very similar results, however, the linear regression in one stage showed the best fit (coefficient correlation R^2=0.90) and more normal residual distribution for the data used.
- The coefficients of the preliminary model are: b1 = -7.036, b2 = 1.726, b3 = -1.678, b4 = -0.004, b5 = 0.174, b6 = 0.146 with fixed value h = 5.0.
- The distribution of the data seems well distributed as a function of distance, however, some of the residuals for distances greater than 100 km are those that show the greatest difference.
- Based on previous soil classification surveys for Puerto Rico (Odum et al. 2007) and HVSR relationships, more accurate soil classifications will be incorporated into the regression model.
- Using the same methodology proposed in the crustal GMPE, a model will be developed that incorporates the non-crustal seismicity of Puerto Rico (earthquakes with depth greater than 25 km).

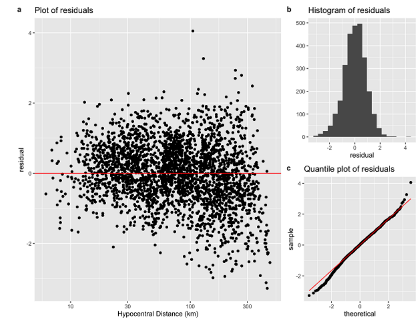


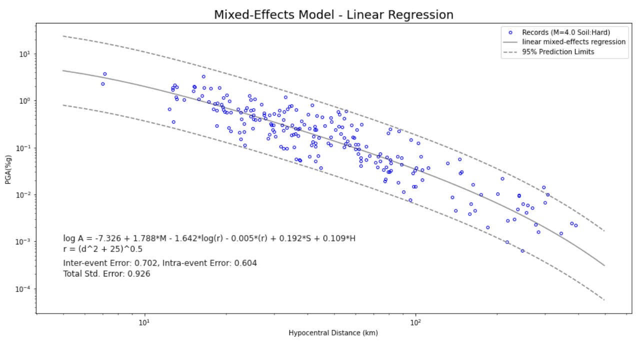


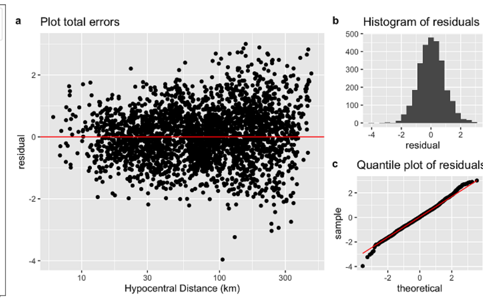

One Stage Model - Linear Regression
Records (M=4.0 Soil:Hard)
one stage linear regression
95% Prediction Limits
log A = -7.036 + 1.726*M - 1.678*log(r) - 0.004*(r) + 0.174*S + 0.146*H
r = (d^2 + 25)^0.5
Res. Std. Error: 0.854, Adj. R-squared: 0.895
PGA(%g)
Hypocentral Distance (km)

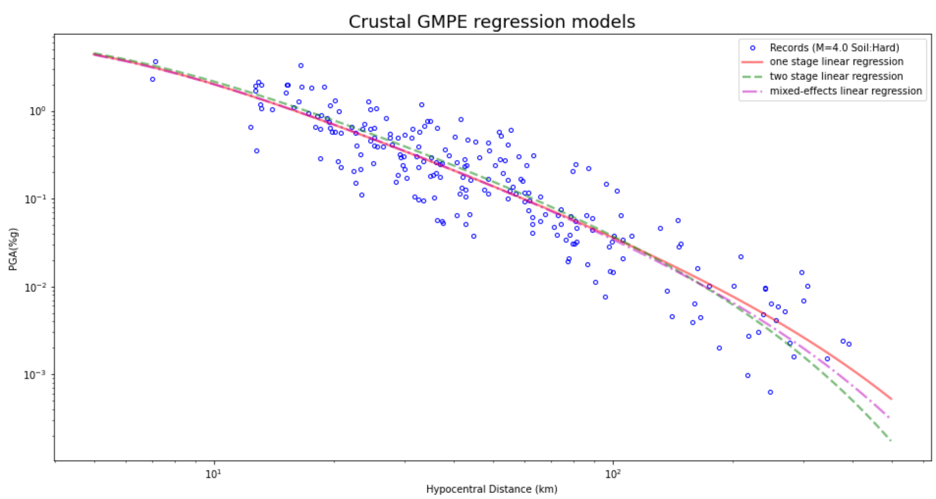

a Plot of residuals
b Histogram of residuals
c Quantile plot of residuals
residual
sample
theoretical
Hypocentral Distance (km)

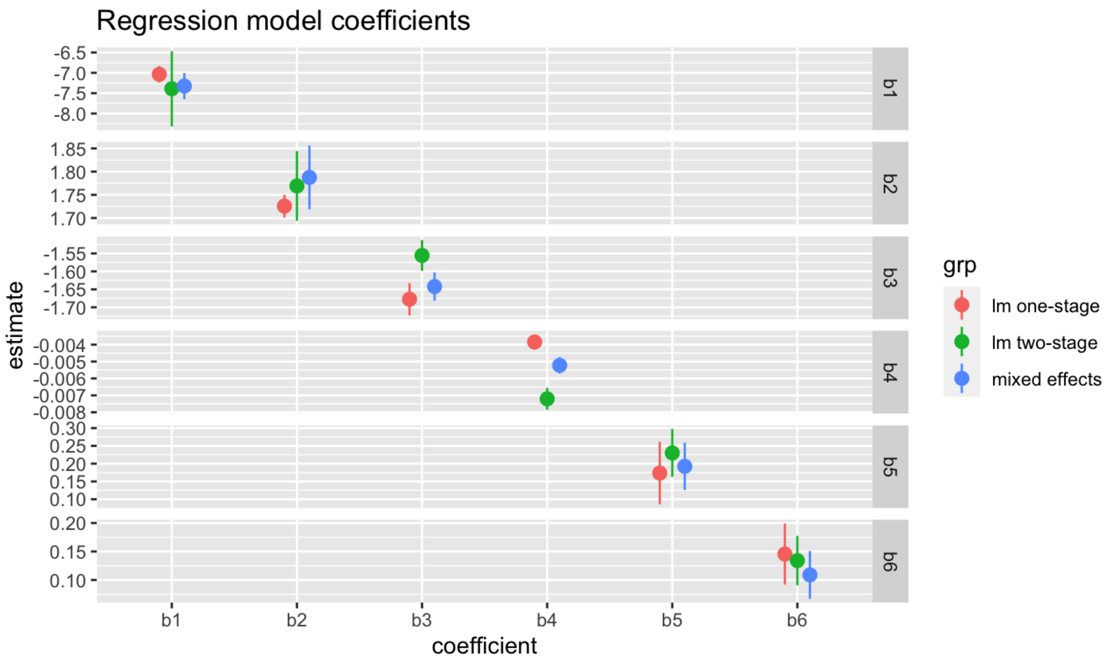

Two Stage Model - Linear Regression
Records (M=4.0 Soil:Hard)
two stage linear regression
95% Prediction Limits
log A = -7.390 + 1.769*M - 1.556*log(r) - 0.007*(r) + 0.230*S + 0.134*H
r = (d^2 + 25)^0.5
Std. Error step 1: 0.600, Std. Error step 2: 0.851
Total Std. Error: 1.041
PGA(%g)
Hypocentral Distance (km)

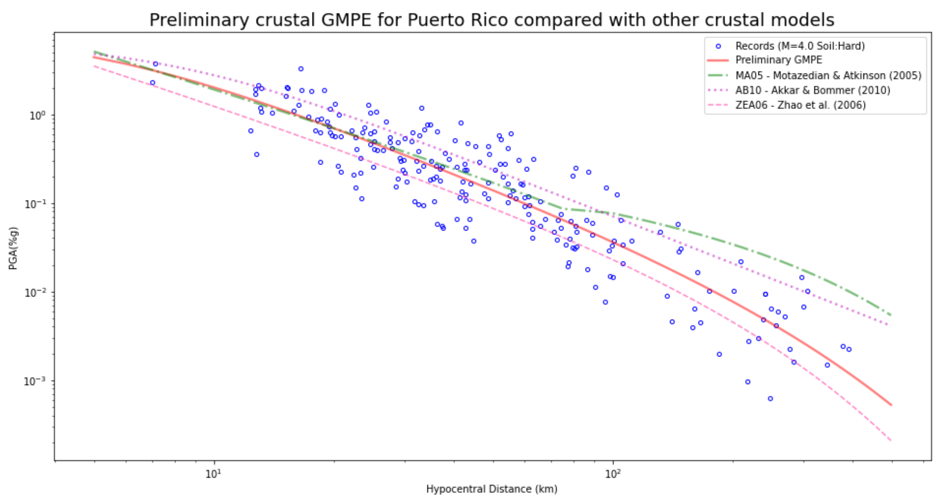

a Plot of residuals
b Histogram of residuals
c Quantile plot of residuals
residual
sample
theoretical
Hypocentral Distance (km)


Mixed-Effects Model - Linear Regression
Records (M=4.0 Soil:Hard)
linear mixed-effects regression
95% Prediction Limits
log A = -7.326 + 1.788*M - 1.642*log(r) - 0.005*(r) + 0.192*S + 0.109*H
r = (d^2 + 25)^0.5
Inter-event Error: 0.702, Intra-event Error: 0.604
Total Std. Error: 0.926
PGA(%g)
Hypocentral Distance (km)


a Plot total errors
b Histogram of residuals
c Quantile plot of residuals
residual
sample
theoretical
Hypocentral Distance (km)


Crustal GMPE regression models
Records (M=4.0 Soil:Hard)
one stage linear regression
two stage linear regression
mixed-effects linear regression
PGA(%g)
Hypocentral Distance (km)


Regression model coefficients
estimate
coefficient
b1
b2
b3
b4
b5
b6
grp
lm one-stage
lm two-stage
mixed effects


Preliminary crustal GMPE for Puerto Rico compared with other crustal models
Records (M=4.0 Soil:Hard)
Preliminary GMPE
MA05 - Motazedian & Atkinson (2005)
AB10 - Akkar & Bommer (2010)
ZEA06 - Zhao et al. (2006)
PGA(%g)
Hypocentral Distance (km)

ABSTRACT

According to the 2020 FEMA Fact Sheet (FEMA, 2020), Puerto Rico and Virgin Islands are located in a high risk region for earthquake damage. In the last year *(05-jul-2019 to 05-jul 2020)* the Puerto Rico Seismic Network (PRSN) recorded 136 earthquakes with magnitudes greater than 4.0 and two events had magnitudes greater than or equal to 6.0. The last update of the seismic hazard maps for Puerto Rico and the US Virgin Islands was performed in 2003. According to Mueller et al. (2010), the Bunce fault, the Muertos Trough and related fault structures were not included in the hazard map. The Great Southern Puerto Rico fault, was considered largely quiescent, but Piety et al. (2008) through paleoseismic studies, evidenced activity in this one. Otherwise, offshore faults in southern Puerto Rico were not considered, because their rates of activity were poorly known and assumed to be most likely small. However, starting in December 2019 the Southwestern Puerto Rico (SWPR) Seismic Sequence has been active and continues to be active in these southern offshore faults. According to the StEER technical report (Miranda et al., 2020), the events that occurred between December 2019 and January 2020 caused damage to approximately 10,000 structures and more than 8,000 people were displaced.

Based on these facts, and considering that previously unknown tectonic fault structures have been revealed by the SWPR Seismic Sequence (Lopez et al., 2020b), a reevaluation of the seismic threat to Puerto Rico is required. This should include the seismic activity that, according to the PRSN catalog, consists of more than 50,000 events since 2002 to date. This new seismic hazard evaluation will include multiple earthquakes with magnitudes greater than M 5 which were not part of the catalog in 2001.

The purpose of this study is generating a new Ground Motion Prediction Equation (GMPE) that incorporates the current seismicity for the region, which unlike the local model used in Mueller et al. (2010) the data will be used directly to obtain the ground motion relationships (Motazedian et al., 2005). This new data now permits to obtain a GMPE from a regression analysis. In the first stage of the research, the aim is generating a preliminary GMPE based on crustal seismicity (events less than 25 km deep) which represents more than 60% of the total registered earthquakes in the PRSN catalog.

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