

**EFFECTS OF NONLINEAR SOIL BEHAVIOR AND
REGIONALIZATION ON HETEROSCEDASTIC
VARIANCE OF GROUND MOTION AMPLITUDES**

**DOĞRUSAL OLMAYAN ZEMİN DAVRANIŞI VE
BÖLGESELLEŞMENİN YER HAREKETİ GENLİKLERİNİN
HETEROSKEDASTİK VARYANSI ÜZERİNDEKİ
ETKİLERİ**

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ABSTRACT

EFFECTS OF NONLINEAR SOIL BEHAVIOR AND REGIONALIZATION ON HETEROSCEDASTIC VARIANCE OF GROUND MOTION AMPLITUDES

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Ground-motion models are developed using global dataset and the main assumption when deriving a ground motion prediction equation (GMPE) is ergodic assumption. In stochastic sense ergodicity defined as the point in the time is uniform over the entire process which means a sample from a process represents the mean behavior of entire process. With the increasing ground motion data, using thousands of records increases aleatory variability (σ) and that forces the recent works focus on non-ergodic GMPEs. Using a global dataset, a series of ground-motion predictive models for acceleration response spectra is proposed. The proposed models include regional adjustments to source, path and site terms with nonlinear soil behavior. The regression coefficients are computed with linear and nonlinear mixed-effect regression algorithms. Furthermore, heteroscedastic variability models for between-event, site-to-site and single-site standard deviations are developed. The between-event sigma model depends solely on magnitude, but the single-site standard deviation model depends on both magnitude and distance. Finally, the site-to-site standard deviation model is given in terms of V_{S30} and spectral acceleration at rock site condition.

Keywords: Ground-motion predictive model, spectral accelerations, heteroscedastic variability, nonlinear site amplification, regional corrections.



ÖZET

DOĞRUSAL OLMAYAN ZEMİN DAVRANIŞI VE BÖLGESELLEŞMENİN YER HAREKETİ GENLİKLERİNİN HETEROSKEDASTİK VARYANSI ÜZERİNDEKİ ETKİLERİ

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Yer hareketi modelleri, küresel veri seti kullanılarak geliştirilirler ve bir yer hareketi tahmin modeli (YHTM) türetilirken ana varsayım, ergodik varsayımdır. Stokastik anlamda, zamandaki nokta olarak tanımlanan ergodiklik, tüm süreç boyunca tekdüzedir. Bu, bir süreçten alınan bir örneğin, tüm sürecin ortalama davranışını temsil ettiği anlamına gelir. Artan yer hareketi verileriyle, binlerce kaydın kullanılması tesadüfi değişkenliği (σ) artırmakta ve bu da son çalışmalarını ergodik olmayan YHTM'lere odaklamaya zorlamaktadır. Bu çalışmada, küresel bir veri seti kullanarak, ivme tepkisi spektrumları için bir dizi yer hareketi tahmin modeli önerilmiştir. Önerilen modeller, doğrusal olmayan zemin davranışı ile kaynak, yol ve saha terimlerine yönelik bölgesel ayarlamalarını içerir. Regresyon katsayıları, doğrusal ve doğrusal olmayan rassal etkili regresyon algoritmalarıyla hesaplanır. Ayrıca, olaylar arası, sahadan sahaya ve tek saha standart sapmaları için heteroskedastik değişkenlik modelleri geliştirilmiştir. Olaylar arası sigma modeli yalnızca deprem büyüklüğüne bağlıdır, ancak tek saha standart sapma modeli

hem büyüklüğe hem de mesafeye bağlıdır. Son olarak, kaya sahası koşullarında V_{S30} ve spektral ivme cinsinden sahadan sahaya standart sapma modeli verilmiştir.

Anahtar Kelimeler: Yer hareketi tahmin modeli, spektral ivmeler, heteroskedastik varyans, doğrusal olmayan zemin büyütmesi, bölgesel düzeltmeler.



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SYMBOLS AND ABBREVIATIONS

Symbols

f_D	Depth function
f_{HYP}	Hypocentral depth model
f_{In}	Linear site effects function
f_M	Magnitude scaling function
f_{nl}	Nonlinear site effects function
f_N	Dummy variable for the normal style-of-faulting
f_R	Dummy variable for the reverse style-of-faulting
$f_{R,AA}$	Anelastic attenuation function
$f_{R,GS}$	Geometrical spreading function
f_s	Site amplification function
$f_{Z1.0}$	Deep soil effect function
h	Pseudo-depth term
h_{800}	Depth to shear wave velocity reaches 800m/s
M	Moment magnitude
PGA_r	Maximum ground acceleration value for reference rock that calculated for $V_{S30} = 760$ m/s
R_{JB}	Joyner-Boore distance
R_{RUP}	Rupture distance
T	Period
V_C	Period dependent limiting velocity
V_{S30}	Average shear wave velocity of upper 30m layer of soil
V_{Smax}	Maximum shear wave velocity

V_{Smin}	Minimum shear wave velocity
V_{ref}	Period dependent reference rock shear wave velocity
Z_{HYP}	Hypocentral depth
Z_{TOR}	Depth of upper edge of the fault rupture
$Z_{1.0}$	Depth to shear wave velocity reaches 1 km/s
δB_e	Between-event residual
δW_{es}	Within-event residual
δS_{2s}	Site to site residual
$\delta W S_{es}$	Single-site within-event residual
σ	Total standard deviation
τ	Between-event standard deviation
ϕ	Within-event standard deviation
ϕ_{ss}	Single-site within-event standard deviation
ϕ_{S2S}	Site-to-site standard deviation

Abbreviations

GMPM	Ground Motion Predictive Model
NGA	Next Generation Attenuation Project
NGA-West2	Next Generation Attenuation Project West 2 Database
PGA	Peak Ground Acceleration
PSA	Pseudo-Spectral Acceleration

1. INTRODUCTION

This section has separated into subtopics. Those subtopics are about ground motion predictive model developments from ergodic to partially non-ergodic models and the introduction of ergodic and partially non-ergodic models. Also development of regional models are given in this section.

1.1. Ground Motion Predictive Models

The ground-motion predictive models (GMPMs) are used to indicate expected shaking levels using predictive factors such as earthquake magnitude, distance and shear wave velocity in seismic hazard analysis. Ground motion amplitudes are often estimated using GMPMs. These models typically provide ground-motion intensity measures (GMIMs). They are mostly generated by empirical model for active crustal regions. Empirical regression models are commonly used to develop GMPMs for active crustal regions, where the models are based on statistical relationships between measured ground motion amplitudes and a set of predictive factors that are easily obtainable. The degree of development and refinement of GMPEs has evolved with the progress of ground-motion databases and associated technologies have advanced. While first GMPMs represent ground-motion with very simple equations (e.g., Douglas, 2003), with the development of advanced predictive models, GMPMs are defined by the combination of event, distance, and site terms (e.g., Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Choi and Youngs, 2008; Akkar et al., 2010). The ground-motion records used by GMPMs developers were compiled from similar tectonic settings, assuming that differences between countries and regions are negligible. They represent the same mean value for each combination of sources and locations and do not include regional or site-specific details. For example, early GMPMs by Abrahamson and Silva (2008) or Akkar et al. (2010) were derived using compiled dataset with similar tectonic regimes and recorded at different sites and these GMPMs did not reflect the regional differences. Scasserra et al. (2009) investigated the Next Generation Attenuation (NGA) models and recorded ground

motions in Italy. The study found that incorporating regional adjustments to the attenuation with distance terms improved the accuracy of the models. Since then, the NGA West-2 project (Bozorgnia et al., 2014), as well as the NGA-East (Goulet et al., 2021) and NGA-Sub (Bozorgnia et al., 2021), have collected large regional datasets of ground motion records (with one dominant region in each dataset). The NGA-East and NGA-Sub projects were specifically focused on stable continental and subduction regions, respectively. The increase in amount of strong-motion data allows model developers to include the regional corrections in the GMIMs. Mostly, they include regional corrections with additional regression parameters such as region-specific anelastic attenuation, linear site amplification terms (e.g., Boore et al. 2014).

With the compilation of RESORCE database (Akkar et al., 2014), Kotha et al. (2017) and Kuehn and Scherbaum (2016) achieved a reduction in aleatory variability (σ) by considering regional adjustment. Kotha et al. (2020) expanded their research by using a broader database found and aleatory variability increased when compared to their previous model. Other studies, such as Stafford (2014), Landwehr et al. (2016), and Marek et al. (2013), have primarily focused on single-site variability and have attempted to explain regional differences using distance attenuation.

The effect of soil amplification behavior on ground motion variability is one of the research topics that have gained importance in recent years for research areas like geotechnical earthquake engineering or engineering seismology. Despite the increasing number of acceleration time series of strong ground motions (observed earthquake records), ground motions and variability cannot be fully described. Many studies only account linear site amplification and did not consider the nonlinear site behavior in their functional form (e.g., Stafford, 2014; Landwehr et al., 2016; Marek et al., 2016; Kuehn et al., 2016). Since the work of Abrahamson and Silva (1997), this effect has also been used in GMPMs. For this purpose, many soil amplification models have been built (Abrahamson and Silva, 1997; Walling et al., 2008; Sandıkkaya et al., 2013; Kamai et al., 2014; Seyhan and Stewart, 2014; Sandıkkaya and Dinsever, 2018) and these models have

been used to model ground effects in GMPMs (Abrahamson et al., 2014; Akkar et al., 2014; Boore et al., 2014; Campbell and Bozorgnia, 2014;).

In addition, GMPMs are derived from local, or regional or global data compiled from different tectonic regimes and recorded at different sites assuming the ergodicity (Anderson and Brune, 1999). Developing GMPMs with different coefficients for different regions is the first step in removing the ergodic assumption (Stafford, 2014). In recent years, researchers and practitioners have been able to partially eliminate the ergodicity by utilizing well-recorded ground motions at individual sites from numerous earthquake events. They achieved this by calculating repeated site effects and subtracting these effects from the variability of ground-motion. GMPMs with standard deviations of individual stations have been developed for use in large projects.

The existence of multiple records at a site in modern ground-motion datasets let to the calculation of site-to-site variability. And it leads to decrease in aleatory variability. Al Atik et al. (2010) defined total residuals as the difference between the logarithm of the recorded ground-motions and the predicted GMIMs from GMPMs which can be partitioned into between-event (δB_e) and within-event (δW_{es}) residuals.

$$\Delta = \delta B_e + \delta W_{es} \quad (1.1)$$

The subscript e represents the event, the subscript s represents the site and the standard deviations for the between-event (τ) and within event (ϕ) residuals can be computed. In that case σ which represents total ergodic standard deviation is given below:

$$\sigma = \sqrt{\tau^2 + \phi^2} \quad (1.2)$$

The standard deviation of within-event can be divided into two components and the former represents the deviation of the observed ground-motion at a given site (s) from the median event-corrected ground-motion prediction, while the latter represents the site- and event-corrected residual. The standard deviations of the residuals that describe the variability from one earthquake to another and from one record to another are referred to as ϕ_{s2s} and ϕ_{ss} , respectively. The complete ergodic standard deviation is given below:

$$\sigma = \sqrt{\tau^2 + \phi_{ss}^2 + \phi_{s2s}^2} \quad (1.3)$$

Where σ_{ss} represents single-site standard (Marek et al., 2011) deviation and written as follows:

$$\sigma_{ss} = \sqrt{\tau^2 + \phi_{ss}^2} \quad (1.3)$$

In this study, region-specific GMPMs are developed by modifying the model coefficients with regional adjustments through regression analyses with an extended dataset that is composed of the major shallow active crustal regions. We extend previous studies (e.g., Stafford, 2014; Kotha et al. 2016, 2020; Kuehn and Scherbaum, 2016; Lanzano et al., 2019) to assess how additional regional parameters affect the accuracy of GMPMs, with a special emphasize on nonlinear soil behaviour. To this end, we first merge the available strong-motion datasets to obtain a wide range of data to focus on regionalization. Then, the three-stage regression is conducted to estimate the model parameters: (i) the coefficients of the global model are computed, (ii) the regionalization is performed, and (iii) the heteroscedastic variance components are computed. Finally, the proposed GMPMs is compared with the mostly used models.

This study composed of six chapters. In Chapter 1 gave the development of GMPMs, its developments and literature review. Chapter 2 describes the compiled dataset and gave the statistics about the dataset which used in this study. It also describes the regions which are used in regional model.

Chapter 3 introduces the GMPMs and standard deviation models which are developed in this study. It also introduces the model coefficients and the parameters which are constrained.

Chapter 4 introduces the regression analyses that are performed in this study. It starts with global model, describes the computation of the model coefficients and gives the information about limitation of the models. Then it describes the regional model and computation of the regional corrections. It also includes the statistical testing that is performed to decide whether using different regional coefficients are needed or not. At the end of this Chapter removal of homoscedastic assumption and developed heteroscedastic variance model is introduced.

Chapter 5 compares the proposed model with the recently developed and known GMPMs which are derived using global or local datasets and tests the performance of the developed model.

The dissertation's conclusion is presented in the last Chapter, which includes the summary of the entire study and a proposal for further research. The proposed research topics aim to address the shortcomings of the current procedures and suggest ways to improve future versions of the study. Essentially, this final Chapter serves as a conclusion to the entire dissertation.

2. DATABASE

A compiled dataset is used for this study. NGA-West2 dataset (Ancheta et al., 2014) is used as a primary source of earthquake recordings. To overcome the small number of recordings from local datasets in NGA-West2, we included waveforms from European datasets (Akkar et al., 2014; Luzi et al., 2016) and local databases from Iran, Japan, and Turkey (Kale et al., 2015; Dawood et al., 2016; Alipour et al., 2020). For the metadata information and waveforms, we gave priority to national datasets if global or regional datasets include the event or waveform. The selection criteria for the recordings used in the generation of the proposed GMPMs are listed below:

2.1. NGA-West2 Database (Ancheta 2014)

Following the NGA-West1 project (Power et al., 2008), a set of GMPMs for active crustal regions has been developed. This database is used by many GMPM developers, but there are some problems in the application of the GMPMs. This forced the developers of GMPMs to expand the database with additional data and simulation results. For this purpose, the NGA-West2 project was started to extend the NGA-West1 database, which is mainly used, considering the problems found in GMPM production. They focused on some issues, including the decomposition of single-site standard deviation.

The development of the NGA-West2 uses similar methodology for data compilation and processing as was that of used in NGA-West1 (Chiou et al., 2008). Recent events are included using the same criteria with NGA-West1. Most of the events are within the hypocentral (Z_{hyp}) depth of 20 km. In Figure 2.1. magnitude and distance plot of NGA-West1 and NGA-West2 databases can be seen. It is seen that many small-moderate magnitude events are included to the database which was the one of the problems detected in NGA-West1 project. Number of records in two databases can be seen in Figure 2.2-3.

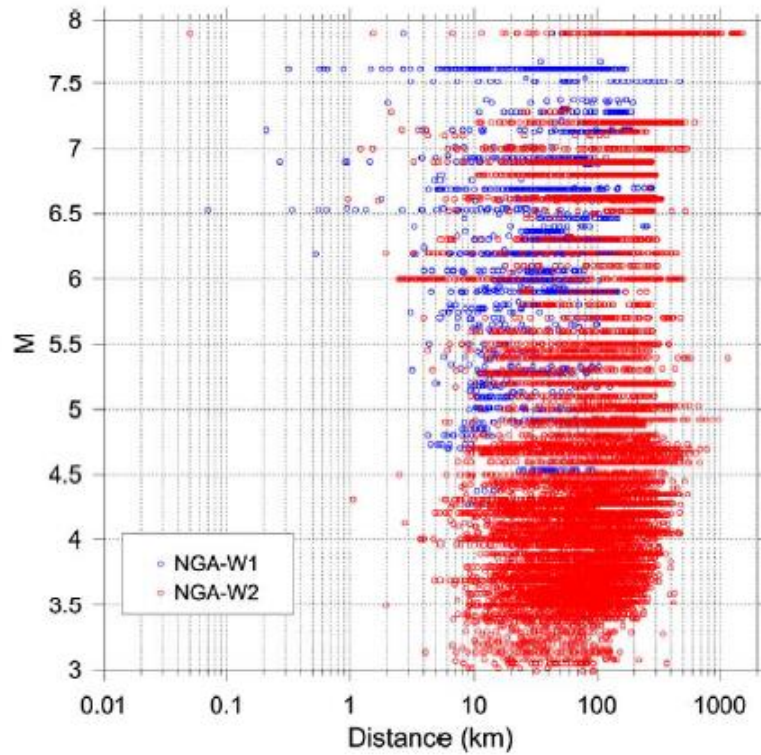


Figure 2.1. R_{rup} - M distribution for recordings of both NGA-West databases (Adapted from Ancheta et al., 2014)

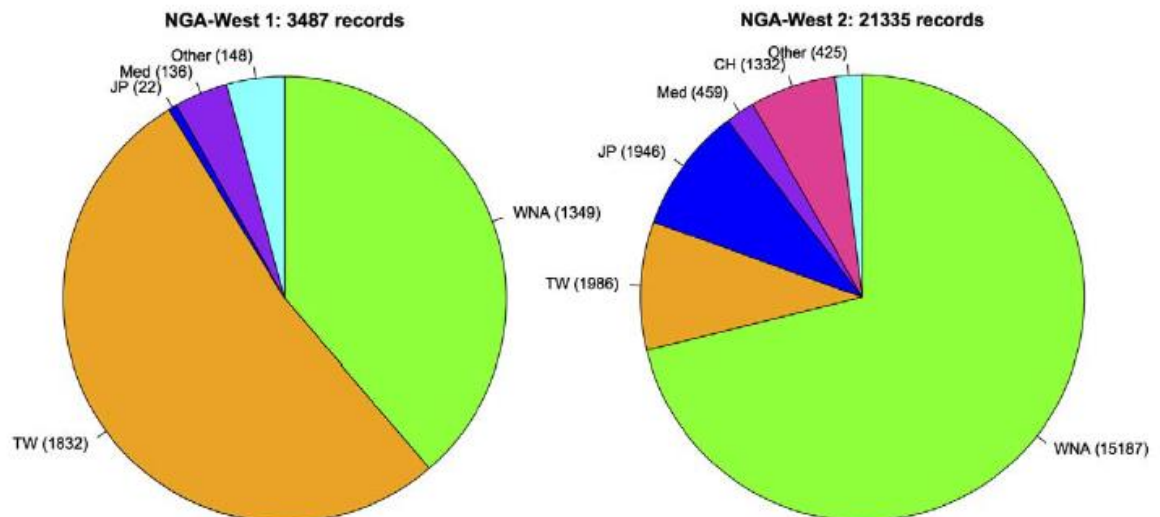


Figure 2.2.

Figure 2.2. Number of records for new and previous NGA databases for compiled regions (Adapted from Ancheta et al., 2014)

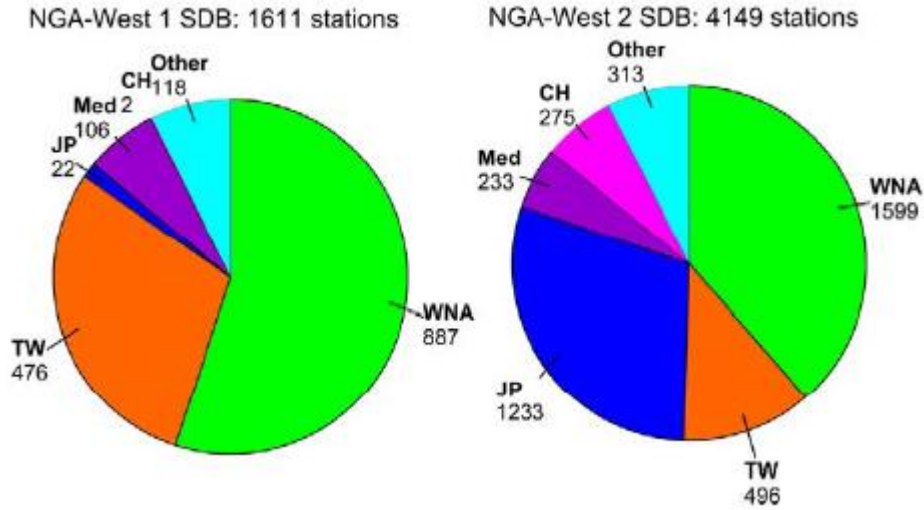


Figure 2.3. Number of stations used in NGA databases (Adapted from Seyhan et al., 2014).

The authors of the study made several criteria for selecting the ground motion recordings from the NGA-West2 database. First, they chose recordings from stations located at ground level or at the lowest level of the structure, including borehole recordings and structural arrays. Second, they only selected recordings with a reasonable signal-to-noise ratio that could be verified through visual inspection. Third, they only selected recordings for which the location of the recording station was known. Finally, when more than one instruments were located on the same base, the authors selected one of them.

Finite fault models are achieved directly from researchers or from publications. If published finite fault models are not available, they developed a simulated finite fault using the location of the hypocenter, magnitude, and focal mechanism (see Ancheta et al., 2013 for details). In this way, the rupture geometry was determined to compute the GMPM parameters. The site dataset includes information regarding station coordinates, as well as parameters like V_{S30} (average shear wave velocity of the uppermost 30 meter) and basin depths ($Z_{1.0}$, $Z_{1.5}$, and $Z_{2.5}$, which define depth in meters for velocities of 1000, 1500, and 2500 m/s). About 49% of the V_{S30} values are obtained from measurements. If the profile depth is less than 30m, they computed V_{S30} values using empirical relationships proposed

by Boore (2004) and Boore et al. (2011) to compute V_{S30} . They applied these relationships for different profile depths applying the procedure proposed in Seyhan et al. (2014). Figure 2.4 shows V_{S30} and number of site distribution of the databases both for NGA-West1 (left) and NGA-West2 (right). Site-to-source parameters are computed instead of collecting from literature. The computed parameters are distance metrics (e.g., epicentral distance, hypocentral distance, Joyner-Boore distance etc.).

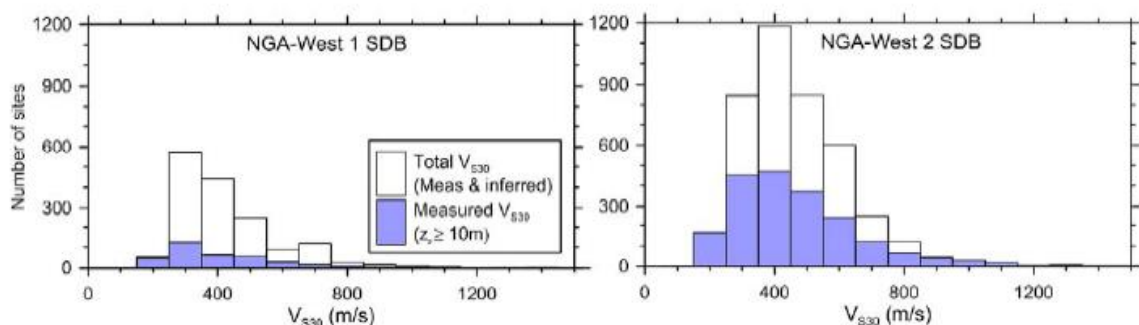


Figure 2.4. Number of sites for the V_{S30} bins for the NGA-West1 (left) and NGA-West2 (right) sites. The color-filled bars show measured V_{S30} profiles (adapted from Seyhan et al., 2014).

2.2. KiK-Net Database (Dawood et al. 2016)

For the development of GMPMs, the Kiban-Kyoshin network (KiK-net) database is a valuable tool because it contains a larger number of strong motion data. It also has borehole measurements which give possibility to detailed site amplification studies. Dawood et al. (2016) used a protocol for automated processing and introduced ground motion database for the use in GMPMs development.

After the Kobe earthquake which occurred in 17 January 1995, Japan established numerous seismic networks to improve earthquake monitoring and response capabilities, including the KiK Net. It consists of 692 stations with two seismographs, one on the surface and one in the borehole. The depths of the

borehole instruments are generally between 100-250 m. The velocity profiles are obtained using the downhole PS-logging method and the profiles are retrieved from the KiK-Net website. The seismographs of F-Net network are also used in this study. The F-Net catalog provides earthquake information and moment tensor solutions. They have used the records between October 1997 and December 2011.

An automated protocol is used because of higher number of recordings consisted in the database (see Dawood et al., 2016 for details). They compared the same records with the NGA-West2 database to verify the automated processing. The observed usable frequency band was narrower compared to the NGA-West2 database. Earthquake source parameters were compiled from the F-Net catalog for both the databases because it is considered to be more reliable than KiK-Net. In addition, the **M** from the F-Net catalog was used rather than the conversion equations between **M** and M_{JMA} from KiK-Net. Figure 2.5. shows magnitude-distance and magnitude-focal depth distributions.

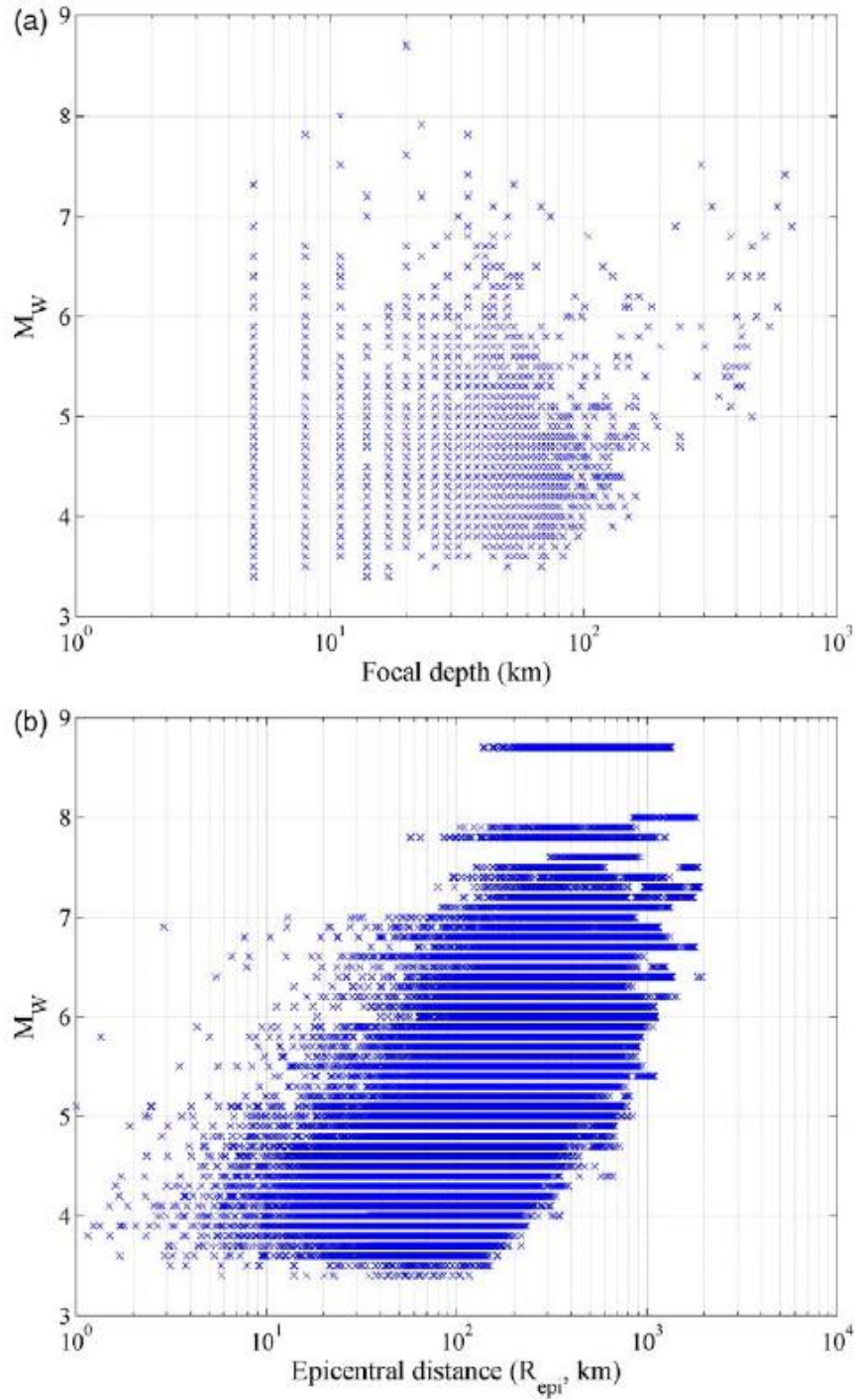


Figure 2.5. Magnitude-depth (a) and Magnitude-distance (b) distribution of the database (adapted from Dawood et al., 2016)

They computed V_{S30} , h_{800} (depth to shear wave velocity reaches 800m/s), etc., to the characterize the soil profiles. Figure 2.6 shows NEHRP site distribution (A: $V_{S30} > 1.500\text{m/s}$, B: $1.500\text{m/s} \geq V_{S30} > 760\text{m/s}$, C: $760\text{m/s} \geq V_{S30} > 360\text{m/s}$, D:

360m/s $\geq V_{S30} \geq 180$ m/s and E: 180m/s $> V_{S30}$) V_{S30} and number of station distributions (right).

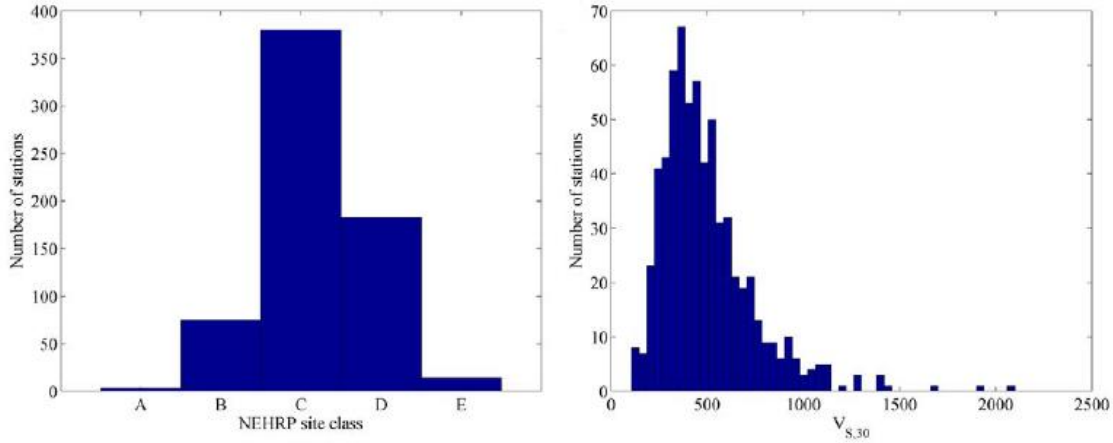


Figure 2.6. NEHRP site class-number of station and V_{S30} -number of station (right) distribution for KiK-Net and F-Net sites (adapted from Dawood et al., 2016).

2.3. RESORCE Database (Akkar et al. 2014)

The database named Reference Database for Seismic Ground Motion in Europe (RESORCE) is aimed to prepare a database compiled from Europe and surrounding areas using recent events from Greece, Italia, Switzerland and Turkey.

The local or national seismic networks are generally preferred as the primary source for earthquake location information due to their higher reliability compared to international seismic agencies. They used different sources to compile the database. Basic structure of the database and sources they used are given in Figure 2.7. The V_{S30} values for the stations are calculated by utilizing the shear wave velocity profiles obtained from various literature studies using site exploration techniques, as shown in Figure 2.8. Distance measures (e.g., R_{hyp} and R_{JB}) are computed using earthquake and station metadata. Akkar et al., 2014 is referred for the detail about the processing and distance metric calculations.

Figure 2.9. shows **M** versus R_{epi} (top left), R_{hyp} (top right), R_{JB} (bottom left) and R_{rup} (bottom right) distributions of the database.

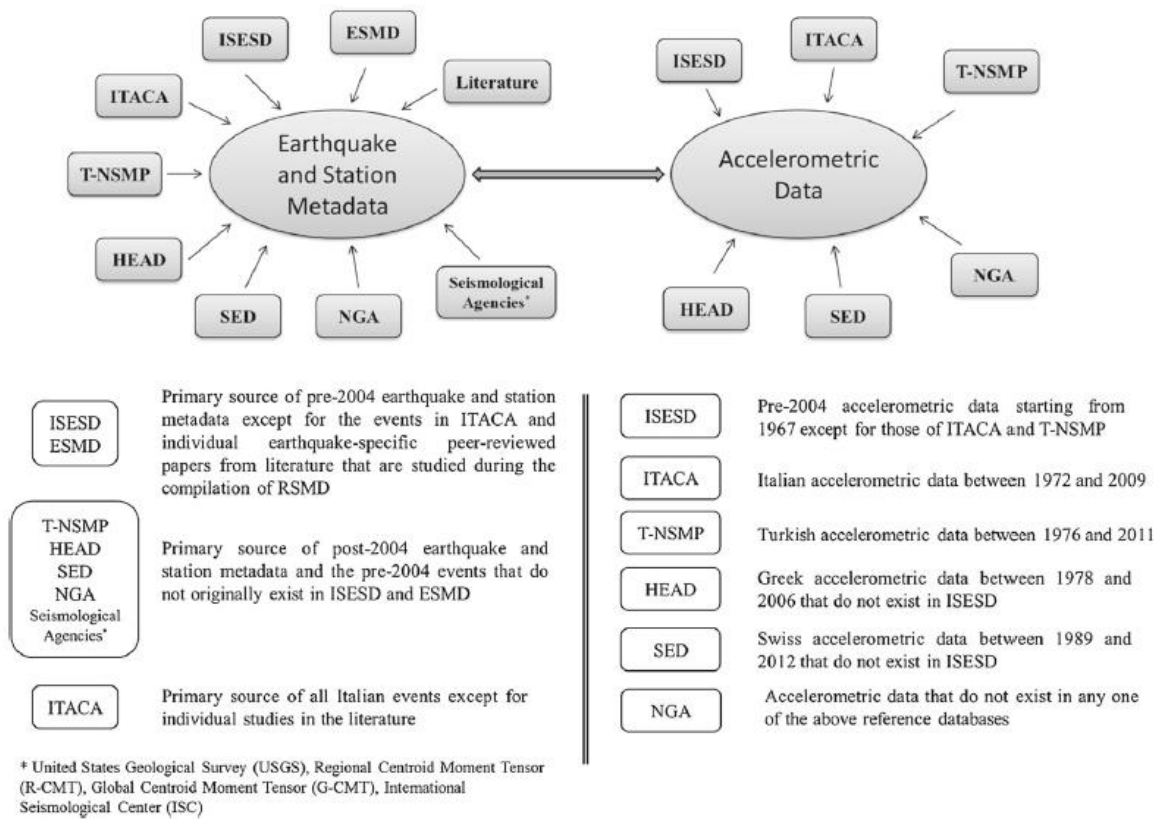


Figure 2.7. Basic components of RESORCE and the sources used to create the metadata and acceleration data (adapted from Akkar et al., 2014)

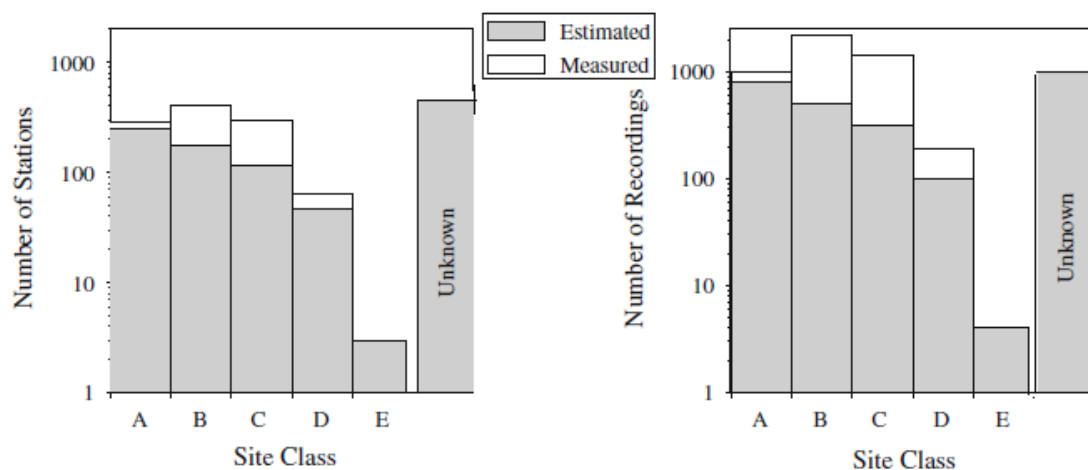


Figure 2.8. Number of strong motion stations (left) and records according to Eurocode 8 boundaries (adapted from Akkar et al., 2014). The vertical bar places on the right with the title "Unknown" shows the

number of accelerograms that cannot be classified (A: $V_{S30} > 800\text{m/s}$, B: $800\text{m/s} \geq V_{S30} > 360\text{m/s}$, C: $360\text{m/s} \geq V_{S30} > 180\text{m/s}$, D: $180\text{m/s} > V_{S30}$ and E: $180\text{m/s} > V_{S30}$).

2.4. Iranian and Turkish Strong-Motion Databases (Kale et al. 2015).

The subsets of EMME database is used for the Turkish and Iranian databases. EMME databank consists of record from Turkey, Iran, Georgia, Armenia, Pakistan and Jordan. They extracted Turkish and Iranian recording from the EMME. Fault geometries are computed using Wells and Coppersmith (1994) when there is no available data in the literature. The strong-motion stations with the measured V_{S30} values are used. Figure 2.10 shows **M**-distance (a) distribution, number of records for **M** (b) and distance bins (c).

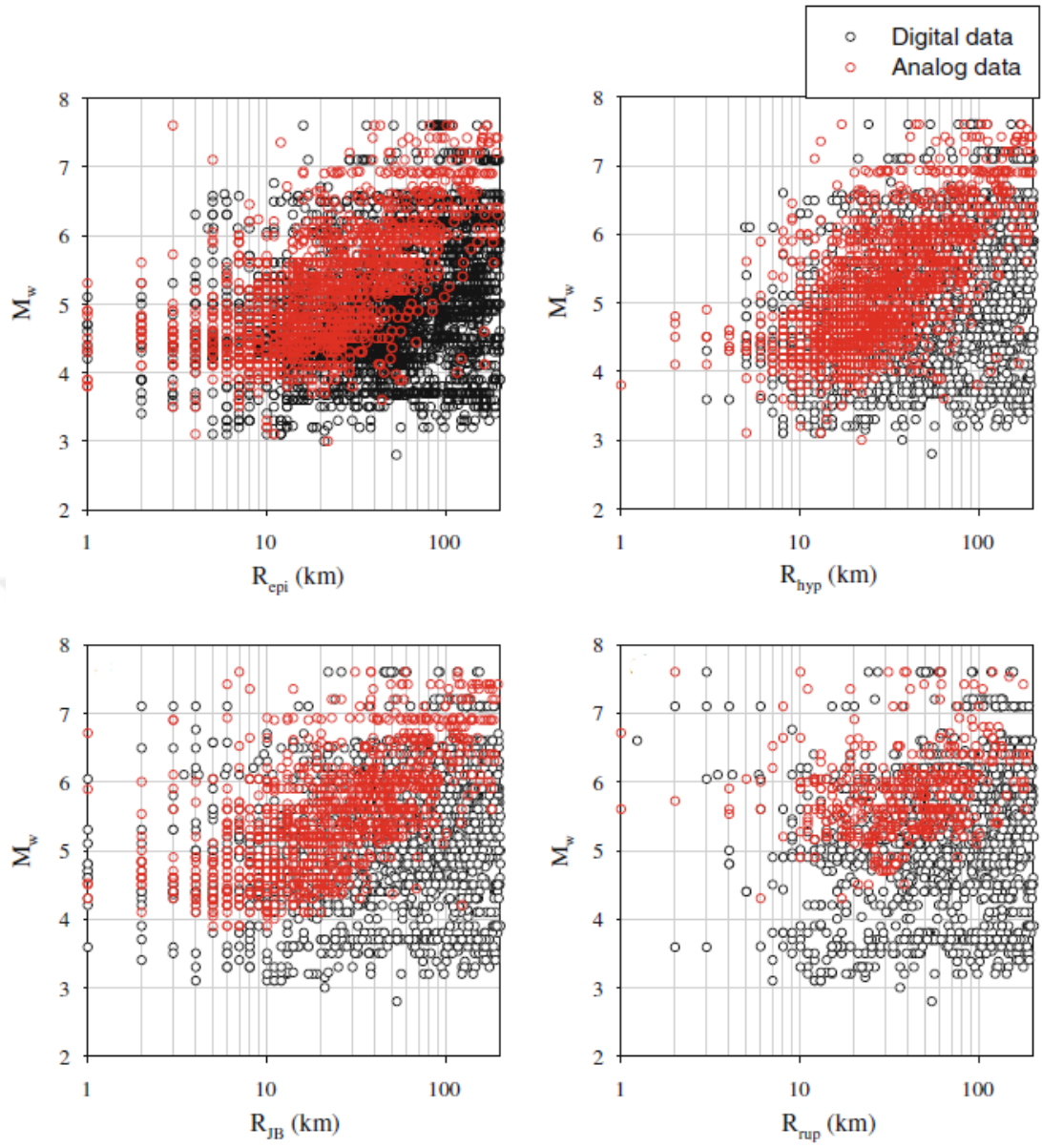


Figure 2.9. M versus R_{epi} (top left), R_{hyp} (top right), R_{JB} (bottom left) and R_{rup} (bottom right) distributions of the database. Circles with red and black colors represents analog and digital records, respectively (adapted from Akkar et al., 2014).

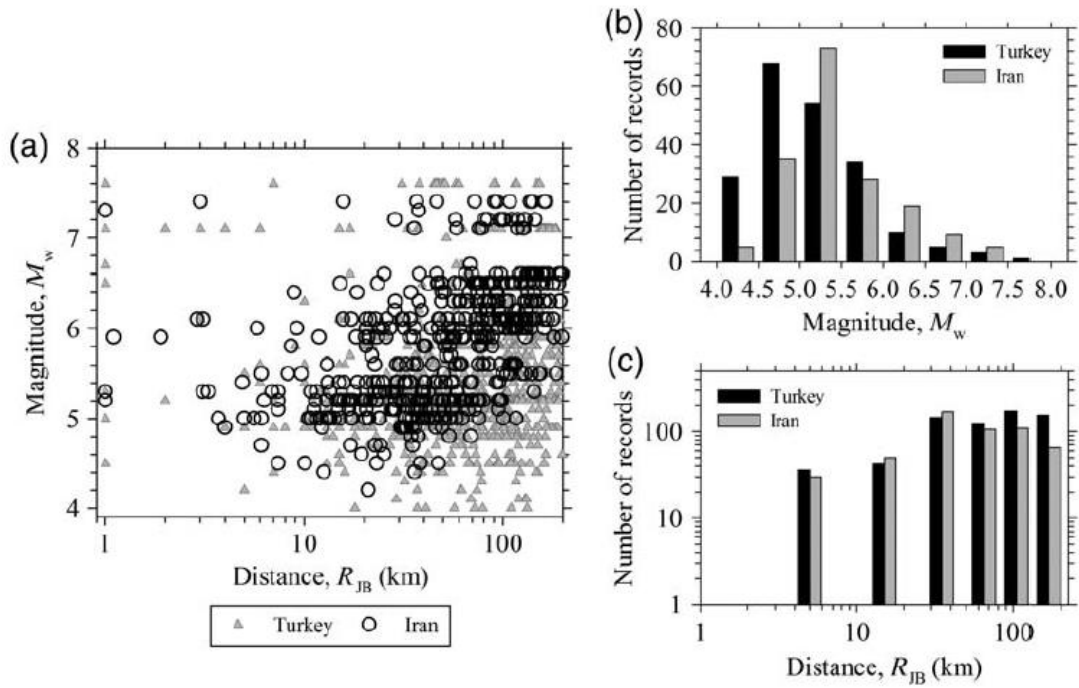


Figure 2.10. Distribution of Turkish and Iranian datasets used in Kale et al. 2015: R_{JB} - M distribution (left), number of records for magnitude (top right) and distance bins (bottom right, adapted from Kale et al., 2015).

2.5. Engineering Strong-Motion Database (Luzi et al. 2016)

Engineering Strong-Motion Database (ESM) is developed to provide uniformly processed data in the Euro-Mediterranean region. It is referred for the reader to Luzi et al., 2016 for details of the database. Only magnitude-distance distribution (Figure 2.11) and site information (Figure 2.12) are provided in this section.

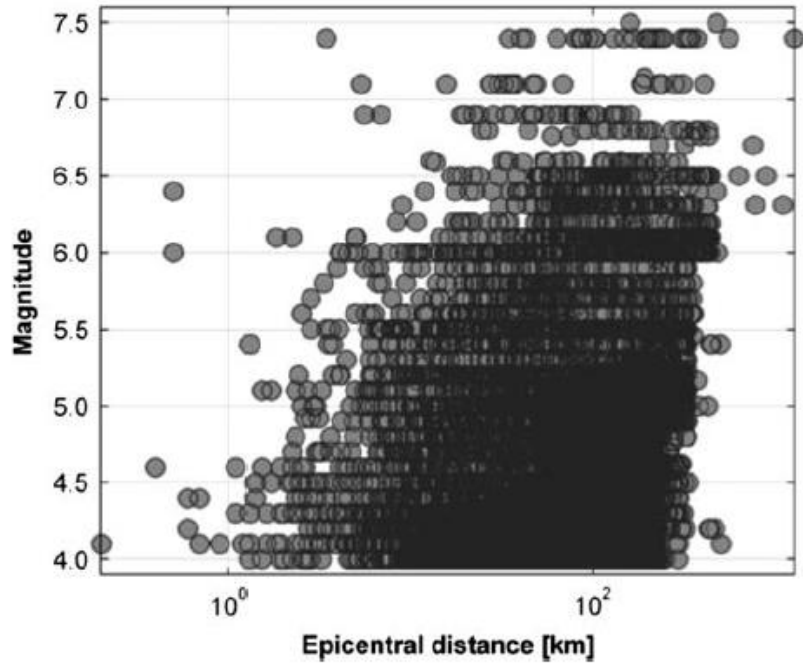


Figure 2.11. Magnitude-distance distribution of ESM database

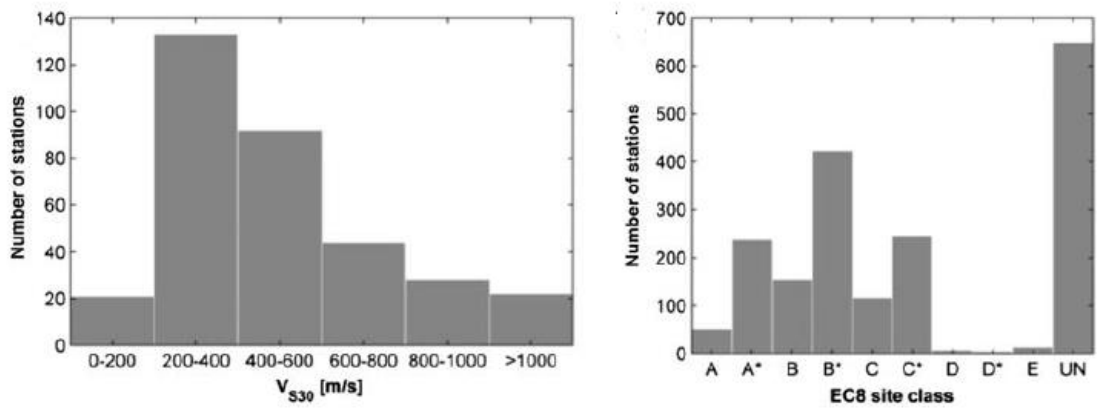


Figure 2.12. Distribution of ESM sites with V_{S30} values (left) and EC8 soil classes (right). Soil classes denoted by asterisk are inferred from surface geology (adapted from Luzi et al, 2016).

The databases which are source of this study are summarized above. Most of the record in compiled dataset is from NGA-West2 and KiK-Net databases. Following additional criteria is applied for the record selection process.

The selection criteria for the recordings used in the generation of the proposed GMPMs are listed below:

- Moment magnitudes, M not less than 3.5,
- The seismic database includes earthquakes with a focal depth shallower than 35 km in the Earth's crust.
- Sites with measured V_{S30} information,
- Records within 300km (Joyner Boore distance, R_{JB}),
- The data set includes events and stations that have at least two records, with the exception for events with a magnitude greater than 6.75 that were recorded at soft sites with a V_{S30} less than 360 m/s, which were included to capture possible nonlinear site effects.
- The magnitude-distance filter proposed in RESORCE database (Akkar et al. 2014) is applied to remove the bias caused by low-amplitude motions near the trigger threshold which is the case for low magnitude and large distance records. The cut-off distances (R_c) linearly increase with magnitude (for $M = 4$, $R_c = 100$ km and for $M = 6$, $R_c = 300$ km). This approach is simpler than the proposed one in NGA-Sub project (Contreras et al. 2022). However, a comparable cut-off distances are computed.

We emphasize that the compiled dataset used in this study is adapted as-is from the original global, regional and local datasets (e.g., NGA-West2, RESORCE, Kik-Net, etc.). This resulted in a non-uniform database in terms of metadata compilation and ground-motion processing scheme. These differences cause additional uncertainties in our proposed GMPMs. For instance, Turkish (Kale et al. 2015), RESORCE (Akkar et al., 2014) and NGA-West2 (Ancheta et al., 2014) datasets followed the same processing and post-processing schemes. The Italian dataset (Luzi et al., 2016) follows a similar approach in the processing procedure but differs in the post processing procedure. In the Japanese database (Dawood et al., 2016), a bandpass filter was applied to the accelerometric data without a post-processing scheme. We also use the distance metrics and magnitudes as

they are provided in the original datasets. Most of the databases includes magnitudes at different scales, but we prefer to use the data that have only reported moment magnitude. We remove events whose magnitudes are given in other scales and we do not prefer applying any conversion equations. In addition, for example, in the Turkish dataset, moment magnitudes were compiled from different international and national seismological agencies (e.g., GCMT, GFZ, etc.). This also leads to uncertainty in the moment magnitudes. The distance calculation procedures of each dataset also differ. This might bring additional uncertainties in distance metrics, especially for R_{JB} less than 20 km. There are also some stations that do not extend to 30 m depth in the V_s profile and they are originated from the NGA-West2 and we use their V_{S30} estimates as they provide. The V_{S30} calculation for these stations is performed using the procedures described in Seyhan et al. (2014). We have accepted additional uncertainties arising from the use of a non-uniform database to produce our proposed GMPMs. The calculation of uncertainties related to the non-uniform database is beyond the scope of this study.

Instead of using political borders, we used eight greater seismic regions according to the Flinn-Engdahl Geographic Regions (FEGR). The database distribution for each region is shown in Table 2.1. Low- to moderate-magnitude events are abundant in all regions, and records from Japan predominate in the database. The distribution of fault types is not uniform; in general, strike-slip earthquakes predominate, and in some regions, there are few records of different fault types. For example, there is no normal event in the database for Taiwan and one strike-slip event in Northwestern Europe. Most of the events are in the depth range of 5-20 km. It is seen that the database is dominated by NEHRP-2020 (BSSC 2020) site class C-CD and has a reasonably good distribution for rock sites (Figure 2.13). However, it contains relatively few records on very soft soils (NEHRP site class E), and Table 2.2. shows the record numbers for the selected regions.

Table 2.1. Database statistics for Flinn-Engdahl Geographical regions

FEGR	Abbreviation	Event Number	Record Number	Magnitude Range	Distance Range (km)	SoF
Alaska, California Nevada, Oregon and New Zealand Regions1	USNZ	124	1737	3.4-7.9	0-299	N: 3 R: 32 SS: 89
Southwestern Japan and Ryukyu Islands East of Asia Japan Kuril Islands- Kamchatka Peninsula	JP	697	12195	3.5-7.5	0-300	N: 178 R: 352 SS: 167
Taiwan	TW	6	1261	5.9-7.6	0-185	N: 0 R: 5 SS: 1
India-Xizang-Sichuan- Yunnan	CH	18	339	4.8-7.9	0-296	N: 1 R: 8 SS: 9
Western Asia 2	WA	102	508	4.4-7.4	0.290	N: 4 R: 55 SS: 43
Middle East-Crimea- Eastern Balkans	GRTR	316	1968	3.5-7.6	0-295	N: 152 R: 19 SS: 145
Western Mediterranean area 3	MED	82	513	3.9-6.9	0-300	N: 45 R: 23 SS: 14
Northwestern Europe	NWE	26	125	3.5-6.4	2-185	N: 1 R: 19 SS: 6

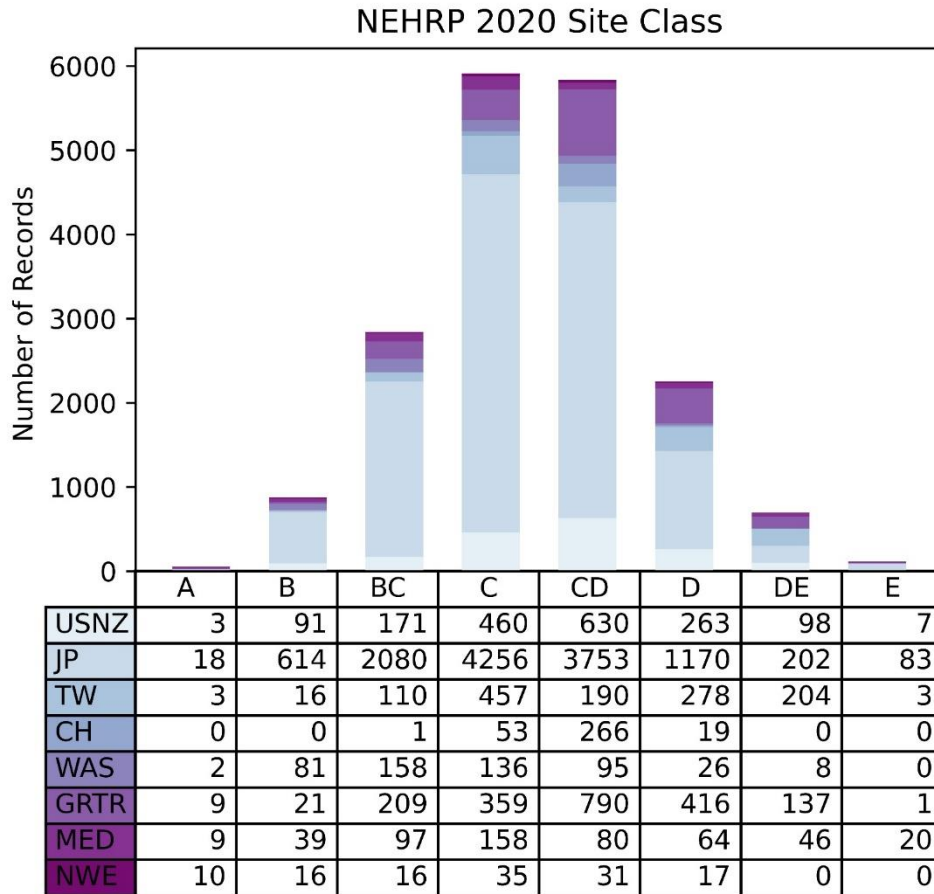


Figure 2.13. NEHRP 2020 Site Class distributions for the global datasets at $T=0.1s$. Different colors indicate different countries.

Magnitude-distance ($M-R_{JB}$) scatter is shown in the left panel of Figure 2.14. The period-wise distribution of the record numbers can be seen in Figure 2.14 (right). Both figures show the breakdown of seismic regions included in the dataset with different color codes. It is seen that low-magnitude and long-distance recordings dominate, and the distribution becomes sparser with increasing magnitude and decreasing distance. Figure 2.14. also shows that the records decrease with the increasing period due to the high-pass filtering selection of the recordings. The number of records decreases after $T > 1s$, and the available records decrease rapidly after $T = 4 s$ (%30 of the records persist in the regression).

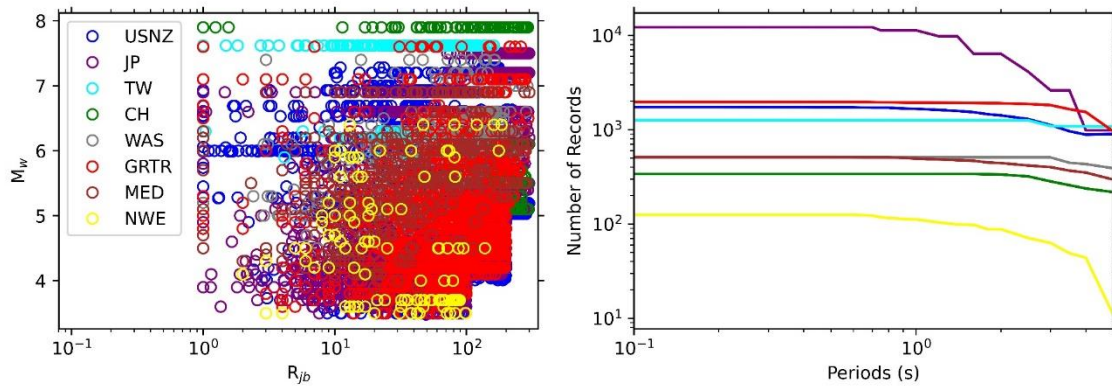


Figure 2.14. R_{JB} - M distribution of the dataset for 0.2s period (left panel) and the number of records with the period (right panel) used to develop GMPMs.

Table 2.2. Earthquakes and record number of countries in each region in the database. (Sandikkaya and Dinsever, 2018)

Region	Country	Earthquake	Record
USNZ	ABD	125	1982
USNZ	New Zeland	2	23
JP	Japan	699	13250
TW	Taiwan	6	1261
CH	China	18	343
WA	Iran	84	395
WA	Armenia	9	41
WA	Turkmenistan	4	34
WA	Jordan	5	39
TRGR	Turkey	271	1884
TRGR	Greece	47	181
WMT	Italy	75	471
WMT	Kosovo	2	6
WMT	Macedonia	5	36
NWE	France	1	2
NWE	Germany	2	7
NWE	Switzerland	7	52
NWE	Australia	16	64

3. GROUND MOTION PREDICTIVE MODEL

We aim to develop a GMPMs with the smallest number of predictor variables. Therefore, we used moment magnitude ($\mathbf{M}$), focal depth (Z_{hyp}), style-of-faulting (SoF) and V_{s30} as predictor variables for the proposed GMPMs. In addition, we preferred R_{JB} as a distance measure which is defined by the closest distance between fault rupture projected onto the surface and the considered site. Our GMPM for the natural logarithm of the median prediction of PSA at a 5% damping ratio is given in Equation 3.1.

$$\begin{aligned} \ln(PSA) = & f_M(\mathbf{M}, Region) + f_D(Z_{HYP}, Region) + f_{SoF}(SoF, Region) \\ & + f_R(\mathbf{M}, R_{JB}, Region) + f_S(V_{s30}, Z_1, PSA_r, Region) \end{aligned} \quad (3.1)$$

The functional form includes the event, distance, and site terms and it accounts for the regional differences. In the GMPMs, $f_M(\mathbf{M}, Region)$, and $f_D(Z_{HYP}, Region)$ represent the magnitude scaling and the depth dependency of GMIM, respectively. The difference due to the style of faulting is expressed by $f_{SoF}(SoF, Region)$. $f_R(\mathbf{M}, R_{JB}, Region)$ includes both geometric and anelastic attenuation and scales the ground motion with distance. Finally, $f_S(V_{s30}, Z_1, PSA_r, Region)$ is for site effects.

The functional form for the magnitude scaling is given in Equation 3.2. and was adapted from Abrahamson et al. (2014) due to its simplicity to capture both low- and high-magnitude behavior. It includes a tri-linear magnitude scaling with a quadratic term. The regression coefficients (a_1 , a_4 , and a_5) and regional corrections ($a_{1,r}$, $a_{2,r}$, and $a_{3,r}$) are computed with mixed-effect regression (lme4; Bates et al. 2014), as described in the next section. M_1 and M_2 are the hinging magnitudes at which the magnitude scaling of ground-motion behavior changes. M_1 and M_2 are taken as 6.75 and 5.5, respectively.

$$f_M(\mathbf{M}, \text{Region}) = \begin{cases} a_{1,r} + (a_{2,r})(M_2 - M_1) + (a_{3,r})(\mathbf{M} - M_2) + a_4(8.5 - M_2)^2 & \text{for } \mathbf{M} < M_2 \\ a_{1,r} + (a_{2,r})(\mathbf{M} - M_1) + a_4(8.5 - \mathbf{M})^2 & \text{for } M_2 \leq \mathbf{M} < M_1 \\ a_{1,r} + a_5(\mathbf{M} - M_1) + a_4(8.5 - \mathbf{M})^2 & \text{for } \mathbf{M} \geq M_1 \end{cases} \quad (3.2)$$

Deeper events produce larger amplitudes since the stress drop increases relatively when the focal depth increases. To include the focal depth effect, we used the functional form of Campbell and Bozorgnia (2014), as expressed by Equation 3.3. ($a_{6,r}$ is the coefficient for the regional dependency of the depth model). Some of recent NGA-Sub GMPMs use depth-to-top-of rupture as a predictor variable but we prefer to use Z_{HYP} , although this complicates the hazard integral and if required it can be converted to mean hypocentral depth, Z_{HYP} which is a function of Z_{TOR} , if needed, by applying the conversion given in Parker et al. (2022).

$$f_D(Z_{HYP}, \text{Region}) = \begin{cases} 0, & Z_{HYP} \leq 7 \\ a_{6,r}(Z_{HYP} - 7), & 7 < Z_{HYP} \leq 20 \\ 13a_{6,r}, & Z_{HYP} > 20 \end{cases} \quad (3.3)$$

The ratio of PSA values obtained from normal-slip earthquakes to strike-slip earthquakes (N:SS) and the ratio of PSA values for reverse events (R:SS) are expressed by Equation 3.4. The reference model addresses the SoF effect by multiplicative coefficients on dummy variables. We did not consider the magnitude effect in our predictive model to keep the functional form simpler and focus on regional effects (magnitude distribution for each region is not uniform). Style-of-faulting scaling is given below, where $a_{7,r}$ and $a_{8,r}$ are region-dependent model coefficients and the f_N and f_R dummy variables for the normal and reverse events, respectively.

$$f_{SoF}(\text{SoF}, \text{Region}) = (a_{7,r})f_N + (a_{8,r})f_R \quad (3.4)$$

The distance scaling comprises two terms representing the geometrical spreading and the anelastic attenuation. The spreading effect is expected to increase with increasing magnitude; in other words, the decrease in spectral acceleration with respect to distance will be slower for a large-magnitude earthquake than for a small-magnitude earthquake. Therefore, the geometric spreading term is expressed as a first-order function that depends on earthquake magnitude, as expressed by Equation 3.5. The coefficient b_1 , region-dependent regression coefficient $b_{2,r}$ and pseudo-depth term (h) are explained in the next section.

$$f_{R,GS}(M_w, R_{JB}, Region) = [b_1 + b_{2,r}(M - 6.75)] \ln(R) \quad (3.5)$$

The anelastic attenuation term is assumed to be more effective at long distances ($R > 80$ km), as expressed in Equation 3.6. $b_{3,r}$ is the region-dependent coefficient for the anelastic attenuation and R is defined as $\sqrt{R_{JB}^2 + h^2}$.

$$f_{R,AA}(R, Region) = \begin{cases} 0 & \text{for } R \leq 80 \text{ km} \\ (b_{3,r})(R - 80) & \text{for } R > 80 \text{ km} \end{cases} \quad (3.6)$$

The site effect is a combination of linear site effect, soil nonlinearity, and basin effect. Functional forms for each term are adapted from Chiou and Youngs (2014; CY14 hereafter). The functional form for the linear site amplification is expressed by Equation 3.7.

$$\ln(F_{ln}) = \begin{cases} (c_{1,r}) \ln\left(\frac{V_{s30}}{V_{ref}}\right), & V_{s30} < V_c \\ (c_{1,r}) \ln\left(\frac{V_c}{V_{ref}}\right), & V_{s30} \geq V_c \end{cases} \quad (3.7)$$

where $c_{1,r}$ is the regression coefficient, V_{ref} is defined as the reference Vs at which site amplification takes unity and taken as $V_{s30} = 760$ m/s. V_c is the period dependent limiting velocity at which the ground-motion intensity no more scales with V_{s30} , thereafter.

The nonlinear site amplification function is expressed by Equation 3.8.

$$\ln(F_{nl}) = c_2 \left[e^{c_3(\min(V_{s30}, 760) - 360)} - e^{c_3(400)} \right] \ln\left(1 + \frac{PSA_r}{c_4}\right) \quad (3.8)$$

where c_2 , c_3 and c_4 are regression coefficients, and PSA_r is the reference PSA value at V_{ref} . Instead of using reference PGA value, we preferred PSA_r for ease of implementation in hazard studies. The PSA_r values are modified with between event residuals (η_i) in performing regression analyses. The period-dependent c_4 provides a smooth transition and calculated with the nlme (Pinheiro et al., 2022).

To include the deep-soil effect, we use the depth at which the shear wave velocity reaches 1.0 km/s ($Z_{1.0}$). The $Z_{1.0}$ term of the model is developed by CY14 and used in this study, in this function c_5 and c_6 are regression coefficients. Equations 3.9-3.11 applies the difference between measured and expected $Z_{1.0}$, $\Delta Z_{1.0} = Z_{1.0} - E[Z_{1.0} | V_{s30}]$. The $E[Z_{1.0} | V_{s30}]$ is region-dependent. To estimate $E[Z_{1.0} | V_{s30}]$ in Japan we use the equation given in CY14 (Eq. 3.10). Ahdi et al. (2022) proposed a new relation to predict the depth to Vs reached 2.5 km/s however we cannot pursue with the new model due to for non-Japan data we have only $Z_{1.0}$ values. But, we prefer the updated $E[Z_{1.0} | V_{s30}]$ model instead of using the one in

CY14 (Equation 3.11.) which is derived for California (Nweke et al., 2020) and assume that it is applicable to other regions.

$$f_{z_{1.0}} = c_5(1 - e^{-\Delta Z_{1.0}/c_6}) \quad (3.9)$$

$$\ln(z_{1.0}) = \frac{-5.23}{2} \ln\left(\frac{V_{S30}^4 + 571^4}{1360^4 + 571^4}\right) \quad (3.10)$$

$$z_{1.0} = 1502 - 758.2 \left[1 + \operatorname{erf}\left(\frac{\log(V_{S30}) - \log(325.74)}{0.3287}\right) \right] \quad (3.11)$$

The total residuals can be partitioned into between-event (δB_e) and within-event terms (δW_{es}), according to the definition in Al Atik et al. (2010), expressed by Equation 3.12. The subscript e and s represent the event and site, respectively. These residuals follow a normal distribution with zero means, and τ and ϕ correspond to the standard deviations for the between-event and within-event residuals, respectively.

$$\Delta = \delta B_e + \delta W_{es} \quad (3.12)$$

The within-event residuals can be further separated into two terms: $\delta S2S_s$ and δWS_{es} . The term $\delta S2S_s$ refers to the difference between the observed ground motion at a particular site and the median prediction of ground motion corrected for the event effects. δWS_{es} denotes the single-site within-event residual. Thanks to the abundant and well-recorded ground-motion data at individual sites from multiple earthquakes, it is possible to compute and eliminate the repeated site response term. Their standard deviations are denoted ϕ_{S2S} and ϕ_{SS} . The total standard deviation is expressed by Equation 3.13.

$$\sigma = \sqrt{\tau^2 + \phi_{SS}^2 + \phi_{S2S}^2} \quad (3.13)$$

Although the region-specific coefficients are used to compute median estimates, we did not consider regionalization for the standard deviation components. The standard deviation models are from previous studies, particularly those conducted as part of NGA projects (e.g., NGA West-2 GMPMs; Al Atik et al., 2015; Abrahamson and Gülerce, 2022; Parker et al., 2022). The trilinear magnitude-dependent between-event standard deviation model is given in Equation 3.14. τ_1 and τ_2 define the between event variability for $M \leq 5.5$ and $M > 6.75$.

$$\tau(M) = \begin{cases} \tau_1 & M \leq 5.5 \\ \tau_1 + (\tau_2 - \tau_1) \frac{(M - 5.5)}{1.25} & 5.5 < M \leq 6.75 \\ \tau_2 & M > 6.75 \end{cases} \quad (3.14)$$

Similarly, the magnitude and distance-dependent single-site within-event standard deviation model is given in Equation 3.15. where ϕ_1 and ϕ_2 defines the variability similar to between-event standard deviation for $M \leq 5.5$ and $M > 6.75$. $\Delta\phi_R$ is the intercept for the distance dependency, R_1 and R_2 are period dependent distance limits where the constant standard deviations are used.

$$\phi_{SS}(M) = \begin{cases} \phi_1 & M \leq M_1 \\ \phi_1 + (\phi_2 - \phi_1) \frac{(M - 5.5)}{1.25} & M_1 < M \leq M_2 \\ \phi_2 & M > M_2 \end{cases} \quad (3.15)$$

$$\phi_{SS}(M, R_{JB}) = \begin{cases} \phi_{SS}(M) & R_{JB} \leq R_1 \\ \phi_{SS}(M) + \Delta\phi_R \left(\frac{\ln(R_{JB}/R_1)}{\ln(R_2/R_1)} \right) & R_1 < R_{JB} \leq R_2 \\ \phi_{SS}(M) + \Delta\phi_R & R_{JB} > R_2 \end{cases} \quad (3.16)$$

The proposed model for site-to-site standard deviation is expressed by both V_{S30} and PSA_r and given in Equation 3.17. d_0 is the intercept, d_1 and d_2 are the slopes for V_{S30} and PSA_r dependency, respectively. PSA_r is the PSA value at $V_{S30} = 760$ m/s which corresponds to reference site condition, PSA_{r_upp} and PSA_{r_low} are the period dependent values that limits the ϕ_{S2S} at high- and low-amplitudes, respectively.

$$\phi_{S2S} = \sqrt{d_0^2 + d_1^2 [\ln(V_{sig})]^2 + d_2^2 [\ln(Y_{sig})]^2} \quad (3.17)$$

where V_{sig} and Y_{sig} is expressed by Equations 3.18-3.19;

$$V_{sig} = \max(\min(600, V_{S30}), 200) \quad (3.18)$$

$$Y_{sig} = \max(\min(PSA_{r_upp}, PSA_r), PSA_{r_low}) \quad (3.19)$$

4. REGRESSION APPROACH

We applied a three-stage procedure for the regression analyses. In Step I, using the candidate model (without any regional corrections), we performed a regression analysis with linear and nonlinear mixed-effects regression algorithms (lme4 and nlme packages in R; Bates et al., 2014, Pinheiro et al., 2022). That is, model coefficients are computed for the global model. We then performed a set of statistical analysis and decided which regional adjustments (or corrections) are needed. The regional corrections are computed using lme4 in Step II. These coefficients serve as region-specific corrections for the global model. Instead of fitting the curves to the residuals, we implement a random-effects regression algorithm to compute coefficients for regional corrections as this provides more robust results. Finally, in Step III, we removed the homoscedastic variance assumption and used a heteroscedastic variance model for τ , ϕ_0^2 , and ϕ_{s2s}^2 that are dependent on magnitude, distance, V_{s30} , and PSA_r , respectively.

4.1. Step I: Regressions for the Global Model

The model coefficients for the global GMPMs are computed at this step (by setting all regional terms to 0). The coefficients for the magnitude (a_1, a_2, a_3, a_4, a_5), depth (a_6) style-of-faulting (a_7, a_8), geometrical spreading (b_1, b_2), anelastic attenuation (b_3) and site amplification (c_1, c_2, c_5) are computed with lme4, whereas the computation of nonlinear terms in the functional form (c_3, c_4) are obtained with nlme.

The Abrahamson et al. (2014; ASK14 hereafter) magnitude scaling function is firstly investigated by visual inspection of the observed data to determine the hinge magnitudes (Figure 4.1.). Like all NGA-West2 GMPMs, the behaviors at low, medium, and high magnitudes are different. Although the limits for the different magnitudes are "period-dependent" (both theoretically and data-dependent), we cannot determine the limits precisely. The hinge magnitudes of M_1 and M_2 are constrained to 6.75 and 5.5, respectively (the limits hold for most

periods). Once these are determined, the regression coefficients are computed. There is no clear trend for the magnitude dependency for the style-of-faulting term (Figure 4.2.) so magnitude independent coefficient is used for the analysis for the simplicity. The depth and SoF coefficients are discussed detailed in the next section.

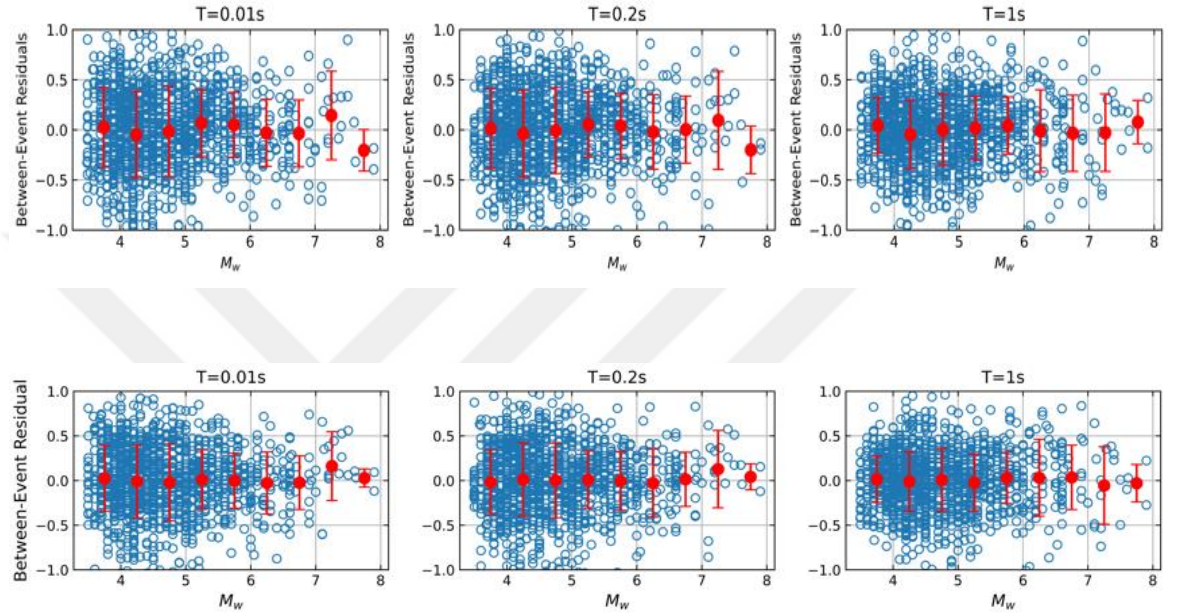


Figure 4.1. Between event residuals for 0.01s (left), 0.2s (middle), 1s (right) panels for the comparison of bilinear (top) and trilinear (bottom) magnitude scaling.

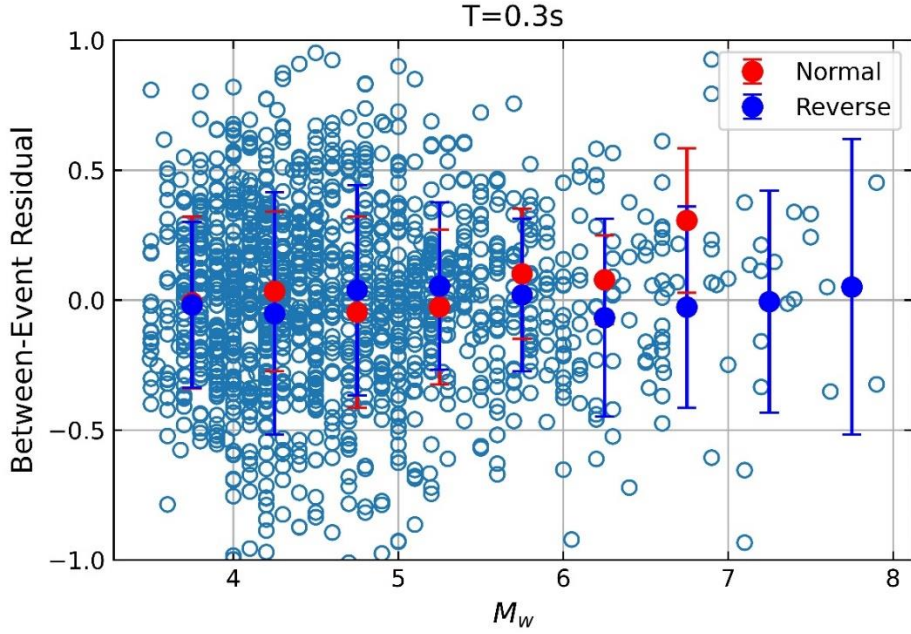


Figure 4.2. Between-event residuals for normal (red) and reverse (blue) faulting.

In the distance scaling, we use the pseudo-depth term (h) to account for the saturation with decreasing distance and it is computed as 7 km by using nlme. The h term, generally depends on magnitude, captures finite-fault effects (Yenier and Atkinson, 2014). We found that using a magnitude-dependent pseudo-depth term does not improve the residual distributions at short distances, we decided to use a fixed value to keep the function simpler.

4.1.1 Site amplification model

It is observed that the database boundaries affect the regression coefficients. The coefficient representing linear site response decreases (more negative) when using a database dominated by for low magnitude earthquakes or distant recordings (Sandikkaya and Dinsever, 2018). For the site amplification model, we first computed nonlinear site coefficients with a subdataset (with moment magnitudes greater than 4.5 and distances up to 80 km). We then recomputed the linear site coefficients and deep soil effect using the entire database.

All data are scaled to common earthquake scenario ($M = 6$ and for strike-slip earthquake) to observe the V_{S30} scaling. It is seen in Figure 4.3. that the ground motion scales with V_{S30} up to a threshold (V_c) and remains constant thereafter. The same plots are observed for all periods (Appendix C) and the dependence on period is shown for the V_c . The period dependent V_c improved the residual distribution for the higher V_{S30} values (Figure 4.4.), remaining plots are given in Appendix B.

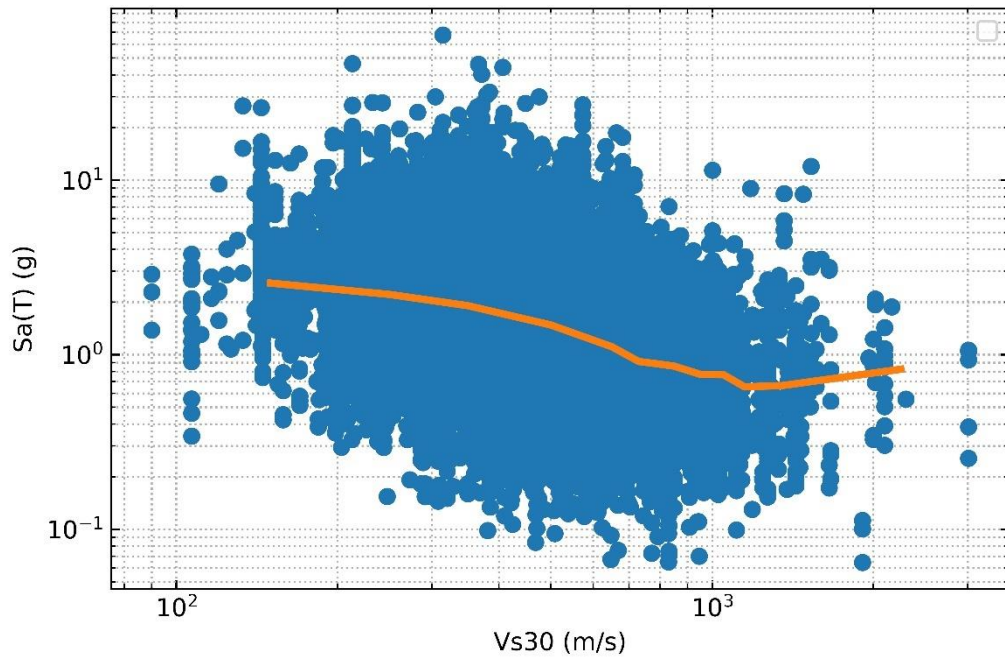


Figure 4.3. V_{S30} scaling at 0.25s period, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

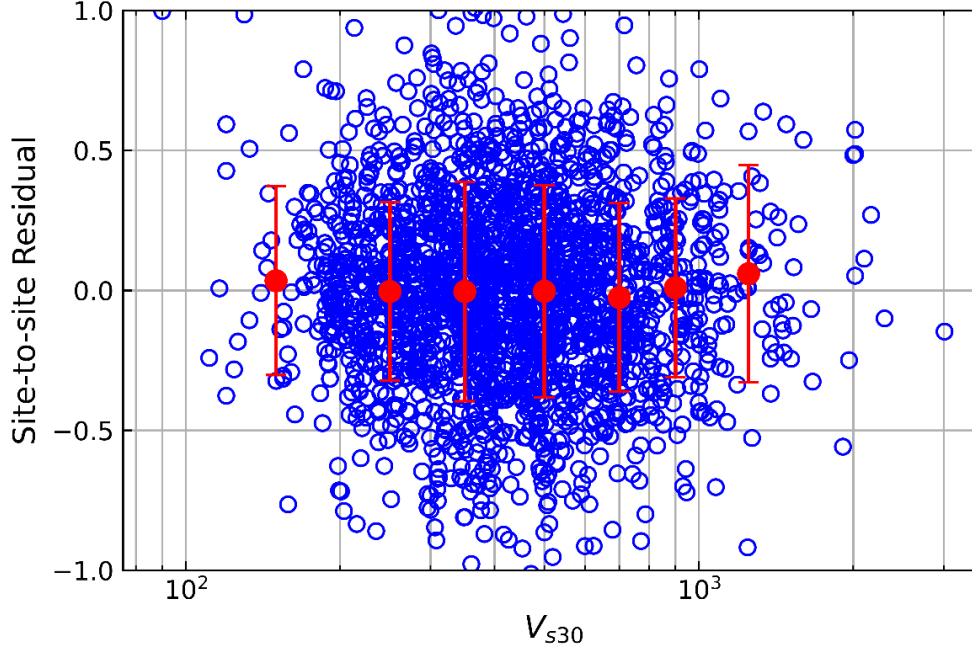


Figure 4.4. Site-to-site standard residuals with V_{s30} at 0.025s.

We compared the model coefficients of the site amplification function with those of the previous models given by BSSA14 and CY14 (Figure 4.5). The linear site amplification coefficient (c_1) is shown in the upper left of Figure 4.5. It is seen that our model lies between BSS14 and CY14 at short periods. The three models give similar results for the mid periods (0.1-0.3s), and as the period increases, the new model estimates the lowest linear amplification.

The nonlinear site amplification is represented by the coefficients c_2 , c_3 and c_4 . The nonlinear coefficient of c_2 (top-right panel) is very similar to CY14 after the period of 0.15s; however, the proposed model yields lower coefficients than the other two models at very short periods. For c_3 (bottom-left panel), which can be attributed to soil stiffness; the difference is prominent at periods lower than 1.5s. The proposed model yields similar c_4 coefficients with CY14 after the period of 1s (BSSA14 uses a fixed amplitude for all periods). Since c_4 limits the nonlinear behavior below the PSA_r values, nonlinearity becomes effective at stronger motions in our model.

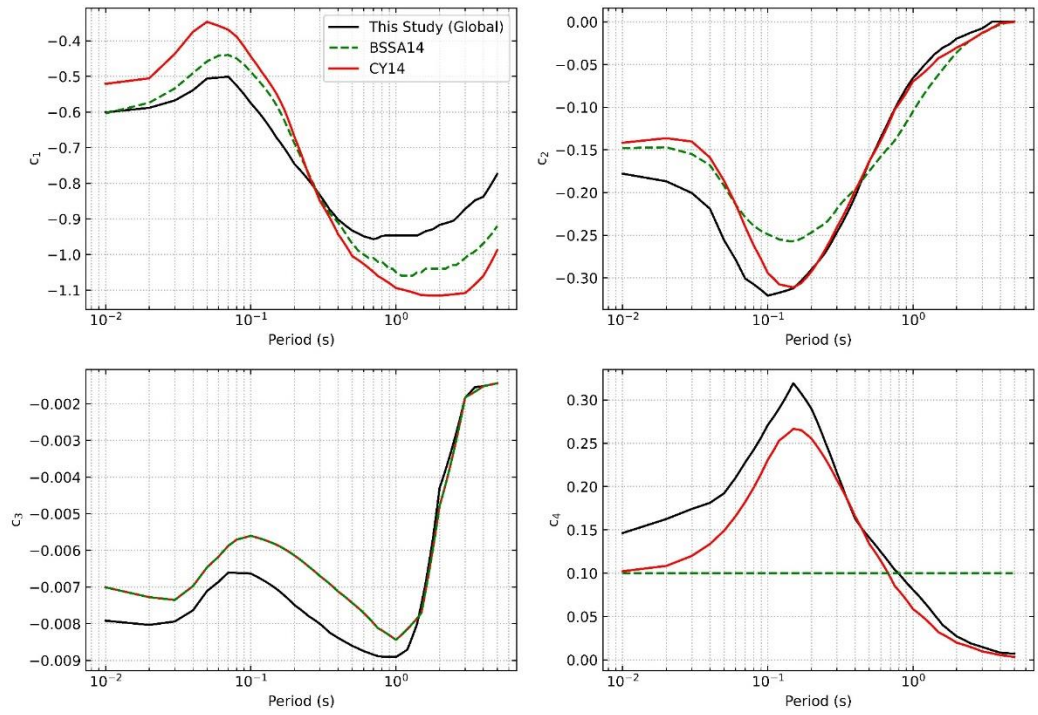


Figure 4.5. Site amplification model coefficients derived in this study and comparison with the BSSA14 and CY14 model coefficients. We used a global linear term for the comparison.

Figure 4.6. shows site amplification with periods for two different input motion (weak and strong) and different V_{S30} values to represent soft to stiff soil sites ($V_{S30} = 180$ m/s, $V_{S30} = 360$ m/s and $V_{S30} = 550$ m/s). For the weak motion level in the short period range our model gives similar amplification values with the CY14 model but for the longer periods our model produces lower amplifications. As the V_{S30} values increase the difference decreases. For the strong motion level our model produces lower amplifications due to lower c_3 coefficients in shorter periods and two model gives similar results for the longer periods. Also, this difference is not prominent for the high V_{S30} values.

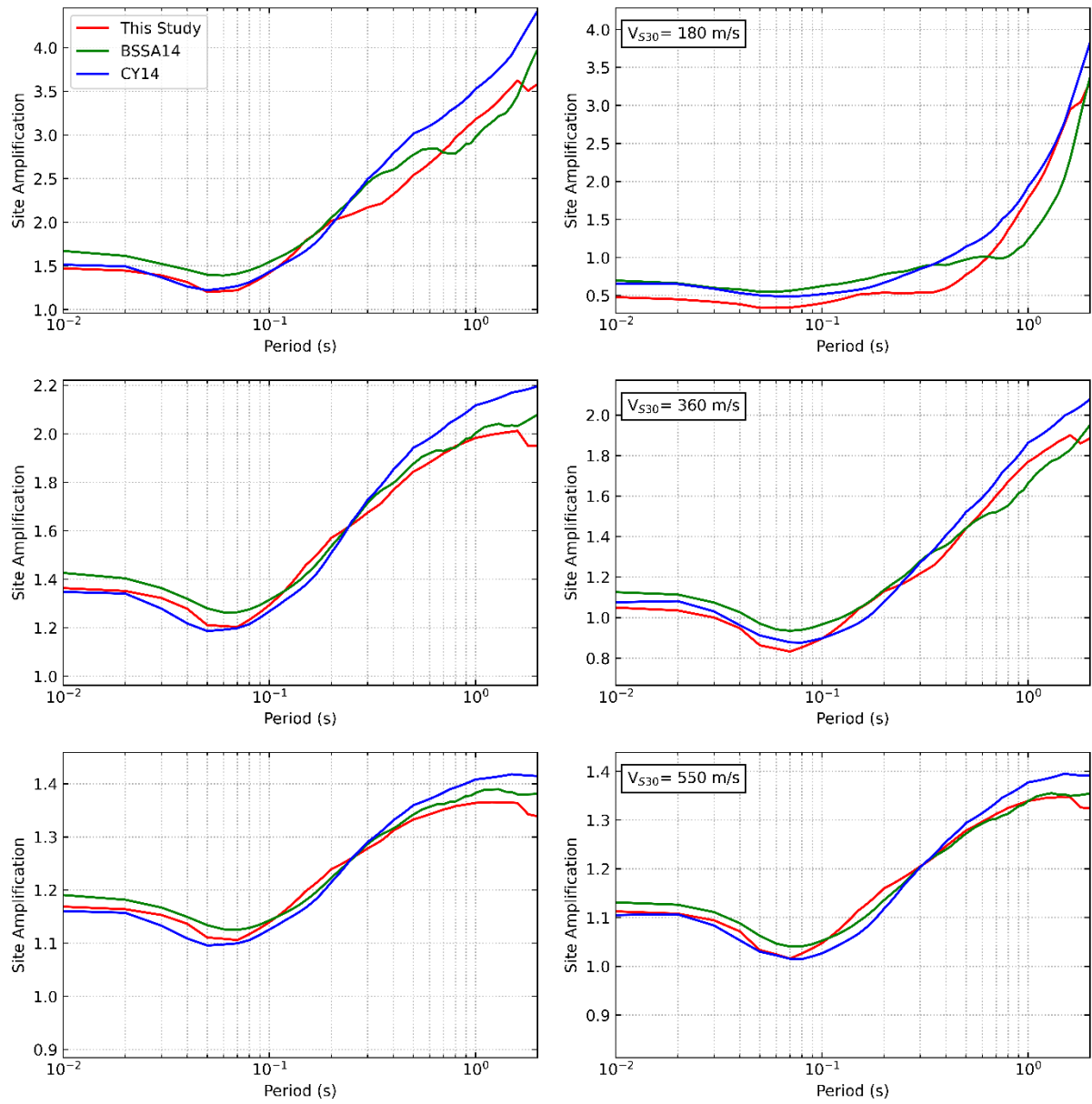


Figure 4.6. Comparison of site amplification function with period for very soft ($V_{S30} = 180$ m/s), soft ($V_{S30} = 360$ m/s) and stiff soil ($V_{S30} = 550$ m/s) for 0.1g and 1g PSA_r levels, depth to bedrock term is not included in the plots.

Figure 4.7. shows PSA_r dependence and V_{S30} dependence can be seen in Figure 4.8., three site conditions from soft to stiff soil sites are used for the comparison of two model and two different periods were selected (0.2s and 1s). At 0.2s and soft soil site our model produces higher amplification but when the PSA_r value increases model shows more nonlinear behavior resulting from the high c_4 and

lower c_3 coefficients where c_4 limits nonlinear behavior below some PSA_r values. It means less nonlinearity will be produced for lower PSA_r values because of the c_4 value for that period. At the period of 1s our model produces lower amplification due to lower linear coefficient at long period range. At both periods this difference is not prominent for the higher V_{S30} values. For the V_{S30} -scaling at 0.2s and for the stiff soil sites all models give similar results but for the lower V_{S30} values more nonlinearity is effective because of the lower c_3 coefficient. Same behavior is also observed at 1s. Appendix B shows comparison with the CY14 model for the V_{S30} and PSA_r scaling for 30 periods (0.01s to 5s).



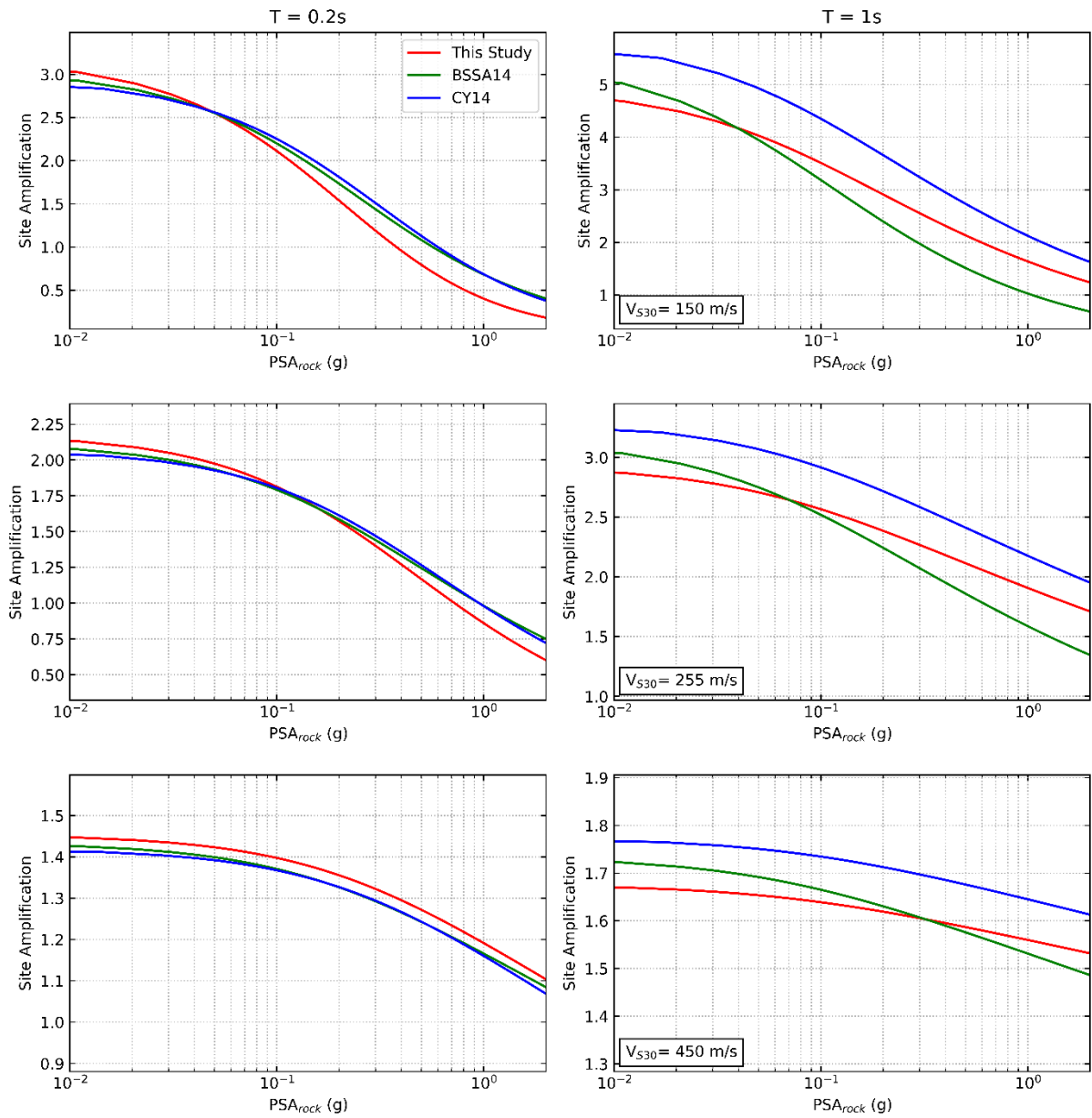


Figure 4.7. PSA_r scaling comparisons for $V_{S30} = 150\text{ m/s}$, $V_{S30} = 255\text{ m/s}$ and $V_{S30} = 450\text{ m/s}$ at 0.2 s (left) and 1.0 s (right), depth to bedrock term is not included in the plots.

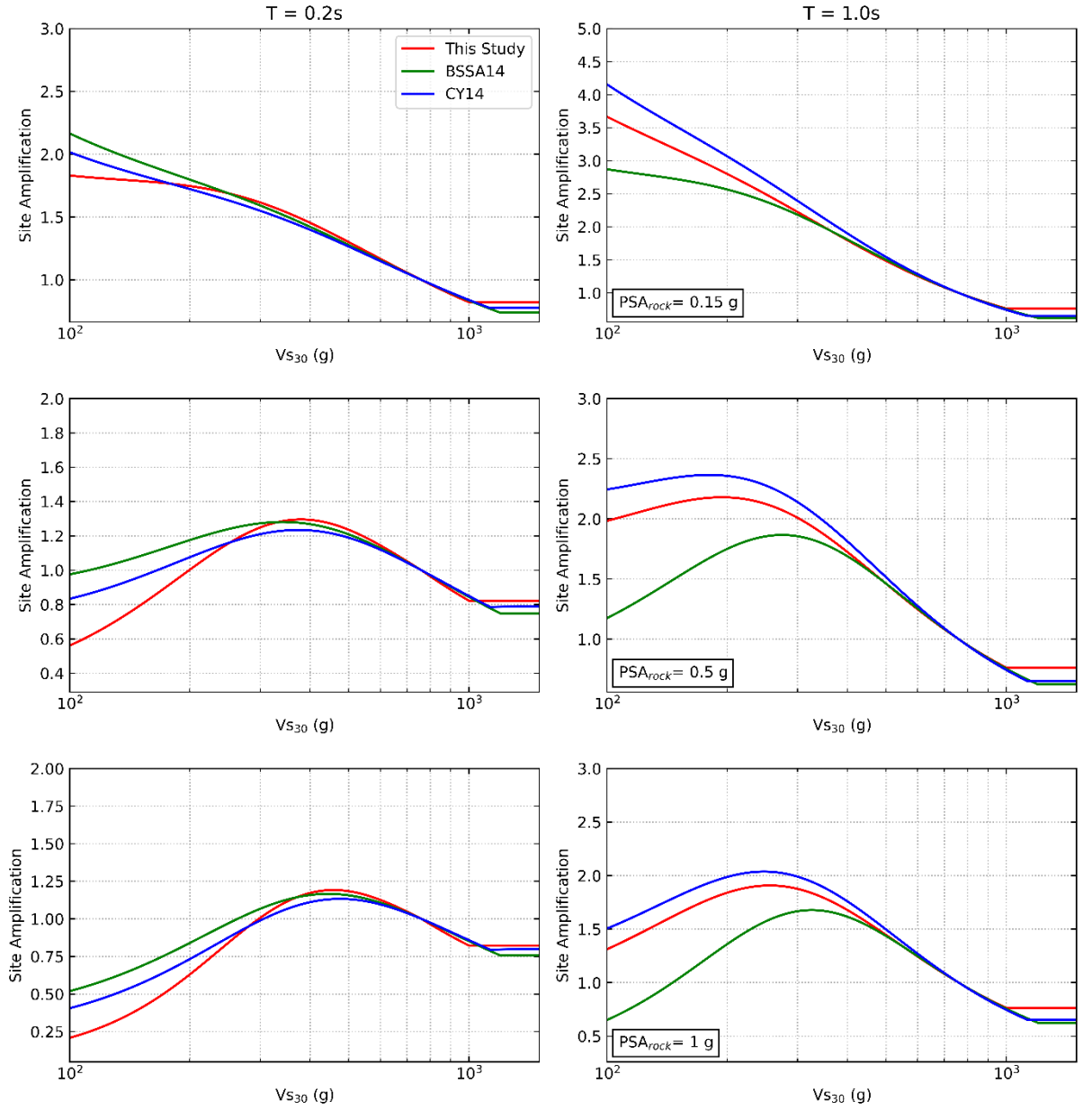


Figure 4.8. V_{S30} scaling comparisons for $PSA_r = 0.15g$, $0.5g$ and $1g$ from top to bottom, respectively at $0.2s$ (left) and $1.0s$ (right), depth to bedrock term is not included in the plots.

4.2. Step II: Regressions for Regional Corrections

In the preliminary analysis, significant differences between regions are observed. Figure 4.10. shows an example of the regional differences in terms of distance. To this end, we scaled all GMIMs to a common earthquake scenario (**M** 6 and strike-slip) and $V_{S30} = 760$ m/s by using the base-case model coefficients derived

in Step I. It is seen that the region-specific geometrical spreading and anelastic attenuation differs from region to region. Also, Figure 4.9. shows the between-event residual distribution of MED region for the global model, there is downward trend with magnitude so regional correction for this region is needed for the magnitude term. The regional coefficients are computed separately for each term. Then, we applied both visual inspection and the statistical F-test to determine whether global or regional coefficients should be used. Loosely speaking similar results are not observed in a wide range of periods. In some periods, the hypothesis test failed to reject for the grouping process, for a coefficient (e.g., anelastic attenuation term), however we prefer to regionalize the coefficient due to its periods of interest (the long period behavior of anelastic attenuation disregarded). We discussed the regional corrections for the event, distance, and site terms. For this purpose, we used eight greater seismic regions (Table 2.1.) to describe the regionalization of ground-motion amplitudes.

Finally, the regional corrections for the event, distance, and site terms are discussed. For this purpose, eight greater seismic regions are used (Table 2.1) to describe the regionalization of GMPMs.

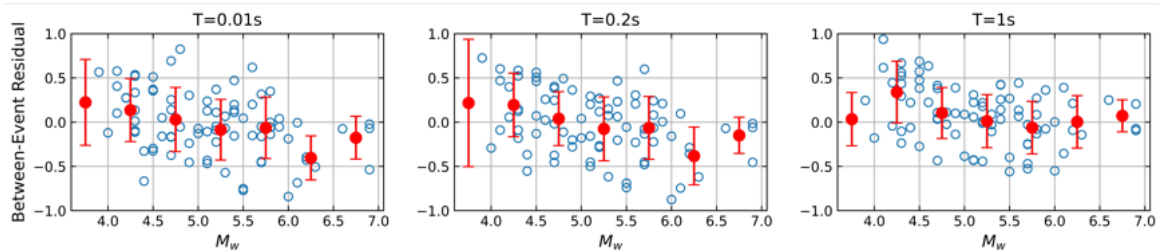


Figure 4.9. Between-event residual distribution of MED region for global model.

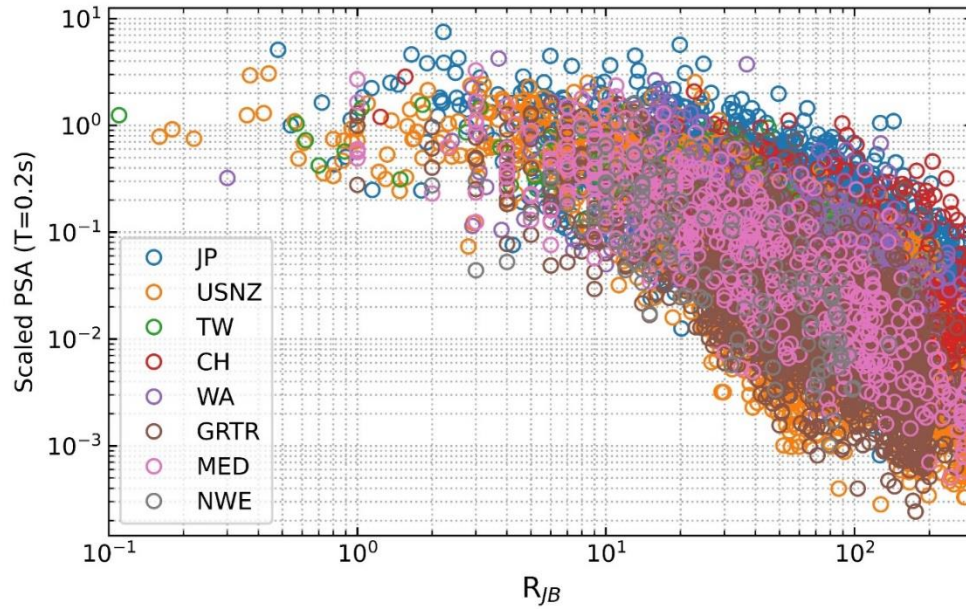


Figure 4.10. The modified PSA values (all data is scaled to $M = 6$ and $V_{S30} = 760$ m/s for the strike-slip scenario) were obtained by extracting the event and site terms using the model coefficients computed in the previous section.

4.2.1 Hypothesis Testing

The global coefficients represent overall model behavior while individual coefficients represent difference from the global model. To clearly explain the procedure that is applied, a table for the null hypothesis and results of our hypothesis testing is proposed. In that case our null hypothesis (H_0) is global region is meaningful in case of rejection null hypothesis separate coefficients for each region is statistically significant (Table 4.1.). It is seen that testing result are not prominent across all periods considered (Table 4.2.). For example, when moderate-magnitude term is considered, rejection of null hypothesis is valid at 0.01s and fail to reject at 1s for JP and CH as we noted above this relationship is not exist across all periods. It is expected that difference between models for the magnitude term exist in lower periods (it is also seen in Figure 5 that difference between regions are prominent for the lower periods and with increasing period all regions converge, this is physically explainable). Exception for the NWE and TW resulted from the data sparsity low moderate magnitude data resulted in

higher confidence intervals and resulted in fail to reject null hypothesis this can be seen also in Figure 5 of the paper. Also, some of the fail to reject result are close the rejection boundary. To consider all these situations we decided to use separated coefficients. One exception is for the style-of-faulting term as it is also noted in the following section that grouped coefficient for the style-of-faulting term is used because low of recording and few different faulting types in some regions led to unreliable coefficients in the analysis (e.g., no normal event in TW and one event in NWE). Besides, after hypothesis testing, we observed that style-of-faulting scaling for only JP and MED are significantly different than others.

Table 4.1. Hypothesis testing conducted on model

H_0 =Global coefficient	Fail to reject H_0 (✖)	Coefficient is not statically significant it should be included to global
H_1 =Separated Coefficients for Region	Reject H_0 (✓)	Separate coefficients are meaningful

Table 4.2. Results of hypothesis testing

	Coefficient	USNZ	JP	TW	CH	WA	GRTR	MED	NWE
Regional Term	a1,r (0.01s)	✓	✓	✓	✓	✓	✓	✓	✓
	a1,r (0.2s)	✓	✓	✓	✓	✓	✓	✓	✓
	a1,r (1s)	✓	✓	✓	✓	✓	✓	✓	✓
Moderate Magnitude	a2,r (0.01s)	✓	✓	✖	✓	✓	✓	✓	✖
	a2,r (0.2s)	✓	✓	✖	✖	✓	✓	✓	✖
	a2,r (1s)	✓	✖	✖	✖	✓	✓	✓	✖
Low Magnitude	a3,r (0.01s)	✓	✓	✓	✓	✖	✓	✓	✓
	a3,r (0.2s)	✖	✖	✓	✓	✖	✓	✓	✓
	a3,r (1s)	✓	✓	✓	✖	✖	✓	✓	✓
Style-of-Faulting Reverse and Normal	a7-8,r 0.01s)	✖	✓	✖	✖	✖	✖	✓	✖
	a7-8,r (0.2s)	✖	✓	✖	✖	✖	✖	✓	✖
	a7-8,r (1s)	✖	✓	✖	✖	✖	✖	✓	✖
Anelastic Attenuation	b3,r (0.01s)	✖	✓	✓	✓	✓	✓	✖	✓
	b3,r (0.2s)	✓	✖	✓	✓	✓	✖	✓	✓
	b3,r (1s)	✓	✖	✖	✓	✓	✓	✓	✖
Site Term	c1,r (0.01s)	✓	✖	✓	✓	✓	✖	✖	✖
	c1,r (0.2s)	✓	✓	✖	✖	✓	✓	✓	✖
	c1,r (1s)	✓	✓	✖	✓	✖	✖	✖	✓

4.3. Regionalization for Event Term

After a preliminary analysis, we found that the coefficients representing the behavior at low and moderate magnitudes vary from region to region. First, we considered the magnitude saturation effect, which is noticeable at high magnitudes and small distances. For this purpose, a_5 , which represents the high magnitude behavior was set to -0.194 and -0.389 for Japan and for other regions, respectively. Then, we computed and compared the region-specific coefficients for low and moderate magnitude scaling (the top panel of Figure 4.12.).

The moderate magnitude scaling coefficients ($a_{2,r}$) are shown in the left of first row of the Figure 4.12. The differences between the models are clear at shorter periods. The lowest coefficient is observed for TW, while JP has the highest for the short periods. All coefficients show a similar trend for long periods.

When the hypothesis testing for the region grouping is conducted, it is rejected almost for all region-specific low-magnitude scaling coefficients ($a_{3,r}$) fail to reject for region-grouping. The highest confidence interval is observed for CH because of the lower number of events in this region but we preferred to use a separate coefficient for the CH. The first row of the right panel shows that $a_{3,r}$ is higher for USNZ and JP than for other regions at short and mid period bands. The lowest coefficients are calculated for CH. The regions have similar scaling at low magnitudes. This can be linked with the regional stress drop differences. The differences, when long periods are concerned, become less prominent, with indicating two major branches: converging of European data and minor differences in other regions.

The relationship between the PSA values obtained from normal-slip and reverse earthquakes to strike-slip earthquakes is computed and regional corrections are investigated. We first emphasize that the style-of-faulting distribution is very sparse in some regions. Low record number and few different faulting types in

some regions led to unreliable coefficients in the analysis (e.g., no normal event in TW and one event in NWE). Besides, after preliminary analysis with F-tests, we observed that style-of-faulting scalings for only JP and MED are significantly different from the other regions. Therefore, we assemble them as a single group and compute the corresponding SoF coefficients. (Second row of Figure 4.12.).

All groups for normal faulting are lower than those for strike-slip events at lower periods and there are no differences in the higher periods. The lowest coefficients are derived at short periods for MED, then as period increases the N:SS ratio increases and finally reaching zero after 0.9 s. After this period the ratio is unity. For JP and other regions similar behavior is observed but the period ranges are different. The scaling for JP linearly ramps between 0.1-0.4 seconds. For other regions the N:SS ratio is constant up to 1.5 s then takes unity after 2.5 s.

Considering the reverse to strike-slip ratio, MED behaves similar to N:SS ratio. On the other hand, the reverse earthquakes in JP produce lower amplitudes when compared to strike-slip earthquakes for all period range. For the other regions the ratio is greater than unity up to 0.4 s. After this period the coefficient converges to zero.

The regional correction for the focal depth parameter in the proposed model is investigated. It is found that this term is negligible for earthquakes of European origin (WA, GRTR, MED, and NWE). The residual distribution is significantly improved when the depth term is included in the functional form for the non-European earthquakes. There are no significant regional differences in the depth term for individual regions. One of the possible explanations for this observation may be the fine-tuning of the magnitude and SoF scaling for these regions.

4.4. Regionalization for Distance Term

The distance scaling is controlled by the geometrical spreading term (b_1) at short distances, and the anelastic attenuation becomes effective at long distances ($R_{JB} > 80$ km). In our preliminary analyses we found that $b_{2,r}$, describes the magnitude-dependent behavior of the geometrical spreading, is significantly different for JP. Thus, $b_{2,r}$ for Japan is taken as 0.1 while for other regions it is computed as 0.2, respectively. Significant differences (based on F-tests) are observed for all regions during the preliminary analysis of b_1 and $b_{3,r}$ but we decide not to consider regionalization for the geometrical spreading term.

The regression analyses are performed for the anelastic attenuation. It is known that the anelastic attenuation is more pronounced at high frequencies as is also seen in Figure 4.11 and Figure 4.12. that the coefficients converge to zero as the period increases. Since a positive coefficient is physically meaningless for the anelastic attenuation, all positive coefficients computed in the regressions are constrained to be zero for longer periods. For short periods, almost no similar trends are observed for the regions, while the coefficients approach zero (or are constrained to zero) as the period increases.

An interesting finding of this study is the anelastic attenuation differences between MED and USNZ data. In the previous studies (e.g., NGA-West2 GMPMs), the faster attenuation of MED is observed. However, in this study, we observe that there is a strong trade-off between geometrical spreading and anelastic attenuation for this region. As given in Figure 4.11., when compared with the US data, the proposed model has lower geometrical spreading coefficient for MED than for USNZ. This resulted in slower attenuation rate in MED. Since significant differences are observed for distance terms during the preliminary analysis of $b_{1,r}$ and $b_{3,r}$, we decide not to consider regionalization for the geometrical spreading term (b_1). Therefore we decided to use a global geometrical spreading term and regional anelastic attenuation term for each region as shown in the first and second columns in the third row of Figure 4.12.,

respectively. The regression analyses are performed for regional anelastic attenuation term. It can be seen that anelastic attenuation is less pronounced in the regions WA, NWE, CH, and GRTR than in USNZ, JP, MED and TW. Lower coefficients indicate that ground motions for these regions at higher frequencies decrease more rapidly with distance than in the other regions. Slower attenuation is observed for CH and GRTR (highest $b_{3,r}$) and faster attenuation in JP and MED. Similar observations are also reached by BSSA14 for the regions CH and GRTR (slower attenuation), JP and MED (faster attenuation). Similar results to previous studies (e.g., NGA-West2 GMPMs) are observed in this study for the anelastic attenuation term when global geometrical spreading term is used. MED and USNZ show a similar trend with slightly faster attenuation in MED. However, we note that strong trade-off between geometrical spreading and anelastic attenuation is observed for MED.

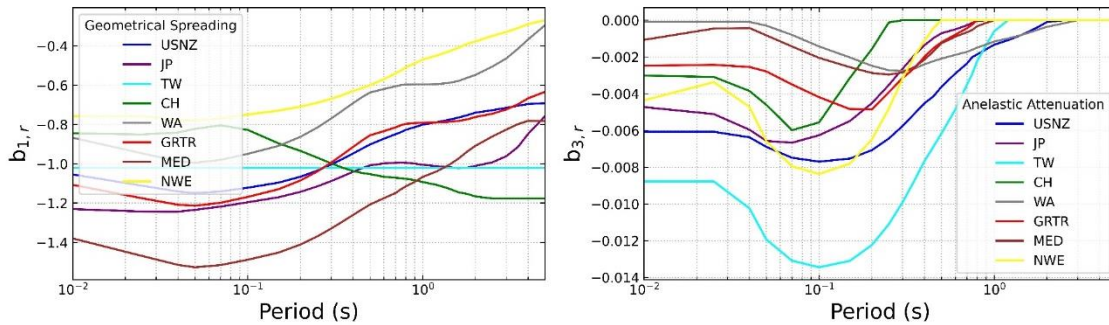


Figure 4.11. Regional parameters those are used in the preliminary analyses to represent different regional distance terms for each greater area for geometrical spreading (left), and anelastic attenuation terms (right).

4.5. Site Regionalization

Even though site amplification is also related to deeper structure of the soil media, the site parameter V_{S30} strictly represents only the features of sediments in the top 30 m. (e.g., Boore et al., 2011). The depth parameter describes high period behavior and is not captured by V_{S30} alone. Regional differences related to basin

structure have been studied. To obtain the differences between regions in the linear site amplification ($c_{1,r}$) coefficient is computed for each region, and significant differences are observed when F-tests are performed. Thus, no regions can be grouped and the individual region-specific coefficients are given in the bottom panel on the right of Figure 4.12. It should be noted here that we did not apply the regional correction for nonlinear site amplification.

Different linear site amplification behavior is observed for the considered regions. The upper bounds of the site amplification are computed for USNZ in almost all spectral periods. The lower bounds at short and long periods are obtained for Western Asia and Western European regions, respectively. All regions have a peak around 0.1s and then decrease with the increasing period. At long periods, some regions (Japan, Greece and Turkey, the United States and New Zealand, and Western Asia) show an increasing trend in the linear site coefficients. In other regions, the coefficients become flat at long periods.

At the end of Step II, we computed the regional term ($a_{1,r}$) at the last stage, after all coefficients are computed, to avoid unexpected effects on the event, distance, and site terms. Since the regional term effects the shape of the spectrum, we used different coefficients for each region, which can be seen in the bottom left panel of 4.12. It is seen that JP has the highest coefficients which can be related to the regional tectonic differences. All regional coefficients peak at different periods and decrease thereafter, as expected from the shape of the spectrum.

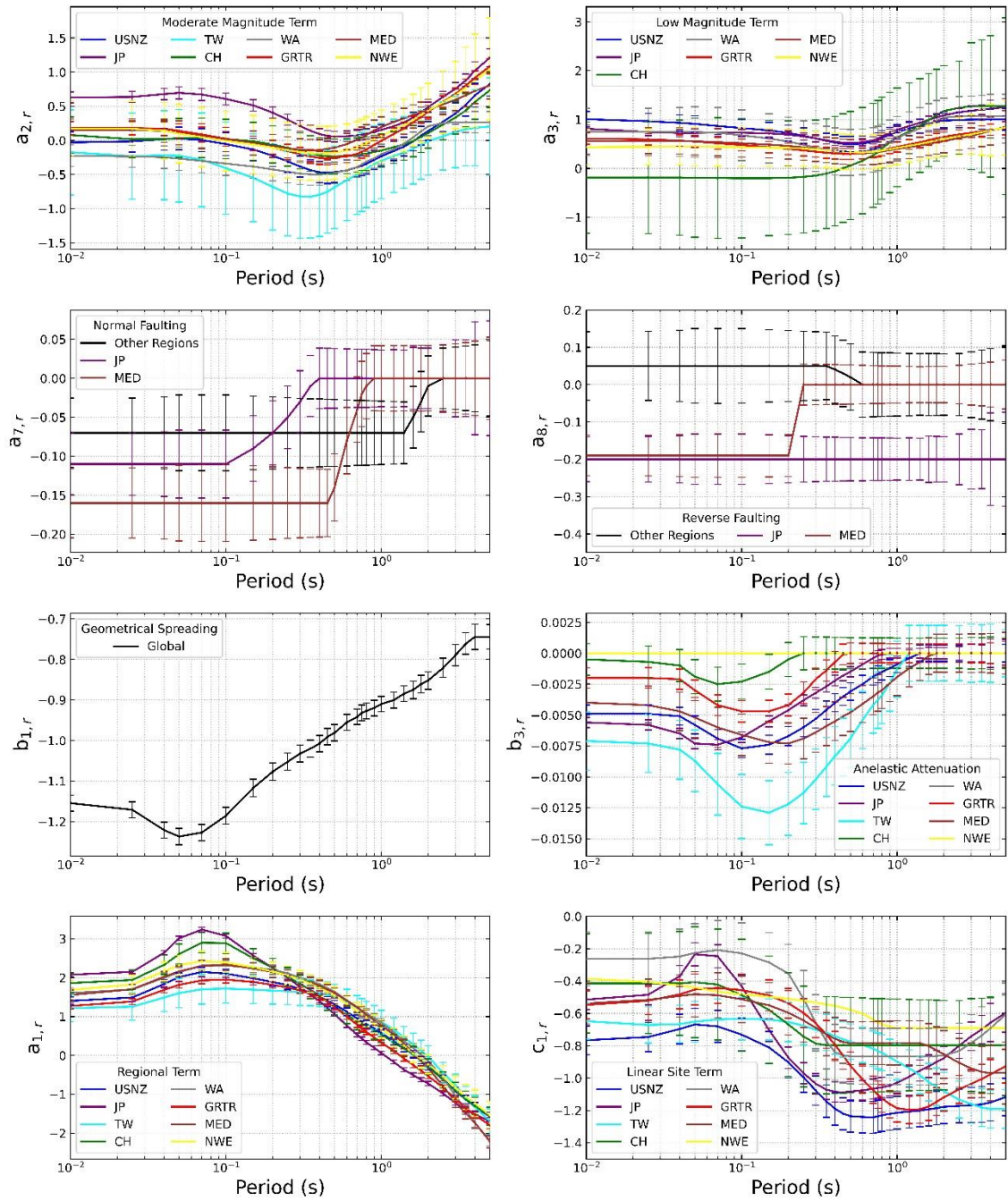


Figure 4.12. Regional parameters those are used to represent different tectonic behaviors for magnitude (first row), style of faulting (second row), distance (third row) terms, regional terms for each greater area (bottom left), and linear site term (bottom right).

4.6. Step III: Residual Analysis and the Heteroscedastic Variance Model

The residual distributions are shown in the left, middle, and right panels of 4.13. at 0.01s, 0.2s, and 1s periods, respectively. In addition, each parameter is divided into specific intervals, and the means and standard deviations of each interval are provided. Between-event residuals are given at the top of the figures. Although there is no predominant trend, between-event residuals of low to moderate magnitude earthquakes are highly scattered. The scatters of site-to-site residuals and single-site within-event residuals indicate the proposed model captures the observed data without any bias. The between-event variability component peaks near 0.1 s, and this effect is explained as possible interaction of varying stress drop and kappa term (Chiou and Youngs, 2014; Abrahamson and Gülerce, 2022). When regionalization is applied, this sharp peak near 0.1s is smoothed, since regional kappa and stress drop differences are included in GMPMs by corrections on the event term.

The standard deviations of the model are computed in Step II under the assumption of homoscedasticity. Preliminary analysis of the variances with homoscedastic assumption revealed that the between-event and single-site standard deviations strongly depend on magnitude. It is also observed that single-site standard deviation is distance-dependent. ϕ_{S2S} is computed for both V_{S30} and PSA_r bins.

A magnitude-dependent trilinear model is developed for the between event component (Figure 4.14.), which is constant below M_1 (τ_1) and above M_2 (τ_2). M_1 and M_2 are set to 5.5 and 6.75, respectively (top panel). The fixed limits were preferred for ease of computation and chosen to be valid for a wide range of periods. The standard deviation decreases linearly with increasing magnitude. Similarly, the magnitude and distance-dependent trilinear ϕ_{SS} is defined. ϕ_1 and ϕ_2 are the standard deviations for magnitudes smaller than 5.5 and greater than 6.75. ϕ_{SS} also decreases linearly in this range for periods up to 3s, after which it decreases with increasing magnitude (middle panel). The same trend is observed

by BSSA14 for the magnitude dependence of the within-event component. The distance-dependency of ϕ_{SS} (also given in the bottom panel of 4.14.) increases with increasing distance. This observation is valid up to 0.9s and does not change thereafter. Period-dependent R_1 and R_2 are the distance limits in which standard deviation is constant above or below.

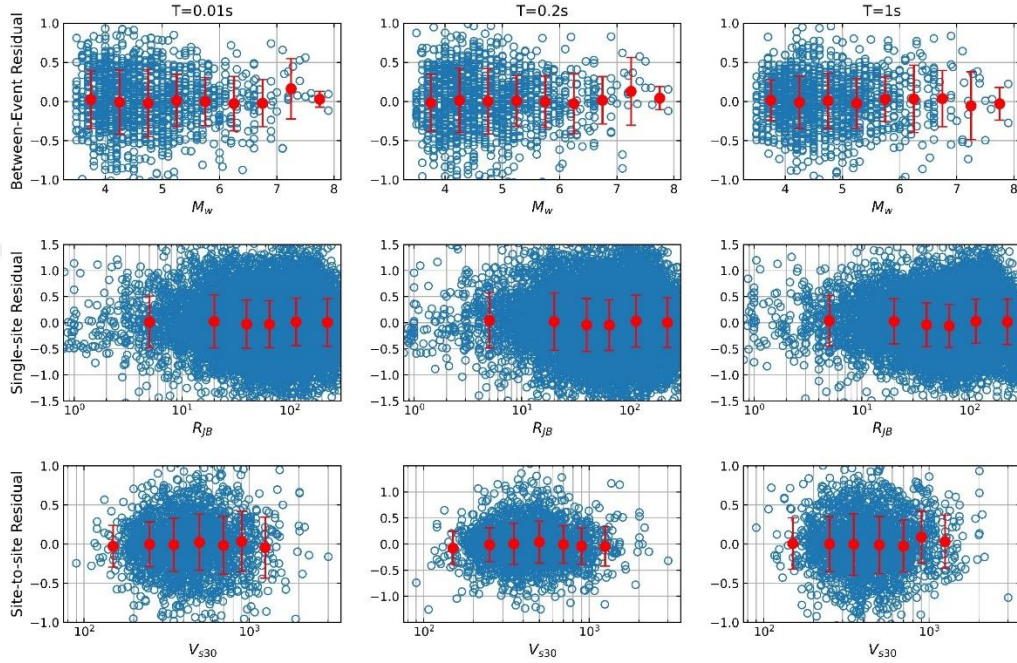


Figure 4.13. Between-event, single-site, and site-to-site residual distribution of developed model for three different periods. Error bars represent the mean and standard deviation of the mean binned residuals

We observed that the site-to-site standard deviation (ϕ_{SS}) is both V_{S30} and PSA_r dependent. To investigate the V_{S30} and PSA_r dependency of ϕ_{SS} , we grouped the site-to-site residuals by V_{S30} bins based on NEHRP 2020 site classes and PSA_r (from very weak to very strong amplitudes) bins. The boundaries of each bin are given in the caption of Figure 4.15. Then, the standard deviation of each bin is calculated. The left column of Figure 4.15. shows the V_{S30} dependence of ϕ_{SS} . The site-to-site standard deviation of Class B sites is usually lower than that of Class C sites. Then the variability starts to decrease as the sites become softer (except at class E & D sites). Thus, we consider capping the standard deviation below 200 m/s and above 600 m/s. These limits are assumed to be period-

independent because visual inspection of the data scatter does not reveal any systematic limits. In Figure 4.15. the PSA_r dependence of ϕ_{S2S} can be seen (right panel) for sites with $V_{S30} < 400$ m/s. The site amplification variability reduces when the PSA_r increases due to nonlinear site effects (Al Atik and Abrahamson, 2010). The study also constrained the standard deviations above and below the upper and lower limits of the PSA_r , similar to the approach taken for V_{S30} dependence. However, due to nonlinearity is controlled by the intensities, we employ period-dependent PSA_r values. 4.15., it can be seen that for each V_{S30} bin we use all ranges of PSA_r but we used the reduced V_{S30} values in PSA_r bins. This step is done for simplicity to understand the basic form of the standard deviation model. We performed mixed-effect regressions to compute the coefficients of the heteroscedastic site-to-site standard deviation model in which the V_{S30} and PSA_r are period-wise considered.

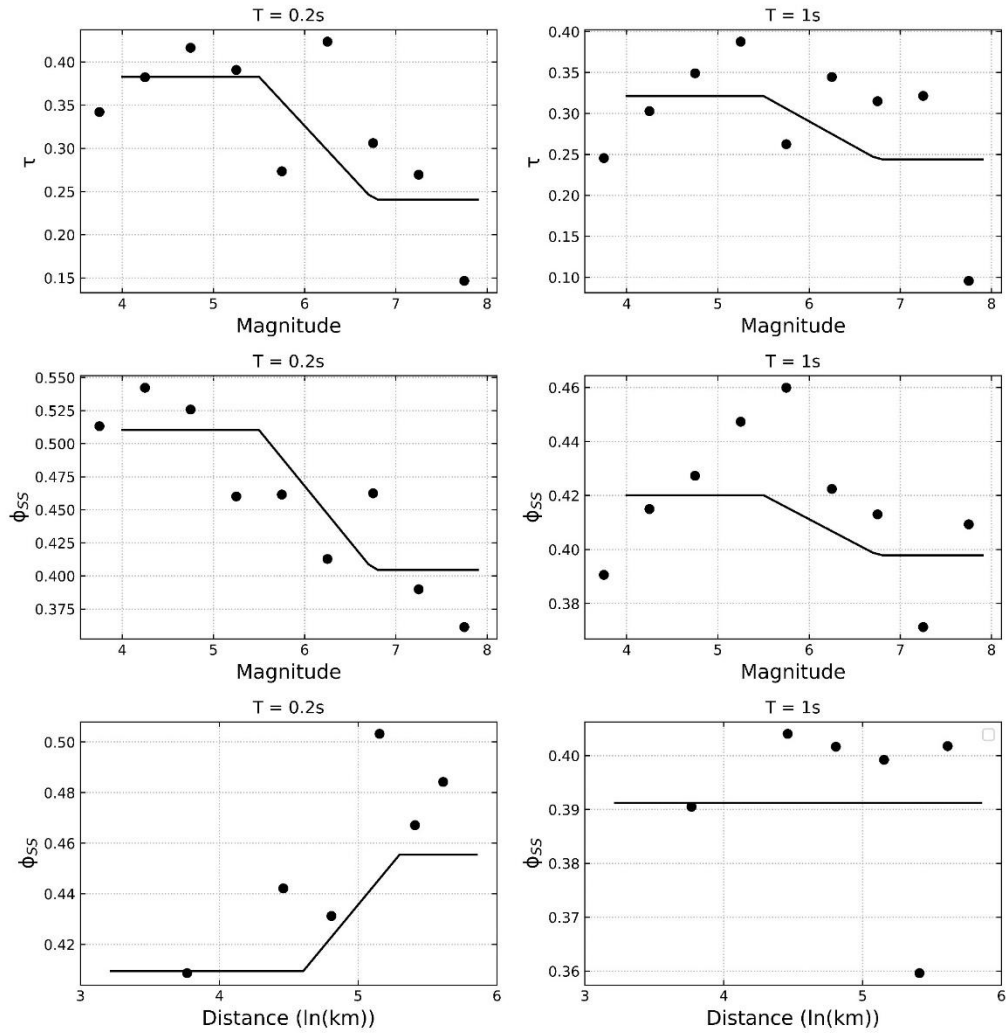


Figure 4.14. Magnitude-dependent heteroskedastic between-event (top) and single-site standard deviation (middle and bottom) for 0.2s (left) and 1s (right) periods.

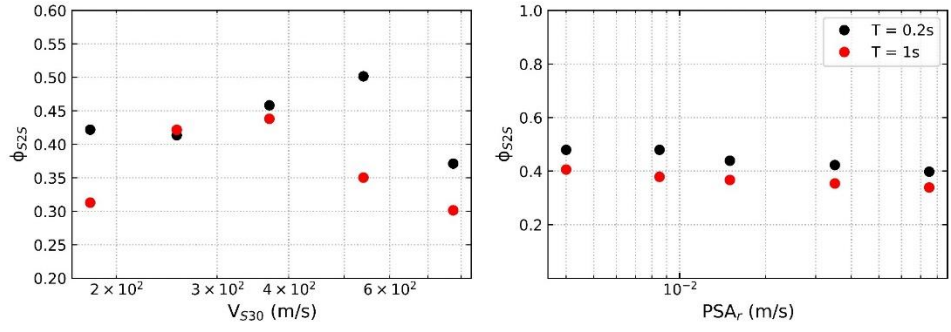


Figure 4.15. Site-to-site standard deviation for V_{S30} (left) and PSA_r (right) bins at $T = 0.2s$ and $1s$. The site groups for NEHRP site classes E, DE, D, CD, C and BC with the V_{S30} bins of ($V_{S30} \leq 150$ m/s), (150 m/s $\leq V_{S30} \leq 210$ m/s), (210 m/s $\leq V_{S30} \leq 440$ m/s), (440 m/s $\leq V_{S30} \leq 640$ m/s) and (640 m/s $\leq V_{S30} \leq 910$ m/s), respectively. Right panel shows PSA_r bins for very weak to strong motion.

The proposed standard deviation models for the τ and ϕ_{SS} components are compared with the Al-Atik et al. (2015; AA15 hereafter) and NGA West-2 variability models for shallow crustal earthquakes models in 4.16. The top panel shows the between-event standard deviation, and it is seen that the standard deviation peaks near $0.1s$ for all models. Note that AA15 uses a magnitude-dependent, period-independent constant standard deviation. The proposed model also peaks near $0.1s$ and decreases with an increasing period for the $M = 5$ (top left). The same peak is noticeable for the $M = 6.75$, and a similar trend is observed for the CB14 model with a lower standard deviation.

The bottom panel shows the single-site standard deviation for the proposed and AA15 variability models. Since the proposed model is distance- and magnitude-dependent, we used two scenarios to show the upper ($R_{JB} = 10$ km) and lower ($R_{JB} = 200$ km) bounds on the standard deviation. The AA15 model falls between the lower and upper period ranges of the model for $M = 5$ up to $0.7s$, after which two models show similar behavior. For $M = 7$, AA15 has the lowest values periods up to $0.7s$ and similar values are observed thereafter.

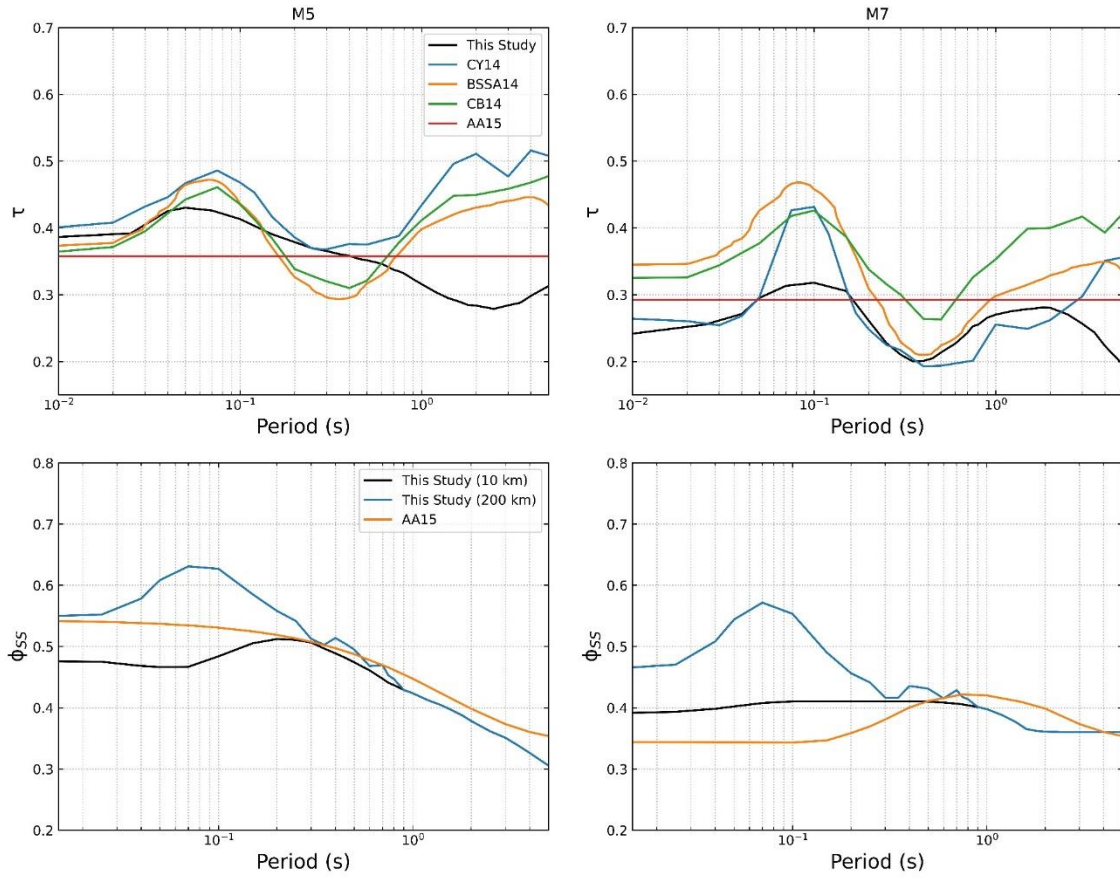


Figure 4.16. Comparison of between-event (top) and single-site variability (bottom) of CY14, BSSA14, CB14 and AA15 for the heteroscedastic standard deviation model for $M = 5$ (left panel) and $M = 7$ (right panel).

5. COMPARISONS WITH THE PREVIOUS MODELS

The median response spectra of our models are compared with the most commonly used GMPMs in Figure 5.1. We used two different distance and magnitude combinations M 6 R 100 km and M 7.2 R 15 km for a strike slip scenario at $V_{S30} = 760$ m /s in the first and second columns of Figure 5.1., respectively.

The first column shows the comparison of the USNZ with the NGA-West2 GMPMs (Abrahamson et al., 2014; Boore et al., 2014; Chiou and Youngs, 2014; Campbell and Bozorgnia, 2014 and Idriss et al., 2014). The proposed model gives lower estimations than the NGA-West2 GMPMs (except Idriss et al., 2014). We note here that the NGA-West2 database used in the GMPMs includes datasets from TW and CH, but we expressed the behavior of each region separately. We found that the regional term ($a_{1,r}$) of USNZ is lower than that of CH but higher than that of TW especially at shorter periods, and the separation of these regions leads to decrease in ground-motion intensity. It is seen that our model is higher than the NGA-West2 GMPMs for periods greater than 1s. The similar observations are also valid for high magnitude scenario. The second and third panels show the estimations of GMPMs for GRTR (Kale et al., 2015 for Turkey and Boore et al. 2021 for Greece) and Europe (Kotha et al., 2020, Bindi et al., 2014, Lanzano et al., 2019 and Akkar et al., 2014). The predictions for GRTR are similar to those of Boore et al. (2021) which is derived with a modification of BSSA14 using the earthquakes from Greece for moderate earthquake scenario. KAAH15 generally produces higher amplitudes at longer periods. For the high-magnitude scenario, the proposed model is consistent with both models, while after 1s, the estimations of proposed model lie between the two models. The difference between Kale et al. (2015) at the moderate magnitude at long periods and the lower ground-motion amplitudes at the high-magnitudes are attributed to the regional adjustments, since the behavior at high magnitudes is controlled by the regional coefficient, which is lower for GRTR, as can be shown in Figure 4.12. On the left side of the third row, it is seen that all models show similar behavior. Akkar et al. (2014) and the proposed model for MED (with lower amplitudes) differ

from the others with increasing period for both for moderate and high magnitude scenarios. MED is slightly lower than the others for the moderate magnitudes. Finally, the last row of Figure 5.1. shows the JP predictions compared to Zhao et al. (2016). Our predictions are generally lower in moderate-magnitude scenario whereas the opposite trend is observed at high-magnitude scenario.

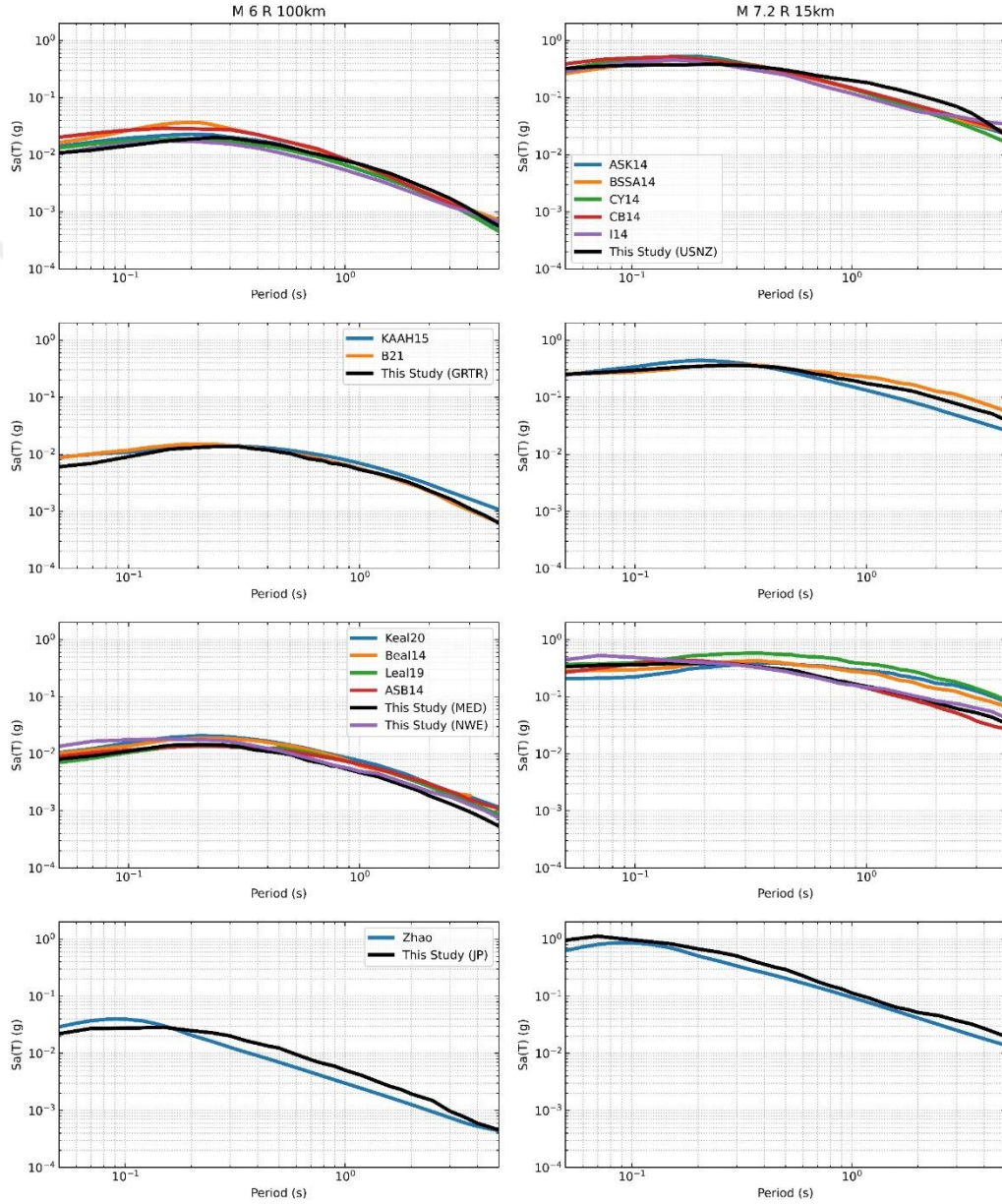


Figure 5.1. Comparison of median estimations for the USNZ (first row), GRTR (second row), EU, and MED and JP regions. Response spectra is estimated for a strike-slip earthquake at the rock ($V_{S30} = 760$ m/s) for two different magnitude-distance scenarios: R_{JB} distances of 100 km

and 15 km and **M** of 6 and 7.2 in the left and right panel of each row, respectively. (Abrahamson et al. 2014, ASK14; Cornell and Bozorgnia 2014, CB14; Idriss et al. 2014, I14; Kale et al. 2015, KAAH15; Boore et al. 2021, B21; Kotha et al. 2020, Keal20; Bindi et al. 2014, Beal14; Lanzano et al. 2019, Leal19; Akkar et al. 2014, ASB14; Zhao et al. 2016; Zhao)



6. DISCUSSIONS AND CONCLUSION

Using worldwide ground-motion collected from available databases, we proposed region-specific GMPMs for the shallow active crustal regions. We computed each coefficient in the mixed-effect regression algorithm instead of residual analysis. The proposed GMPMs emphasize regional differences in ground-motion amplitudes in terms of event, distance and site terms. The consistent predictions with global or local GMPMs prove the strength of the model which is developed in this study.

The findings of the study are summarized as follows:

- Examining the regional term ($a_{1,r}$), it is observed that the intensity of ground motions generated by events from JP is highest, especially at lower periods ($T < 0.3s$). This could be due to the different stress releases from JP events (Oth et al., 2013). Lanzano et al. (2019) observed higher intensity values for JP than in Italy. Our study found that the regional term for MED is lower than for JP.
- We observed that both normal and reverse event scalings are effective at short periods and are not noticeable at high periods except for reverse events in JP. The regional effects on style-of-faulting terms are significantly different for JP and MED than other regions.
- The trade-off between anelastic attenuation and geometrical spreading should be further studied in detail. Also we note that the difficulty in calculating the trade-off between two terms forces us to use a global geometrical spreading term and express all regional differences through the regional anelastic attenuation term.
- The site amplification characteristics are different for each region. A strong correlation is observed between two components of standard deviation (between-event and single-site standard deviations) and magnitude. As magnitude increases, τ decreases, and this trend is period independent.

On the contrary, the behavior of ϕ_{SS} reverses for longer periods. The single-site standard deviation model also includes a mild dependence on distance.

- We also observed a significant site-to-site standard deviation dependence on V_{S30} and PSA_r and expressed it as a function of V_{S30} and PSA_r . Site-to-site variability generally increases with V_{S30} and decreases with PSA_r due to soil nonlinearity.
- Regional corrections applied to the GMPMs reduce the peaks and valleys observed in τ and postulate that the origin of such behavior is due to either stress drop or kappa variations.
- The compilation procedure of each dataset involves differences in the processing of ground motions, distance computation, etc. This introduces additional uncertainty for the GMPMs. However, the region-specific adjustments reduce the degree of uncertainty related to the different procedures used in compiling the database. The variability is transferred into $a_{1,r}$ coefficient in the GMPM. The calculation of uncertainties regarding to using a non-uniform database should be studied later.

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APPENDICES

APPENDIX A- Model Coefficients

Table A.1. Regional coefficients

Periods	$a_{1,USNZ}$	$a_{1,JP}$	$a_{1,TW}$	$a_{1,CH}$	$a_{1,WA}$	$a_{1,GRTR}$	$a_{1,MED}$	$a_{1,NWE}$
0.01	1.402	2.076	1.217	1.861	1.609	1.271	1.555	1.686
0.025	1.490	2.150	1.255	1.942	1.696	1.386	1.702	1.824
0.04	1.836	2.641	1.489	2.328	1.999	1.688	2.024	2.164
0.05	2.015	3.012	1.604	2.607	2.140	1.817	2.163	2.324
0.07	2.148	3.237	1.702	2.900	2.315	1.929	2.297	2.426
0.1	2.105	3.075	1.719	2.890	2.311	1.950	2.339	2.389
0.15	1.983	2.566	1.691	2.500	2.258	1.891	2.235	2.269
0.2	1.888	2.251	1.667	2.253	2.205	1.815	2.145	2.158
0.25	1.809	2.002	1.651	2.026	2.110	1.747	2.058	2.056
0.3	1.707	1.759	1.623	1.835	2.002	1.672	1.958	1.952
0.35	1.608	1.558	1.612	1.686	1.919	1.583	1.875	1.847
0.4	1.513	1.395	1.588	1.538	1.832	1.489	1.793	1.740
0.45	1.414	1.214	1.550	1.386	1.728	1.377	1.695	1.639
0.5	1.316	1.067	1.505	1.267	1.639	1.248	1.608	1.536
0.6	1.123	0.766	1.376	1.038	1.422	0.999	1.403	1.331
0.7	0.948	0.530	1.225	0.876	1.245	0.786	1.232	1.137
0.75	0.876	0.431	1.152	0.812	1.154	0.688	1.134	1.058
0.8	0.808	0.335	1.082	0.757	1.095	0.608	1.050	0.964
0.9	0.694	0.198	0.980	0.635	0.964	0.460	0.905	0.814
1	0.580	0.062	0.859	0.545	0.841	0.330	0.769	0.682
1.2	0.365	-0.166	0.672	0.328	0.599	0.118	0.541	0.466
1.4	0.184	-0.368	0.461	0.179	0.366	-0.079	0.299	0.258
1.6	0.029	-0.503	0.287	0.027	0.196	-0.246	0.084	0.051
1.8	-0.123	-0.626	0.117	-0.138	0.016	-0.390	-0.143	-0.083
2	-0.279	-0.722	-0.028	-0.290	-0.138	-0.530	-0.327	-0.228
2.5	-0.609	-0.982	-0.450	-0.633	-0.591	-0.827	-0.789	-0.531
3	-0.921	-1.220	-0.767	-0.907	-1.041	-1.122	-1.202	-0.821
3.5	-1.134	-1.393	-1.089	-1.134	-1.401	-1.356	-1.493	-1.061
4	-1.325	-1.522	-1.331	-1.300	-1.734	-1.536	-1.731	-1.228
5	-1.574	-1.689	-1.695	-1.562	-2.201	-1.796	-2.215	-1.540

Table A.2. Regional moderate magnitude coefficients

Periods	$a_{2,USNZ}$	$a_{2,JP}$	$a_{2,TW}$	$a_{2,CH}$	$a_{2,WA}$	$a_{2,GRTR}$	$a_{2,MED}$	$a_{2,NWE}$
0.01	-0.0305	0.6276	-0.1742	0.0786	-0.2248	0.1788	0.1493	0.175
0.025	-0.0145	0.6366	-0.2317	0.0168	-0.2351	0.1788	0.1493	0.1705
0.04	0.018	0.678	-0.2178	0.0188	-0.2467	0.1731	0.143	0.1422
0.05	0.0285	0.6964	-0.2249	0.034	-0.2679	0.1389	0.1114	0.0986
0.07	0.0038	0.6722	-0.2848	0.0375	-0.3	0.0863	0.0653	0.0469
0.1	-0.0538	0.607	-0.4059	0.021	-0.3401	0.0241	0.0134	-0.0072
0.15	-0.1339	0.5131	-0.5484	-0.0135	-0.3834	-0.041	-0.0374	-0.059
0.2	-0.2234	0.4065	-0.6808	-0.0596	-0.4248	-0.1032	-0.0818	-0.1052
0.25	-0.3096	0.3021	-0.7791	-0.1094	-0.4598	-0.1583	-0.1163	-0.143
0.3	-0.3825	0.2112	-0.8205	-0.1555	-0.485	-0.2033	-0.1385	-0.1707
0.35	-0.4358	0.1406	-0.8238	-0.193	-0.4984	-0.2361	-0.1471	-0.1875
0.4	-0.4666	0.0926	-0.7966	-0.2191	-0.4993	-0.2555	-0.1421	-0.1929
0.45	-0.4754	0.0659	-0.7524	-0.2331	-0.4884	-0.2612	-0.1242	-0.1871
0.5	-0.4649	0.0566	-0.686	-0.2364	-0.4767	-0.2533	-0.1046	-0.1808
0.6	-0.4392	0.0603	-0.5804	-0.2312	-0.436	-0.2326	-0.0552	-0.1448
0.7	-0.3924	0.0731	-0.5027	-0.2132	-0.3895	-0.1974	0.0116	-0.1044
0.75	-0.3702	0.0833	-0.4627	-0.1989	-0.3523	-0.1662	0.0419	-0.0746
0.8	-0.3442	0.095	-0.4133	-0.1945	-0.311	-0.1344	0.0789	-0.0375
0.9	-0.2852	0.1232	-0.3438	-0.1687	-0.2624	-0.0632	0.1471	0.0162
1	-0.2329	0.1545	-0.3003	-0.1484	-0.2032	-0.0063	0.1947	0.066
1.2	-0.1555	0.2066	-0.2275	-0.0995	-0.1313	0.0932	0.2701	0.1512
1.4	-0.0906	0.2628	-0.1794	-0.0581	-0.0476	0.1765	0.3229	0.2217
1.6	-0.016	0.3353	-0.1221	-0.0112	0.0432	0.2656	0.3732	0.2974
1.8	0.0698	0.414	-0.0648	0.0515	0.132	0.3402	0.4123	0.3685
2	0.1374	0.4866	-0.011	0.1078	0.2063	0.4203	0.4528	0.4356
2.5	0.2758	0.6388	0.0616	0.2335	0.2535	0.5666	0.5287	0.5599
3	0.3938	0.7567	0.1228	0.3343	0.2664	0.6802	0.5955	0.6628
3.5	0.5208	0.8807	0.1637	0.4402	0.2664	0.8029	0.6607	0.7763
4	0.6605	1.0219	0.1843	0.5627	0.2664	0.9173	0.7237	0.8731
5	0.825	1.2126	0.2036	0.7354	0.2664	1.0867	0.8059	1.0464

Table A.3. Regional moderate magnitude coefficients

Periods	$a_{3,USNZ}$	$a_{3,JP}$	$a_{3,CH}$	$a_{3,WA}$	$a_{3,GRTR}$	$a_{3,MED}$	$a_{3,NWE}$	$a_{5,JP}$	$a_{5,Other}$
0.01	1.0072	0.8116	-0.1874	0.7448	0.6102	0.5535	0.4342	1.0072	0.8116
0.025	0.9639	0.7439	-0.1874	0.7448	0.5937	0.5646	0.4403	0.9639	0.7439
0.04	0.9314	0.7241	-0.1874	0.7448	0.5691	0.564	0.4474	0.9314	0.7241
0.05	0.911	0.7259	-0.1912	0.7448	0.5487	0.5539	0.4464	0.911	0.7259
0.07	0.8668	0.7314	-0.197	0.729	0.5145	0.5365	0.4401	0.8668	0.7314
0.1	0.8259	0.7297	-0.2011	0.6761	0.4787	0.5137	0.4337	0.8259	0.7297
0.15	0.7776	0.7159	-0.2002	0.6135	0.4329	0.4873	0.4239	0.7776	0.7159
0.2	0.7236	0.6896	-0.192	0.5476	0.3989	0.4592	0.4192	0.7236	0.6896
0.25	0.6672	0.6539	-0.1745	0.4837	0.3679	0.4308	0.4092	0.6672	0.6539
0.3	0.6126	0.6138	-0.1465	0.4265	0.3413	0.4036	0.3948	0.6126	0.6138
0.35	0.5643	0.5752	-0.1074	0.3796	0.3201	0.379	0.379	0.5643	0.5752
0.4	0.5266	0.5439	-0.057	0.3459	0.3051	0.3579	0.3579	0.5266	0.5439
0.45	0.503	0.5246	0.0045	0.3274	0.297	0.3415	0.3415	0.503	0.5246
0.5	0.4959	0.521	0.0564	0.3253	0.2963	0.3305	0.3305	0.4959	0.521
0.6	0.5063	0.5346	0.1578	0.3402	0.303	0.3255	0.3255	0.5063	0.5346
0.7	0.5453	0.5731	0.2666	0.3785	0.3284	0.3287	0.3387	0.5453	0.5731
0.75	0.5792	0.6094	0.3299	0.4078	0.3434	0.336	0.3495	0.5792	0.6094
0.8	0.6235	0.6546	0.4118	0.4526	0.3644	0.3488	0.3666	0.6235	0.6546
0.9	0.694	0.7359	0.5309	0.5503	0.4102	0.3714	0.3908	0.694	0.7359
1	0.7462	0.7905	0.6351	0.6274	0.4396	0.3979	0.41875	0.7462	0.7905
1.2	0.8159	0.8664	0.7619	0.7295	0.4913	0.4376	0.46445	0.8159	0.8664
1.4	0.8698	0.9319	0.8777	0.8217	0.5339	0.4698	0.50185	0.8698	0.9319
1.6	0.9154	0.995	0.9886	0.9083	0.5764	0.5041	0.54025	0.9154	0.995
1.8	0.9513	1.0437	1.0897	0.9828	0.6177	0.5305	0.5741	0.9513	1.0437
2	0.9765	1.0856	1.1751	1.0384	0.6471	0.5592	0.60315	0.9765	1.0856
2.5	0.9903	1.1483	1.2383	1.0672	0.6941	0.6209	0.6575	0.9903	1.1483
3	0.9985	1.1801	1.2715	1.0672	0.7285	0.6667	0.6976	0.9985	1.1801
3.5	1	1.2022	1.2715	1.0672	0.7605	0.7187	0.7396	1	1.2022
4	1	1.2209	1.2715	1.0672	0.791	0.7693	0.78015	1	1.2209
5	1	1.2532	1.2715	1.0672	0.8211	0.8517	0.8364	1	1.2532

Table A.4. Regional depth, style of faulting and magnitude dependent geometrical spreading coefficients

Periods	a_6	$a_{7,JP}$	$a_{7,MED}$	$a_{7,Others}$	$a_{8,JP}$	$a_{8,MED}$	$a_{8,Others}$	$b_{2,JP}$	$b_{2,Others}$
0.01	0.0418	-0.11	-0.16	-0.07	-0.2	-0.19	0.05	0.1	0.2
0.025	0.0422	-0.11	-0.16	-0.07	-0.2	-0.19	0.05	0.1	0.2
0.04	0.0432	-0.11	-0.16	-0.07	-0.2	-0.19	0.05	0.1	0.2
0.05	0.044	-0.11	-0.16	-0.07	-0.2	-0.19	0.05	0.1	0.2
0.07	0.0447	-0.11	-0.16	-0.07	-0.2	-0.19	0.05	0.1	0.2
0.1	0.0443	-0.11	-0.16	-0.07	-0.2	-0.19	0.05	0.1	0.2
0.15	0.0429	-0.09	-0.16	-0.07	-0.2	-0.19	0.05	0.1	0.2
0.2	0.0412	-0.07	-0.16	-0.07	-0.2	-0.19	0.05	0.1	0.2
0.25	0.0397	-0.05	-0.16	-0.07	-0.2	0	0.05	0.1	0.2
0.3	0.03815	-0.03	-0.16	-0.07	-0.2	0	0.05	0.1	0.2
0.35	0.0366	-0.01	-0.16	-0.07	-0.2	0	0.05	0.1	0.2
0.4	0.03505	0	-0.16	-0.07	-0.2	0	0.04	0.1	0.2
0.45	0.0335	0	-0.16	-0.07	-0.2	0	0.03	0.1	0.2
0.5	0.03195	0	-0.14	-0.07	-0.2	0	0.02	0.1	0.2
0.6	0.029	0	-0.08	-0.07	-0.2	0	0	0.1	0.2
0.7	0.02635	0	-0.04	-0.07	-0.2	0	0	0.1	0.2
0.75	0.0253	0	-0.02	-0.07	-0.2	0	0	0.1	0.2
0.8	0.0242	0	-0.01	-0.07	-0.2	0	0	0.1	0.2
0.9	0.0225	0	0	-0.07	-0.2	0	0	0.1	0.2
1	0.0205	0	0	-0.07	-0.2	0	0	0.1	0.2
1.2	0.0168	0	0	-0.07	-0.2	0	0	0.1	0.2
1.4	0.013	0	0	-0.07	-0.2	0	0	0.1	0.2
1.6	0.009	0	0	-0.05	-0.2	0	0	0.1	0.2
1.8	0.0045	0	0	-0.03	-0.2	0	0	0.1	0.2
2	0.0004	0	0	-0.01	-0.2	0	0	0.1	0.2
2.5	0	0	0	0	-0.2	0	0	0.1	0.2
3	0	0	0	0	-0.2	0	0	0.1	0.2
3.5	0	0	0	0	-0.2	0	0	0.1	0.2
4	0	0	0	0	-0.2	0	0	0.1	0.2
5	0	0	0	0	-0.2	0	0	0.1	0.2

Table A.5. Regional distance coefficients

Periods	b_1	$b_{1,USNZ}$	$b_{1,JP}$	$b_{1,TW}$	$b_{1,CH}$	$b_{1,WA}$	$b_{1,GRTR}$	$b_{1,MED}$	$b_{1,NWE}$
0.01	-1.1545	-0.0049	-0.0056	-0.0071	-0.0005	0	-0.002	-0.004	0
0.025	-1.1709	-0.0049	-0.0058	-0.0073	-0.0007	0	-0.002	-0.0042	0
0.04	-1.221	-0.0051	-0.0065	-0.0078	-0.001	0	-0.0021	-0.0047	0
0.05	-1.237	-0.0058	-0.0073	-0.0087	-0.0019	0	-0.003	-0.0052	0
0.07	-1.2269	-0.0069	-0.0074	-0.0106	-0.0025	0	-0.0042	-0.006	0
0.1	-1.1856	-0.0077	-0.0068	-0.0124	-0.0023	0	-0.0047	-0.0066	0
0.15	-1.117	-0.0074	-0.0055	-0.0129	-0.0015	0	-0.0047	-0.0072	0
0.2	-1.0769	-0.0067	-0.0046	-0.0122	-0.0005	0	-0.0042	-0.0073	0
0.25	-1.0522	-0.006	-0.0038	-0.0113	0	0	-0.0032	-0.0069	0
0.3	-1.0322	-0.0053	-0.0032	-0.0102	0	0	-0.0021	-0.0064	0
0.35	-1.0201	-0.0046	-0.0027	-0.0092	0	0	-0.0014	-0.0059	0
0.4	-1.0077	-0.004	-0.0022	-0.0083	0	0	-0.0007	-0.0055	0
0.45	-0.9907	-0.0035	-0.0018	-0.0076	0	0	-0.0001	-0.0051	0
0.5	-0.9809	-0.0031	-0.0015	-0.0069	0	0	0	-0.0048	0
0.6	-0.9553	-0.0025	-0.0009	-0.0054	0	0	0	-0.0041	0
0.7	-0.9416	-0.0019	-0.0004	-0.0042	0	0	0	-0.0035	0
0.75	-0.9317	-0.0017	-0.0002	-0.0038	0	0	0	-0.0032	0
0.8	-0.9271	-0.0015	-0.0001	-0.0034	0	0	0	-0.00298	0
0.9	-0.9196	-0.0012	0	-0.0024	0	0	0	-0.00242	0
1	-0.91	-0.0009	0	-0.0013	0	0	0	-0.00192	0
1.2	-0.9005	-0.0004	0	0	0	0	0	-0.00122	0
1.4	-0.8844	0	0	0	0	0	0	-0.00072	0
1.6	-0.8751	0	0	0	0	0	0	-0.00022	0
1.8	-0.8611	0	0	0	0	0	0	0	0
2	-0.8519	0	0	0	0	0	0	0	0
2.5	-0.8206	0	0	0	0	0	0	0	0
3	-0.7895	0	0	0	0	0	0	0	0
3.5	-0.761	0	0	0	0	0	0	0	0
4	-0.7442	0	0	0	0	0	0	0	0
5	-0.7442	0	0	0	0	0	0	0	0

Table A.6. Regional linear site coefficients

Periods	$c_{1,USNZ}$	$c_{1,JP}$	$c_{1,TW}$	$c_{1,CH}$	$c_{1,WA}$	$c_{1,GRTR}$	$c_{1,MED}$	$c_{1,NWE}$
0.01	-0.766	-0.5148	-0.6483	-0.4143	-0.2626	-0.5475	-0.5388	-0.3858
0.025	-0.7462	-0.4849	-0.6714	-0.4143	-0.2626	-0.5215	-0.516	-0.4063
0.04	-0.6964	-0.3696	-0.6663	-0.4143	-0.2483	-0.4821	-0.4922	-0.427
0.05	-0.6683	-0.2344	-0.6511	-0.4072	-0.2262	-0.4524	-0.4813	-0.4398
0.07	-0.6803	-0.2467	-0.6376	-0.4213	-0.2084	-0.4428	-0.4882	-0.4653
0.1	-0.7314	-0.4329	-0.6324	-0.4874	-0.2286	-0.4558	-0.5124	-0.482
0.15	-0.8104	-0.703	-0.6379	-0.5776	-0.2849	-0.4888	-0.5501	-0.4969
0.2	-0.9028	-0.8745	-0.6533	-0.6691	-0.3542	-0.5375	-0.5958	-0.5101
0.25	-0.9952	-0.9693	-0.6759	-0.7428	-0.5102	-0.5967	-0.644	-0.522
0.3	-1.0773	-1.035	-0.702	-0.7866	-0.6584	-0.6618	-0.6895	-0.533
0.35	-1.143	-1.0707	-0.7182	-0.7967	-0.7712	-0.7291	-0.7282	-0.5436
0.4	-1.1902	-1.0856	-0.7415	-0.7967	-0.8412	-0.7961	-0.7576	-0.5543
0.45	-1.2199	-1.0878	-0.7604	-0.7967	-0.8596	-0.8611	-0.7762	-0.5655
0.5	-1.2353	-1.0835	-0.7745	-0.7967	-0.8648	-0.9229	-0.7844	-0.5778
0.6	-1.2404	-1.0754	-0.7952	-0.7967	-0.8648	-1.0091	-0.7833	-0.6013
0.7	-1.2427	-1.067	-0.8176	-0.7967	-0.8648	-1.0723	-0.7833	-0.6381
0.75	-1.237	-1.0607	-0.832	-0.7967	-0.8648	-1.1022	-0.7833	-0.6546
0.8	-1.2294	-1.0576	-0.8433	-0.7967	-0.8648	-1.126	-0.7833	-0.6668
0.9	-1.2216	-1.0457	-0.8723	-0.7967	-0.8648	-1.1614	-0.7833	-0.6826
1	-1.2141	-1.0287	-0.8983	-0.7967	-0.8648	-1.1857	-0.7833	-0.6903
1.2	-1.2071	-0.9906	-0.9391	-0.7967	-0.8648	-1.1967	-0.7833	-0.6903
1.4	-1.2001	-0.9535	-0.9822	-0.7967	-0.868	-1.1931	-0.7833	-0.6903
1.6	-1.1928	-0.9263	-1.0249	-0.7967	-0.867	-1.1753	-0.802	-0.6903
1.8	-1.1853	-0.8997	-1.0548	-0.7967	-0.8634	-1.1457	-0.8298	-0.6903
2	-1.178	-0.8762	-1.0809	-0.7967	-0.8604	-1.1187	-0.8529	-0.6903
2.5	-1.1719	-0.8011	-1.1328	-0.7967	-0.8324	-1.0701	-0.9052	-0.6903
3	-1.1672	-0.741	-1.1604	-0.7967	-0.7828	-1.0351	-0.94	-0.6903
3.5	-1.1622	-0.6999	-1.1819	-0.7967	-0.7372	-1.0059	-0.9619	-0.6903
4	-1.1505	-0.6564	-1.1908	-0.7967	-0.691	-0.9764	-0.9692	-0.6903
5	-1.1172	-0.597	-1.1908	-0.7967	-0.606	-0.9261	-0.9679	-0.6903

Table A.7. Site coefficients

Periods	c_2	c_3	c_4	c_5	Vc
0.01	-0.178	-0.008	0.146	0	1418
0.025	-0.191	-0.008	0.171	0	1407
0.04	-0.219	-0.008	0.181	0	1395
0.05	-0.256	-0.007	0.192	0	1388
0.07	-0.301	-0.007	0.228	0	1373
0.1	-0.321	-0.007	0.271	0	1352
0.15	-0.312	-0.007	0.319	0	1318
0.2	-0.29	-0.007	0.29	0	1256
0.25	-0.27	-0.008	0.25	0	1200
0.3	-0.246	-0.008	0.215	0	1138
0.35	-0.225	-0.008	0.186	0.0020	1085
0.4	-0.205	-0.008	0.163	0.0031	1047
0.45	-0.183	-0.009	0.15	0.0035	1016
0.5	-0.164	-0.009	0.141	0.0038	989
0.6	-0.136	-0.009	0.125	0.0038	945
0.7	-0.112	-0.009	0.11	0.0039	912
0.75	-0.102	-0.009	0.104	0.0038	899
0.8	-0.093	-0.009	0.099	0.0038	888
0.9	-0.077	-0.009	0.089	0.0040	872
1	-0.066	-0.009	0.081	0.0040	862
1.2	-0.051	-0.009	0.066	0.0042	855
1.4	-0.038	-0.008	0.052	0.0047	850
1.6	-0.03	-0.007	0.04	0.0057	845
1.8	-0.026	-0.006	0.033	0.0069	840
2	-0.02	-0.004	0.027	0.0080	835
2.5	-0.013	-0.003	0.019	0.0099	830
3	-0.008	-0.002	0.015	0.0114	810
3.5	0	-0.002	0.011	0.0127	800
4	0	-0.002	0.008	0.0136	780
5	0	-0.001	0.007	0.0139	760

Table A.8. Between-event and single-site within-event standard deviation coefficients

Periods	τ_1	τ_2	ϕ_1	ϕ_2	R_1	R_2	$\Delta\phi_R$
0.01	0.3865	0.2417	0.4765	0.3903	100	200	0.072
0.025	0.3919	0.2552	0.4751	0.3934	100	200	0.077
0.04	0.4253	0.2712	0.4683	0.3983	100	200	0.11
0.05	0.4302	0.2952	0.4665	0.4021	100	200	0.142
0.07	0.4261	0.3133	0.4669	0.4077	100	200	0.164
0.1	0.4133	0.3179	0.484	0.4104	100	200	0.143
0.15	0.3906	0.3056	0.5053	0.4104	100	200	0.08
0.2	0.3788	0.2612	0.5122	0.4104	100	200	0.046
0.25	0.3696	0.2279	0.5108	0.4104	100	200	0.031
0.3	0.3654	0.2102	0.5066	0.4104	100	200	0.006
0.35	0.361	0.2002	0.4967	0.4104	100	200	0.006
0.4	0.3583	0.2009	0.4889	0.4104	120	220	0.025
0.45	0.3537	0.2048	0.4815	0.4104	120	220	0.023
0.5	0.3516	0.2135	0.4742	0.41	120	220	0.021
0.6	0.3466	0.2269	0.461	0.4084	120	220	0.007
0.7	0.3375	0.243	0.4474	0.4067	120	225	0.022
0.75	0.3351	0.253	0.4408	0.4055	120	225	0.012
0.8	0.3319	0.255	0.4369	0.404	120	225	0.01
0.9	0.3232	0.2656	0.4292	0.4011	120	225	0
1	0.3159	0.2701	0.4237	0.3978	120	225	0
1.2	0.3037	0.2749	0.4123	0.388	120	225	0
1.4	0.295	0.2775	0.4043	0.3773	120	225	0
1.6	0.29	0.27915	0.3957	0.3652	120	225	0
1.8	0.2847	0.2808	0.3874	0.3622	110	200	0
2	0.2837	0.28045	0.3784	0.361	110	200	0
2.5	0.2788	0.2704	0.3617	0.3601	100	200	0
3	0.2841	0.2566	0.351	0.3601	100	200	0
3.5	0.288	0.2436	0.3381	0.3601	100	200	0
4	0.2983	0.2234	0.3263	0.3601	100	200	0
5	0.3129	0.1959	0.3056	0.3601	100	200	0

Table A.8. Site-to-site standard deviation coefficients

Periods	d_0	d_1	d_2	PSA_{r_upp}	PSA_{r_low}
0.01	0	0.0531	0.059	0.00075	0.15
0.025	0	0.0571	0.0545	0.00075	0.16
0.04	0	0.0632	0.0532	0.00075	0.17
0.05	0	0.0695	0.0659	0.00075	0.18
0.07	0	0.071	0.0658	0.00075	0.19
0.1	0	0.0727	0.0715	0.00075	0.2
0.15	0	0.0664	0.0678	0.00075	0.22
0.2	0	0.059	0.0647	0.00075	0.3
0.25	0	0.0557	0.0597	0.00075	0.25
0.3	0	0.0529	0.0549	0.00075	0.2
0.35	0	0.0531	0.0516	0.00075	0.19
0.4	0	0.0554	0.0476	0.00075	0.18
0.45	0.1543	0.0515	0.0412	0.00075	0.17
0.5	0.1535	0.0534	0.0373	0.00075	0.16
0.6	0.0928	0.061	0.0294	0.00075	0.155
0.7	0.4004	0.0002	0.0198	0.00075	0.15
0.75	0.305	0.0445	0.0205	0.00075	0.15
0.8	0.3306	0.0401	0.0196	0.00075	0.15
0.9	0.4246	0	0.0143	0.00075	0.15
1	0.4271	0.0138	0.0105	0.00075	0.15
1.2	0.3305	0.0503	0.0048	0.00075	0.15
1.4	0.3761	0.0428	0	0.00075	0.15
1.6	0.4677	0	0.006	0.00075	0.15
1.8	0.4006	0.0425	0	0.00075	0.15
2	0.4825	0	0	0.00075	0.15
2.5	0.3025	0.062	0	0.00075	0.15
3	0.485	0	0	0.00075	0.15
3.5	0.4765	0	0	0.00075	0.15
4	0.4495	0	0.0198	0.00075	0.15
5	0.4508	0	0.0317	0.00075	0.15

APPENDIX B- Site Amplification Model

Comparison of V_{S30} And PS_{Ar} Scaling With Choi And Youngs (2014)

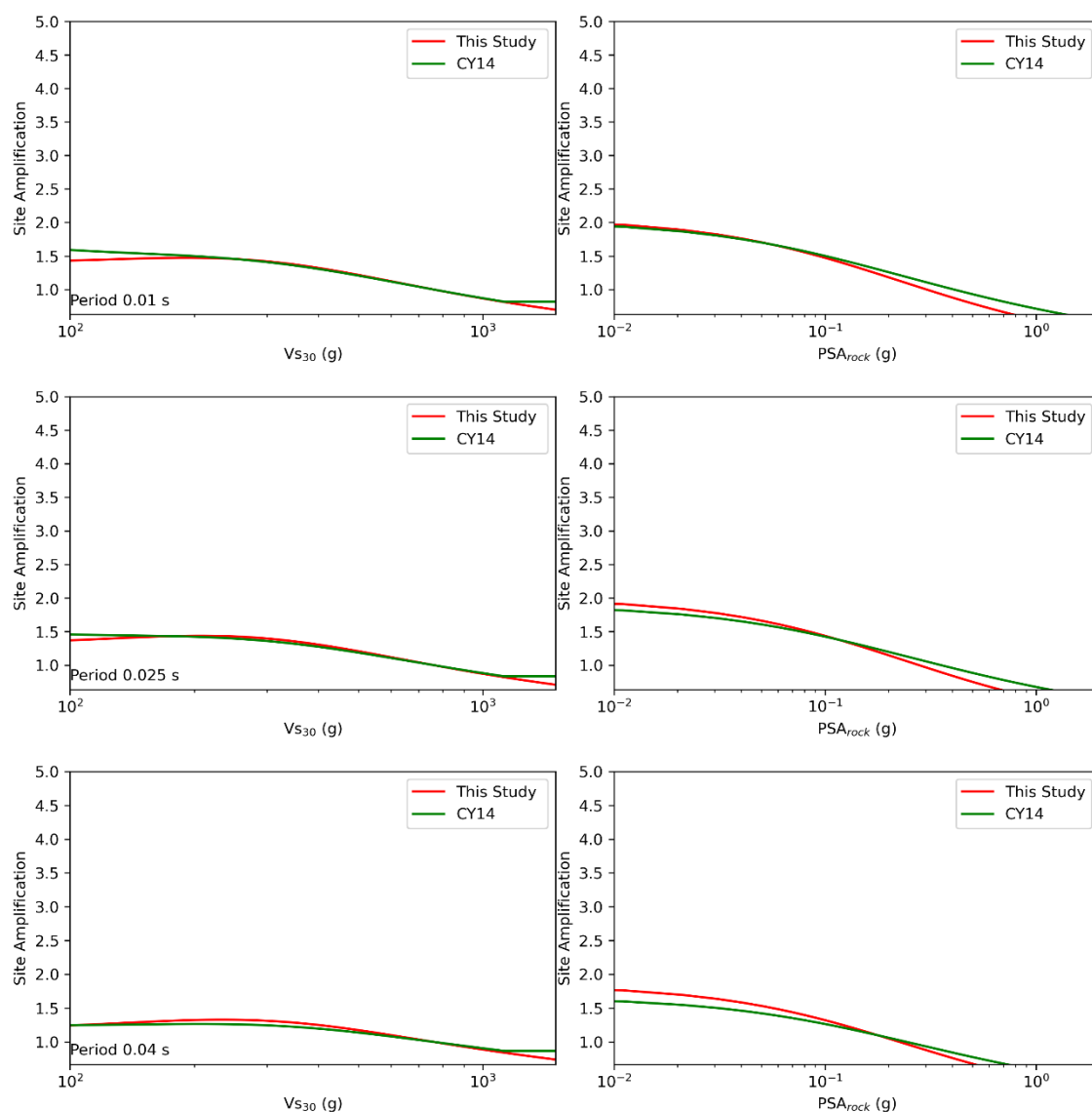


Figure B.1. Site amplification model comparisons with Choi and Youngs (1994) of the V_{S30} (left) PS_{Ar} (right) scalings for 0.01s (top), 0.025s (middle) and 0.04s (bottom).

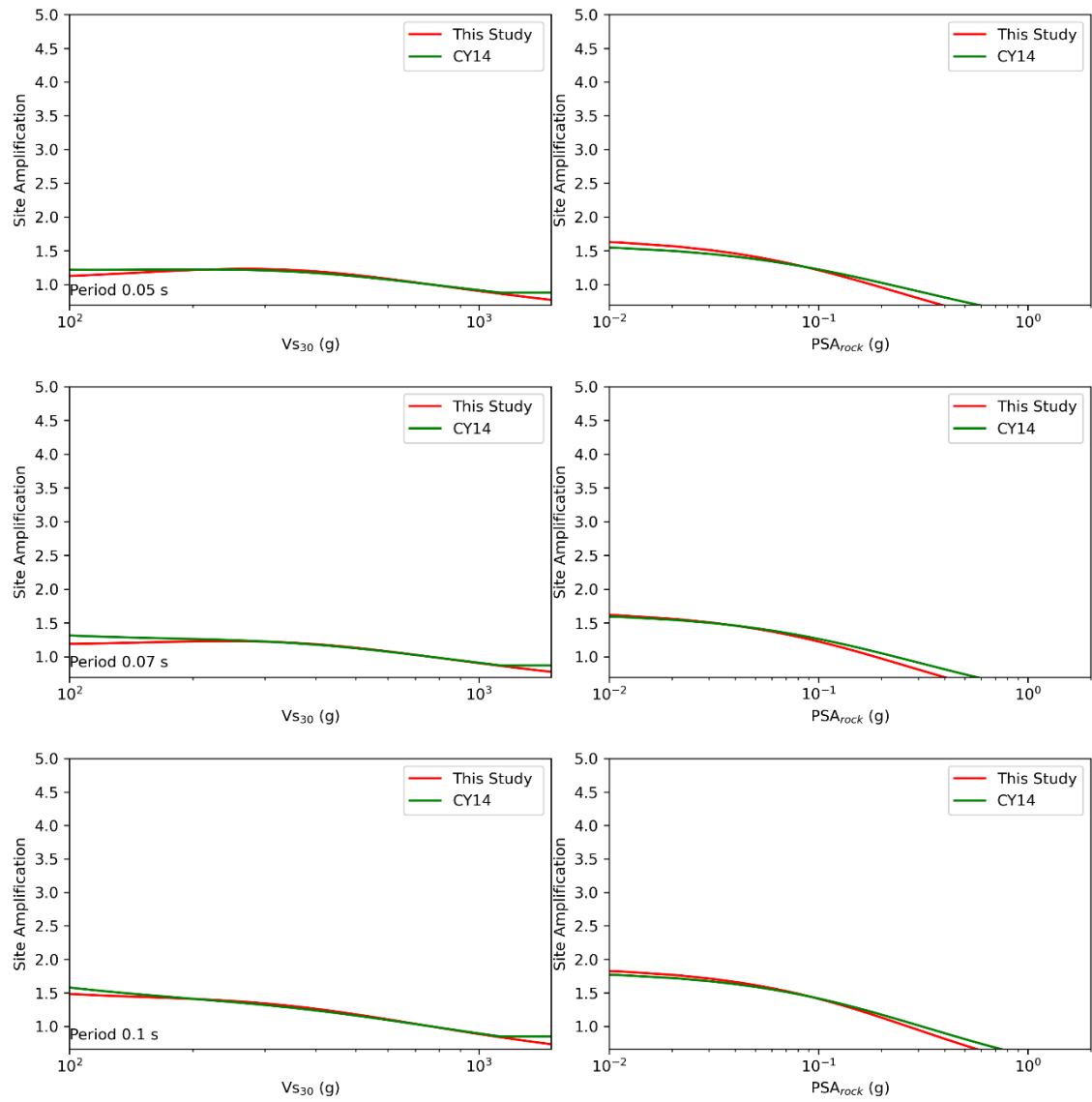


Figure B.2. Site amplification model comparisons with Choi and Youngs (1994) of the V_{s30} (left) PSA_r (right) scalings for 0.05s (top), 0.07s (middle) and 0.1s (bottom).

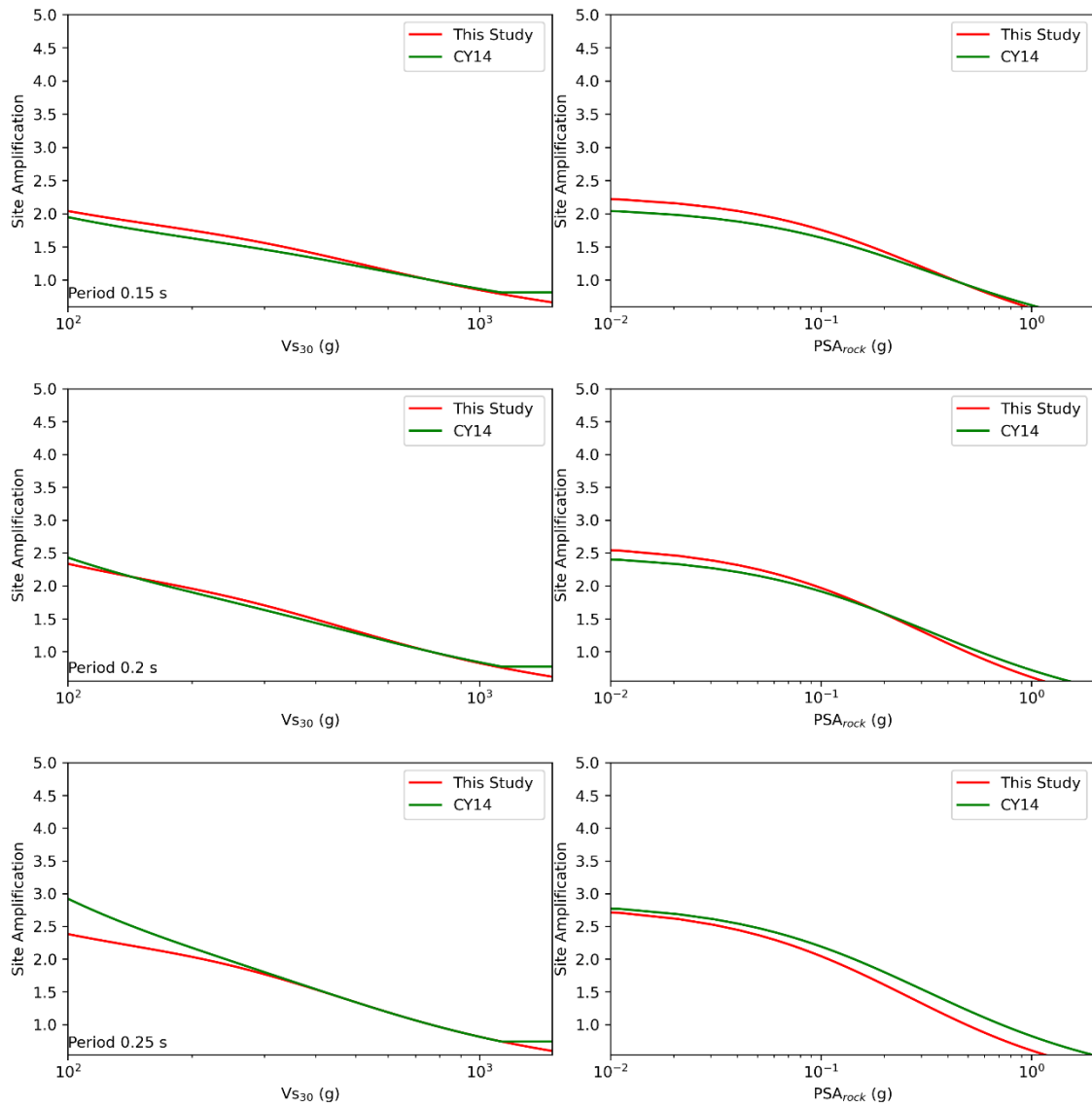


Figure B.3. Site amplification model comparisons with Choi and Youngs (1994) of the V_{s30} (left) PSA_r (right) scalings for 0.15s (top), 0.2s (middle) and 0.25s (bottom).

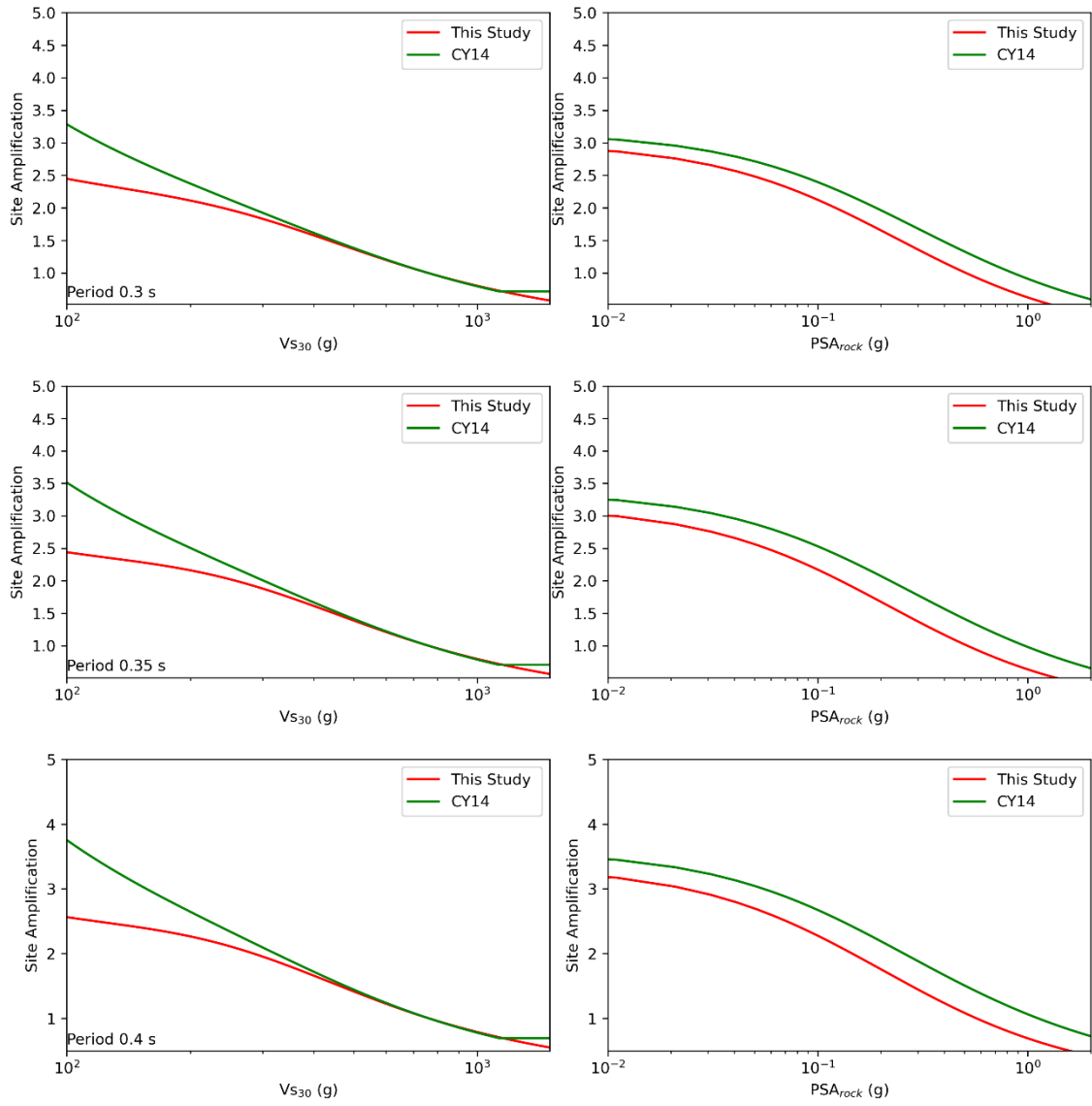


Figure B.4. Site amplification model comparisons with Choi and Youngs (1994) of the V_{S30} (left) PSA_r (right) scalings for 0.3s (top), 0.35s (middle) and 0.4s (bottom).

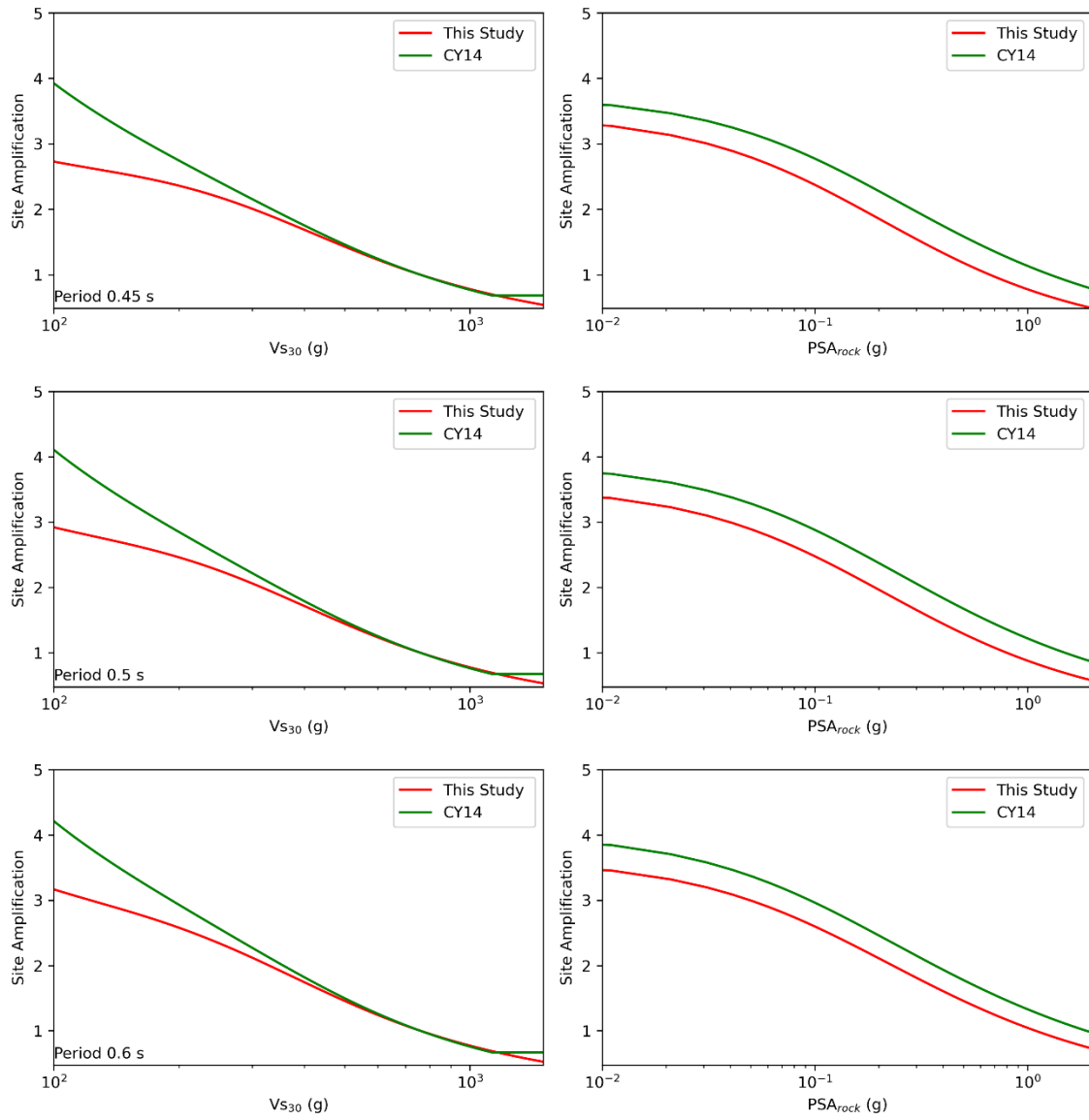


Figure B.5. Site amplification model comparisons with Choi and Youngs (1994) of the V_{S30} (left) PSA_r (right) scalings for 0.45s (top), 0.5s (middle) and 0.6s (bottom).

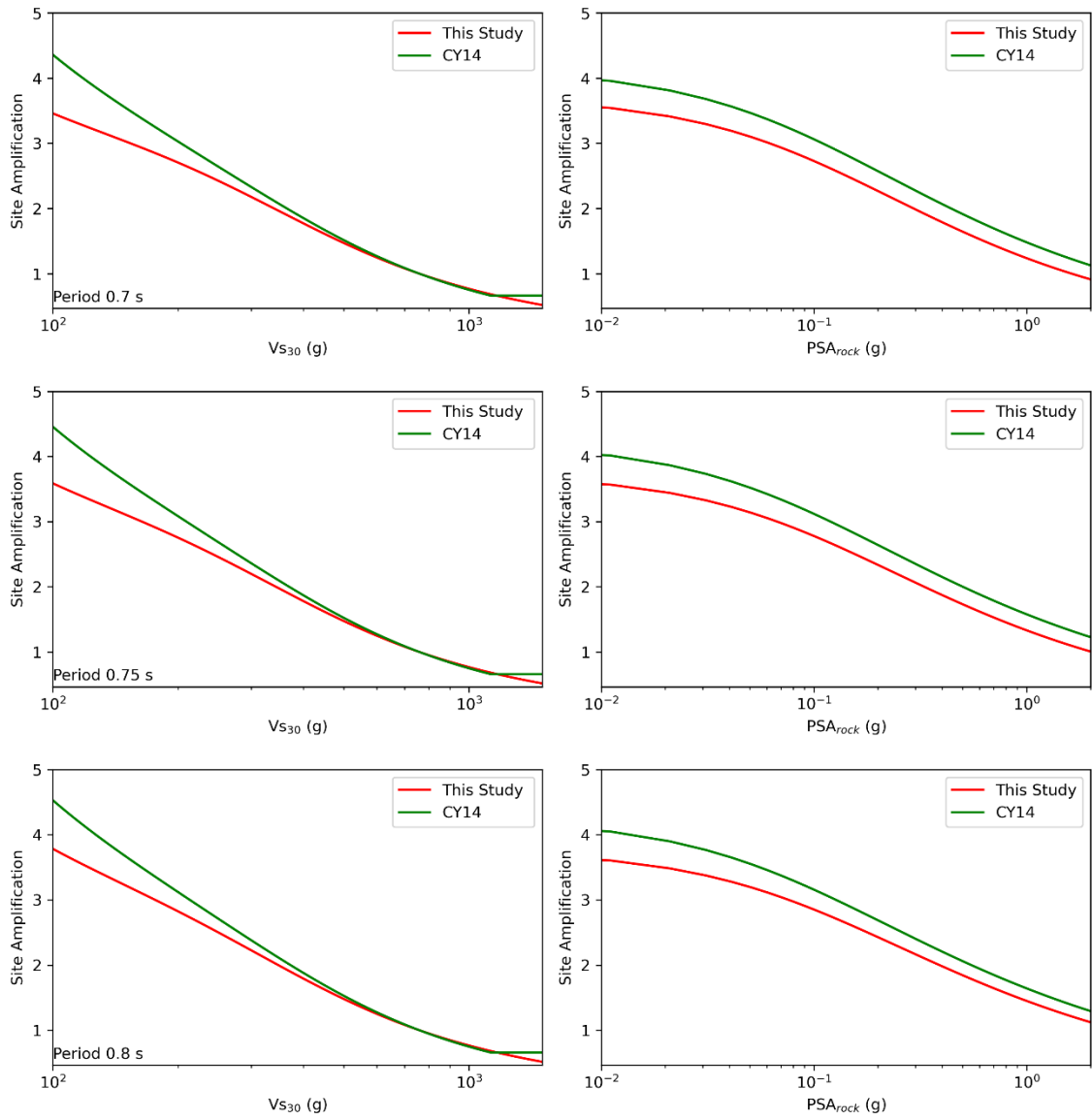


Figure B.6. Site amplification model comparisons with Choi and Youngs (1994) of the V_{S30} (left) PSA_r (right) scalings for 0.7s (top), 0.75s (middle) and 0.8s (bottom).

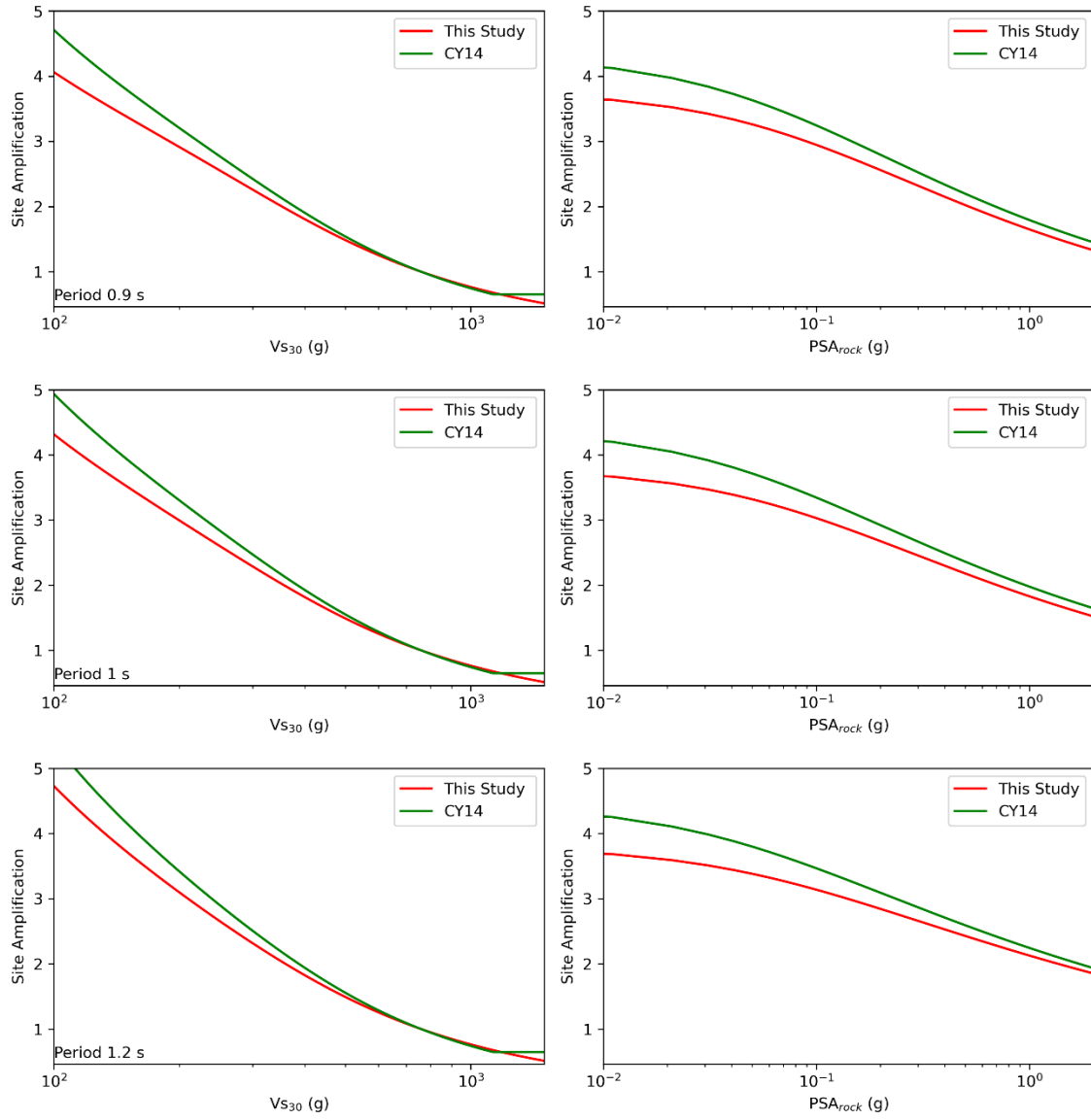


Figure B.7. Site amplification model comparisons with Choi and Youngs (1994) of the V_{S30} (left) PSA_r (right) scalings for 0.9s (top), 1s (middle) and 1.2s (bottom).

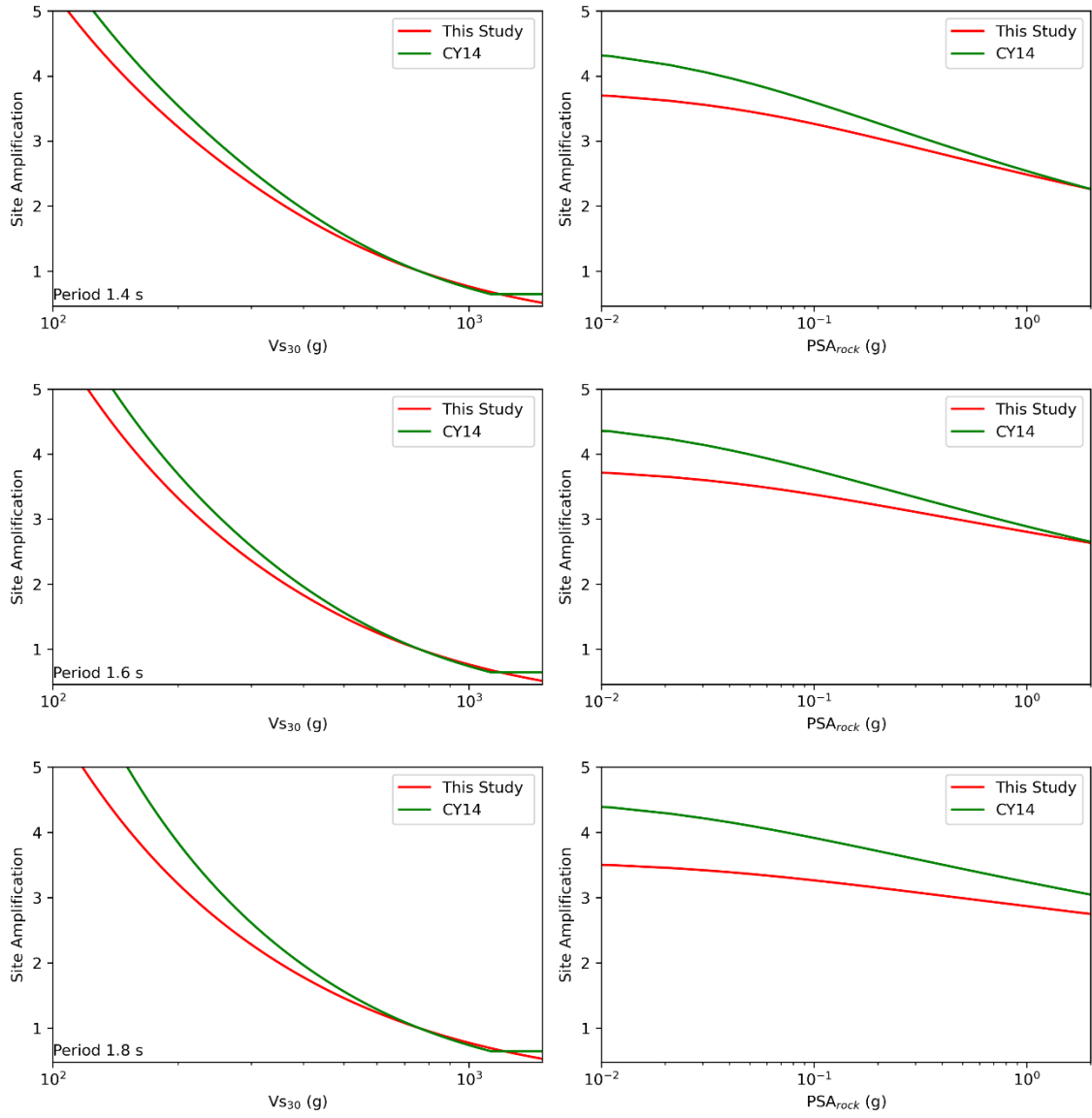


Figure B.8. Site amplification model comparisons with Choi and Youngs (1994) of the V_{S30} (left) PSA_r (right) scalings for 1.4s (top), 1.6s (middle) and 1.8s (bottom).

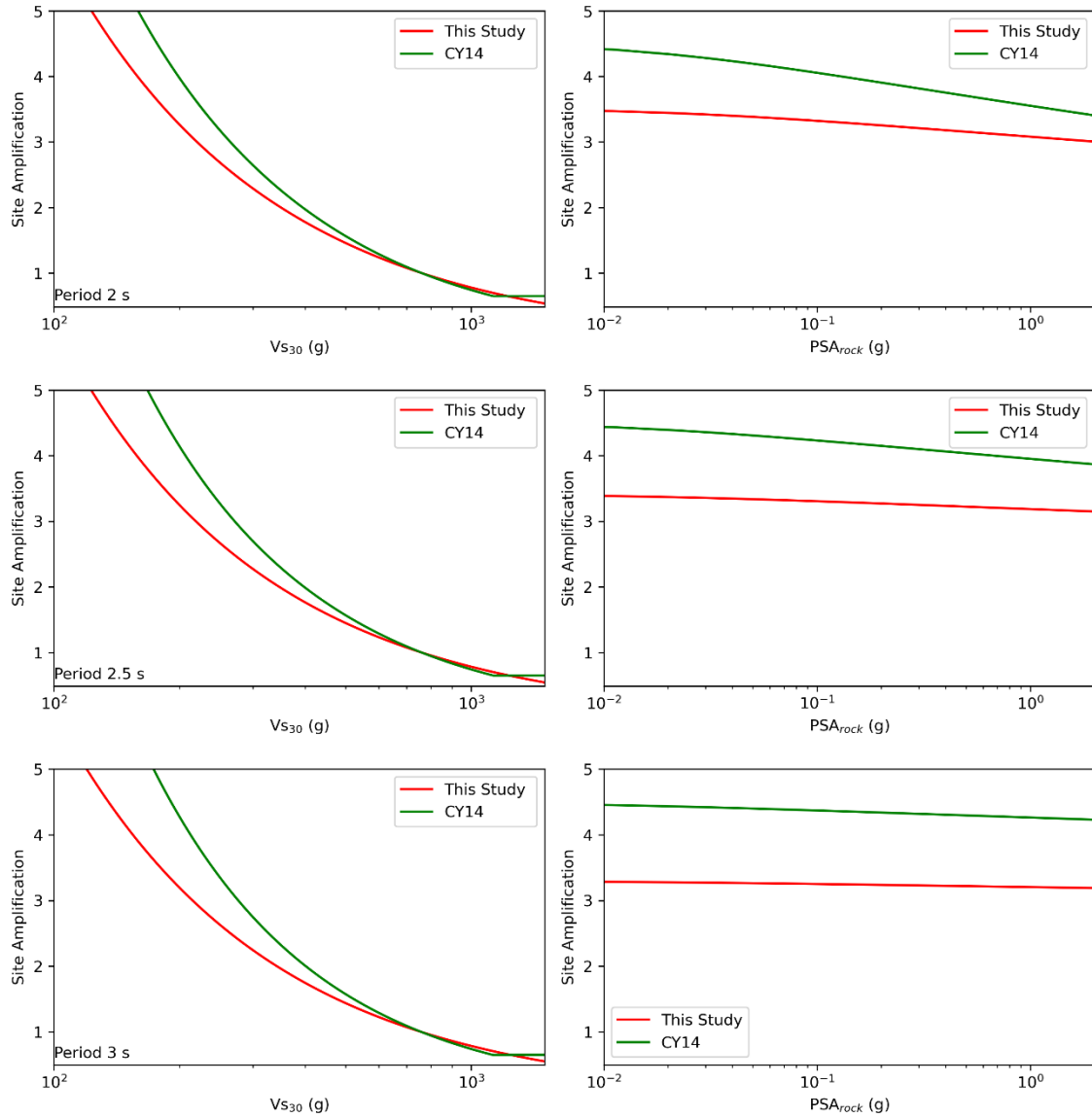


Figure B.9. Site amplification model comparisons with Choi and Youngs (1994) of the V_{S30} (left) PSA_r (right) scalings for 2s (top), 2.5s (middle) and 3s (bottom).

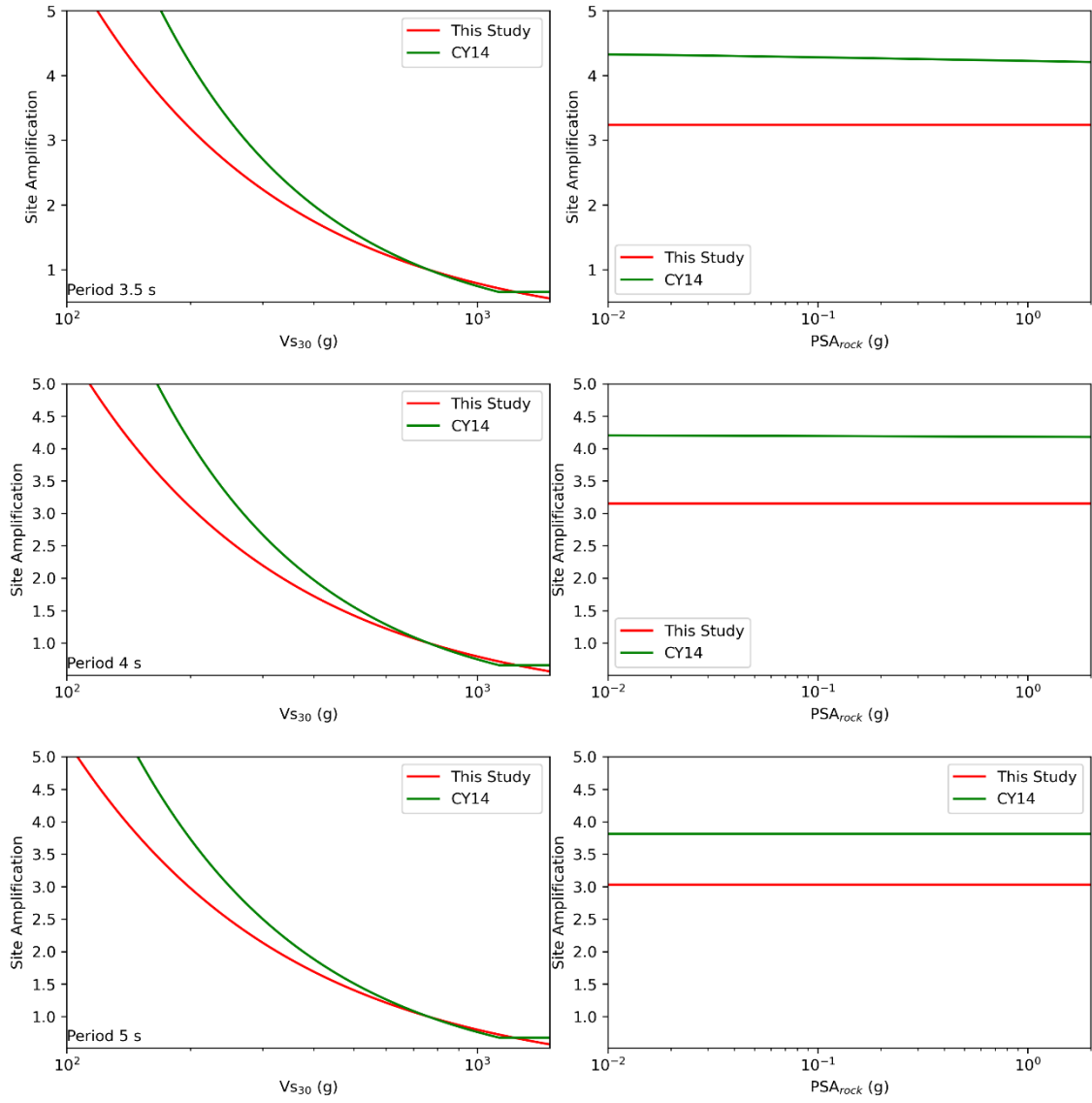


Figure B.10. Site amplification model comparisons with Choi and Youngs (1994) of the V_{s30} (left) PSA_r (right) scalings for 3.5s (top), 4s (middle) and 5s (bottom).

V_{S30} Scaling to Observe the V_c

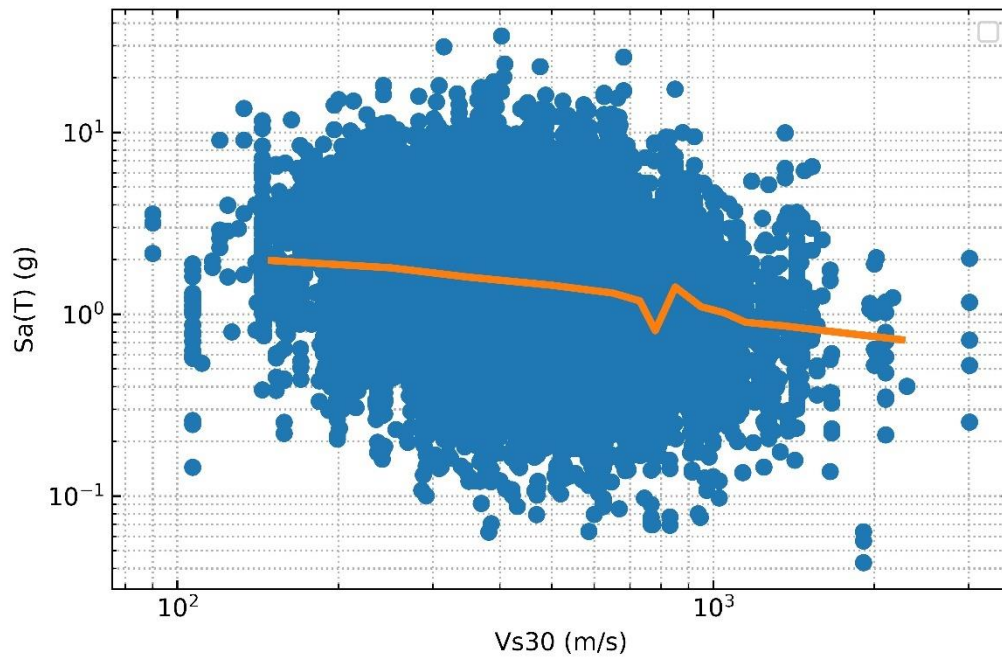


Figure B.11. V_{S30} scaling at 0.01s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

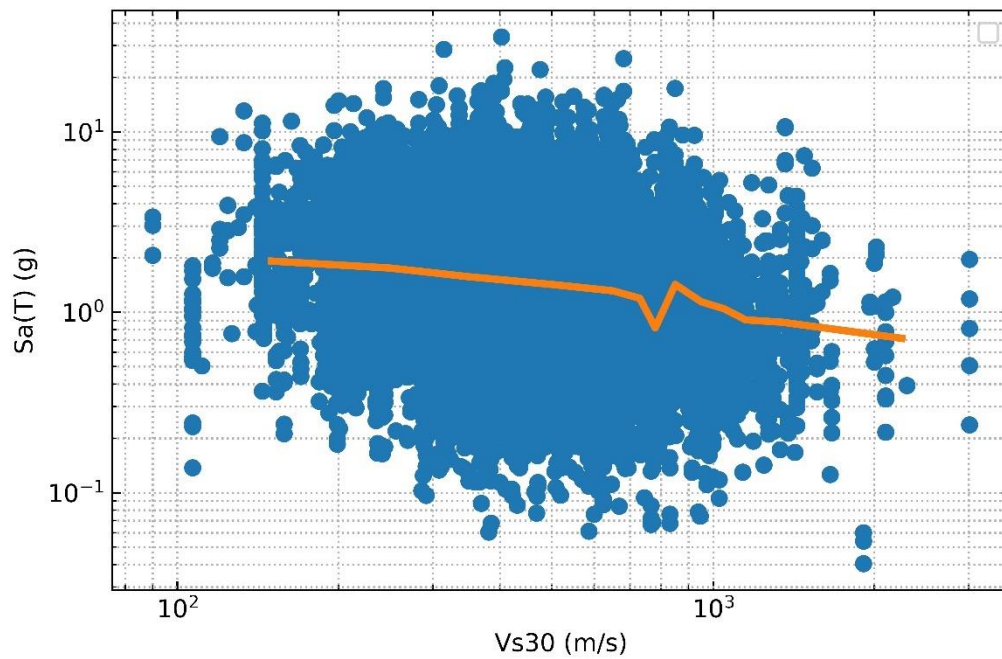


Figure B.12. V_{S30} scaling at 0.025s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

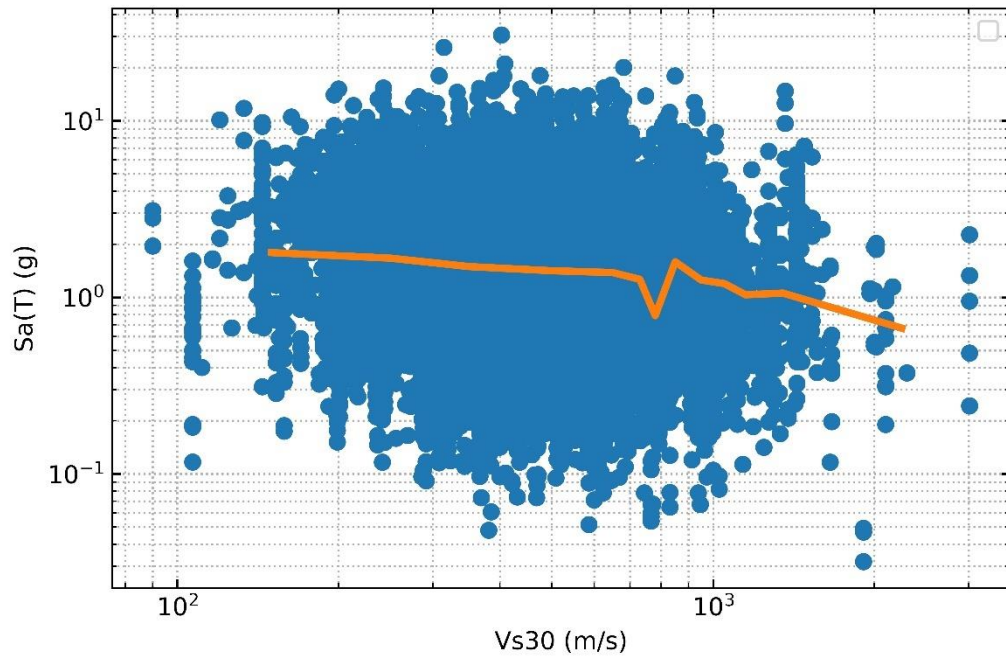


Figure B.13. V_{s30} scaling at 0.04s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

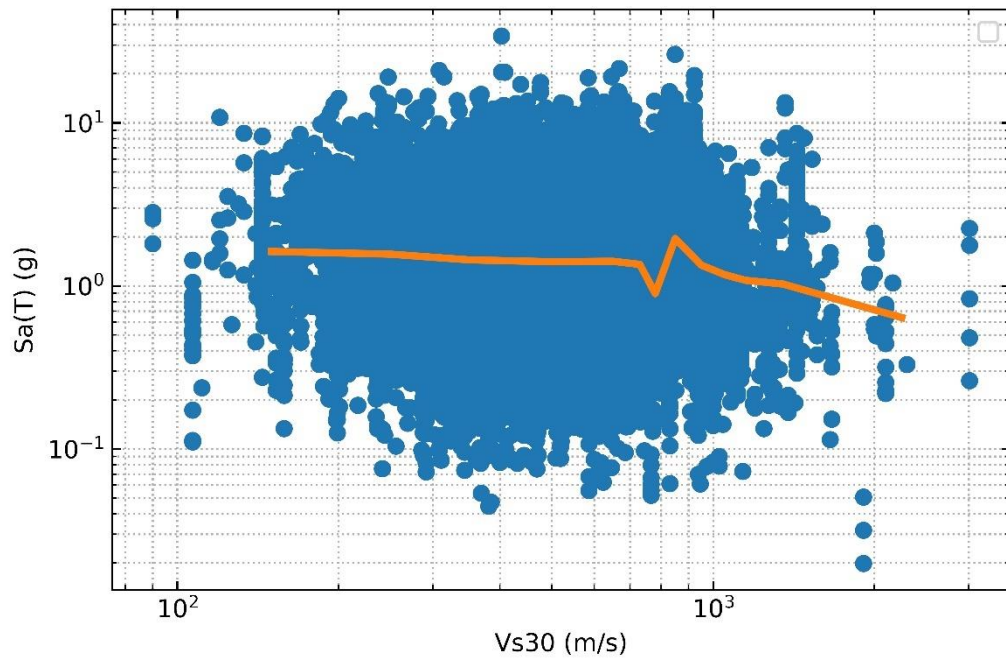


Figure B.14. V_{s30} scaling at 0.05s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

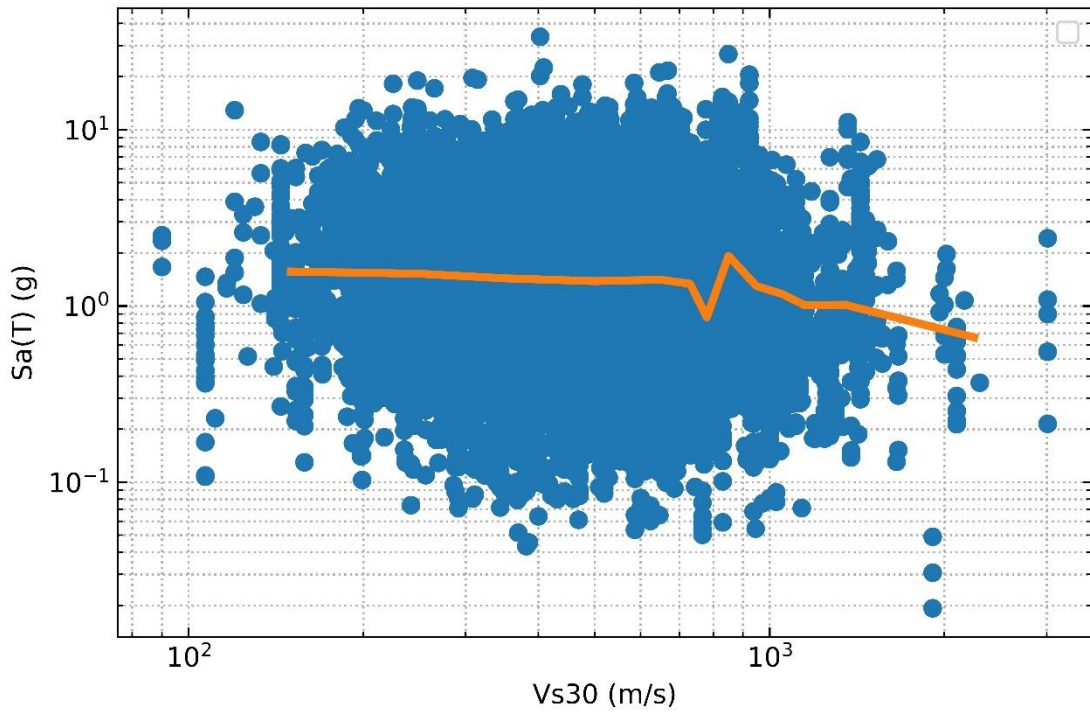


Figure B.15. V_{s30} scaling at 0.07s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

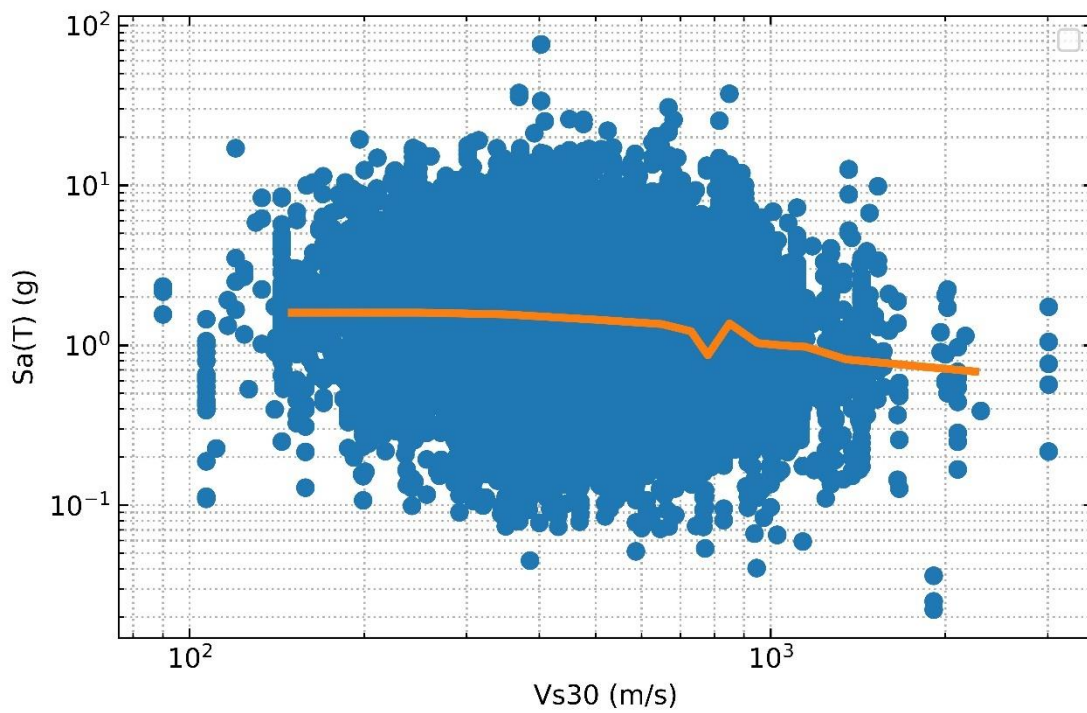


Figure B.16. V_{s30} scaling at 0.1s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

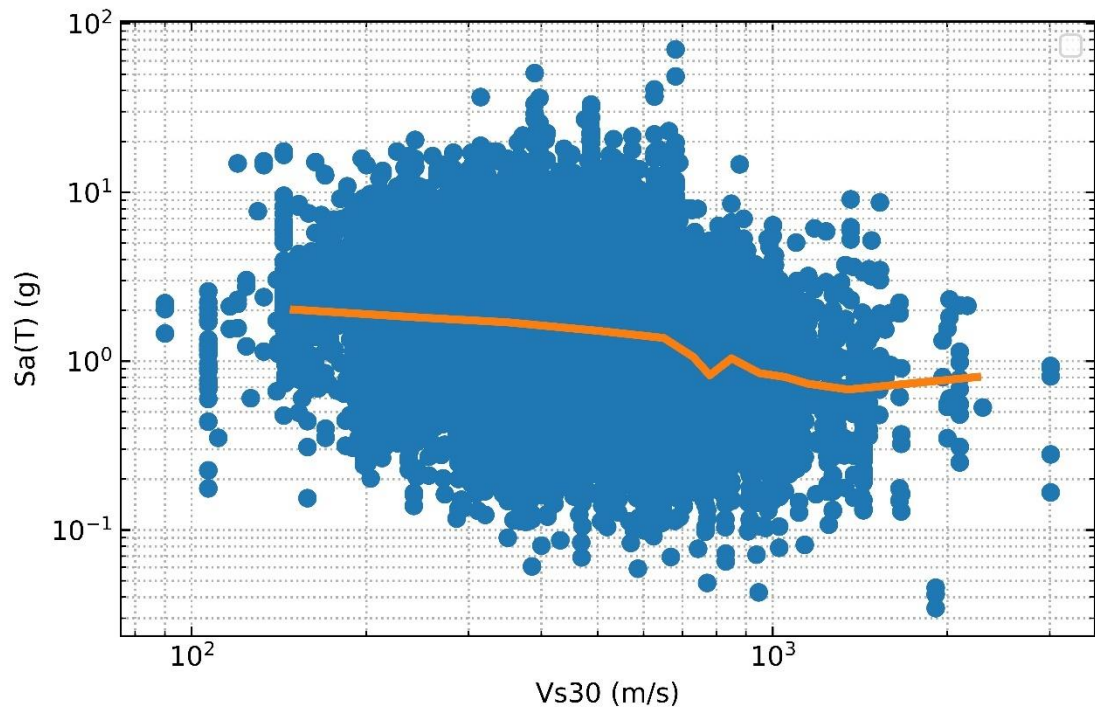


Figure B.17. V_{s30} scaling at 0.15s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

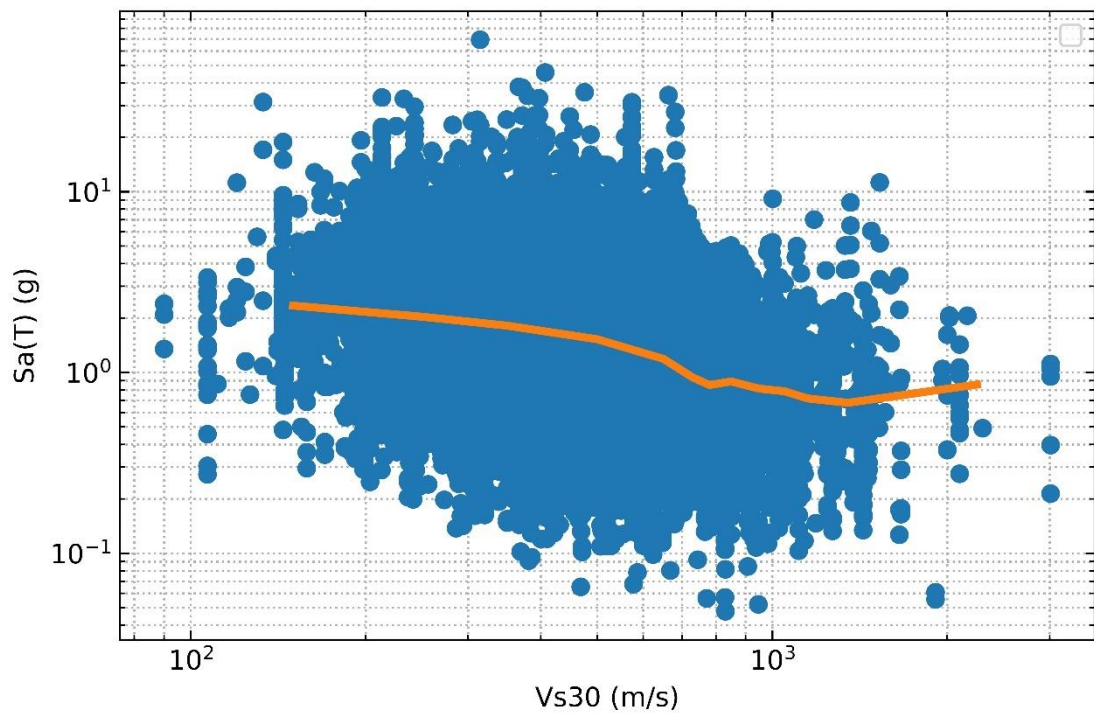


Figure B.18. V_{s30} scaling at 0.2s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

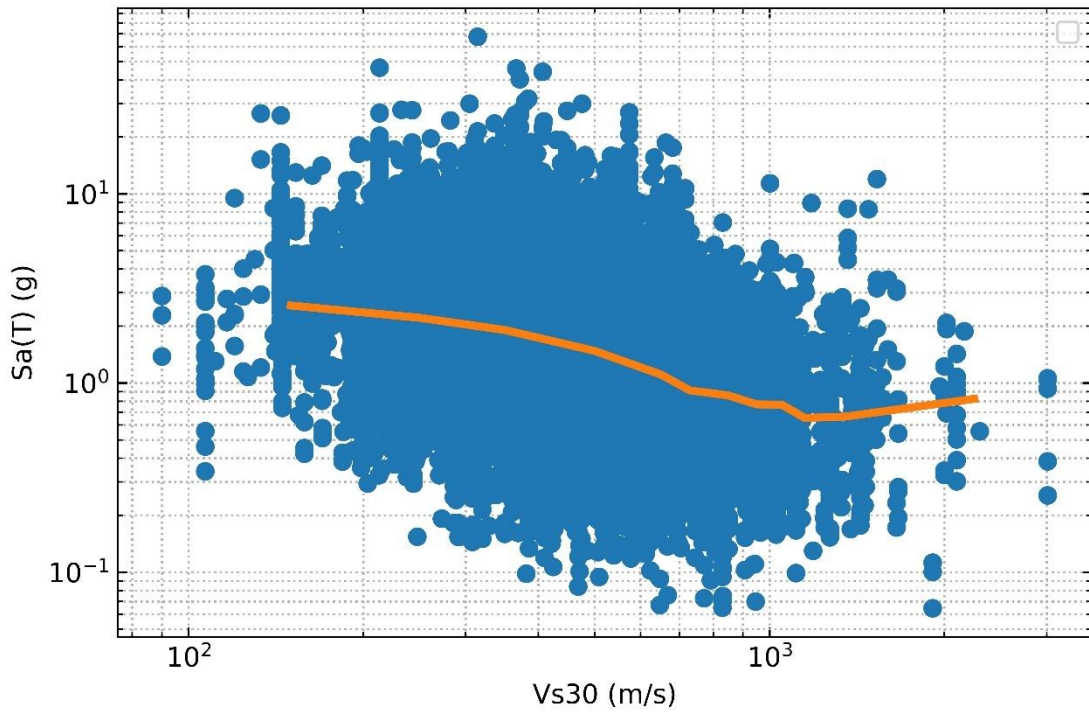


Figure B.19. V_{s30} scaling at 0.25s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

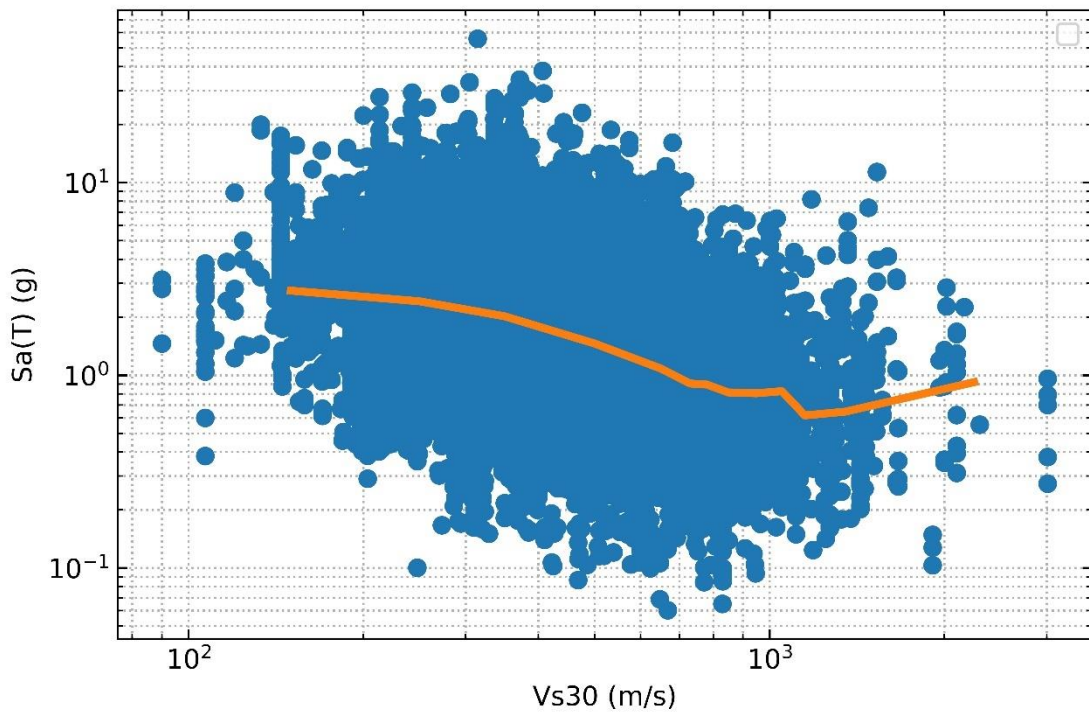


Figure B.20. V_{s30} scaling at 0.3s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

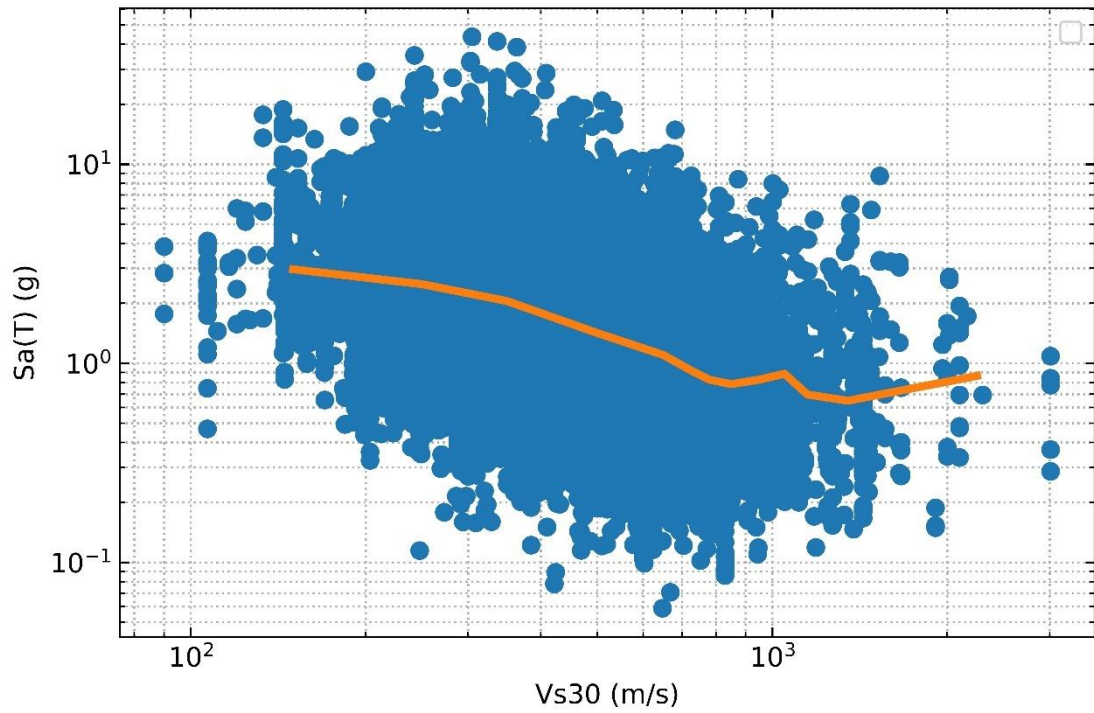


Figure B.21. V_{s30} scaling at 0.35s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

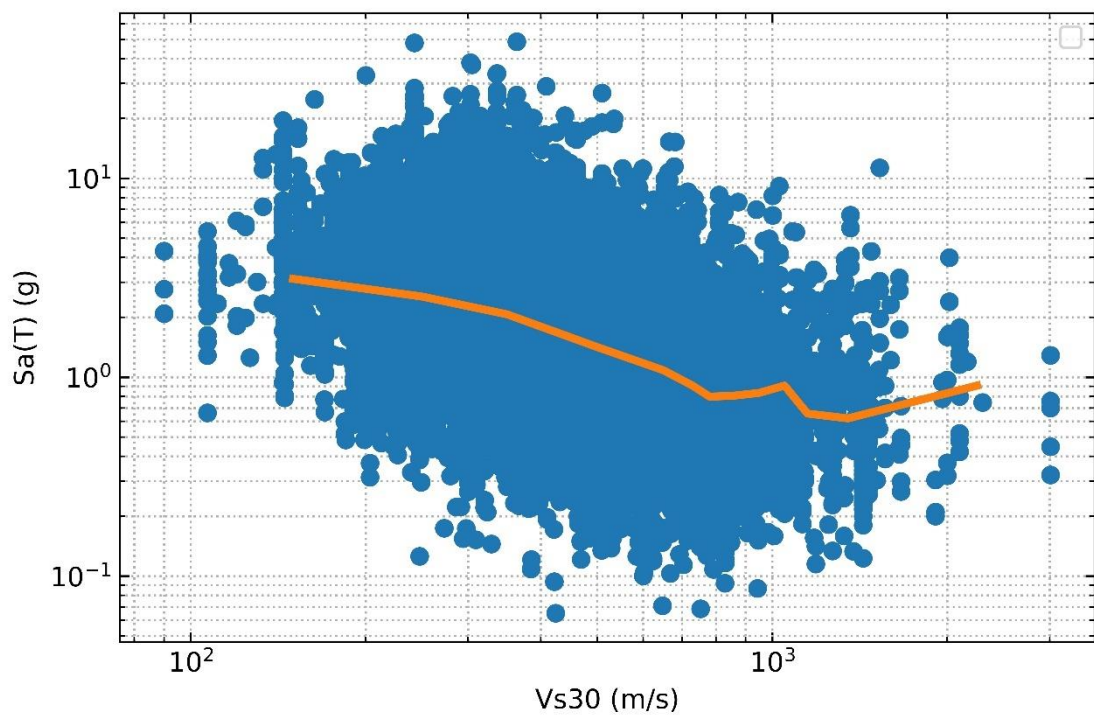


Figure B.22. V_{s30} scaling at 0.4s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

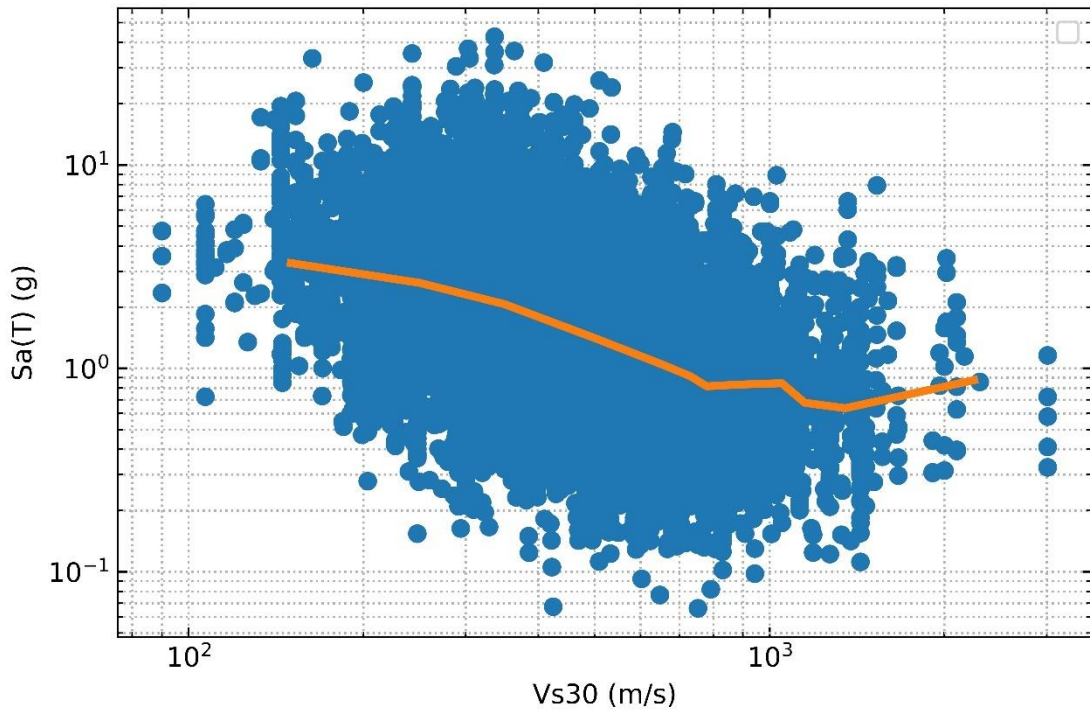


Figure B.23. V_{s30} scaling at 0.45s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

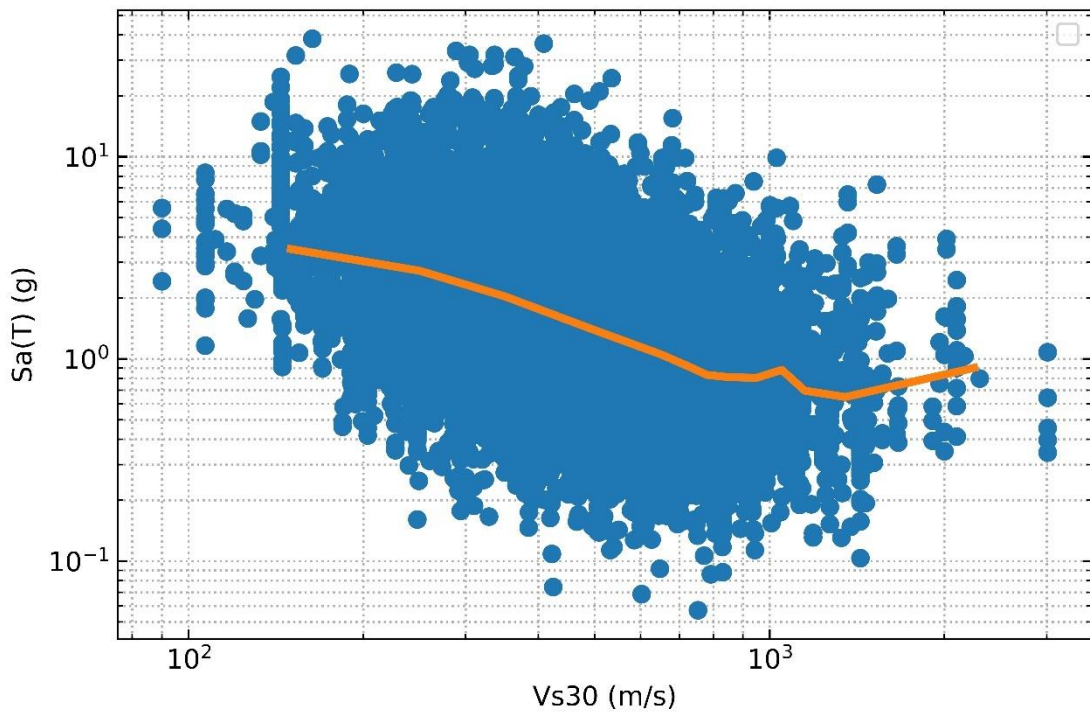


Figure B.24. V_{s30} scaling at 0.5s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

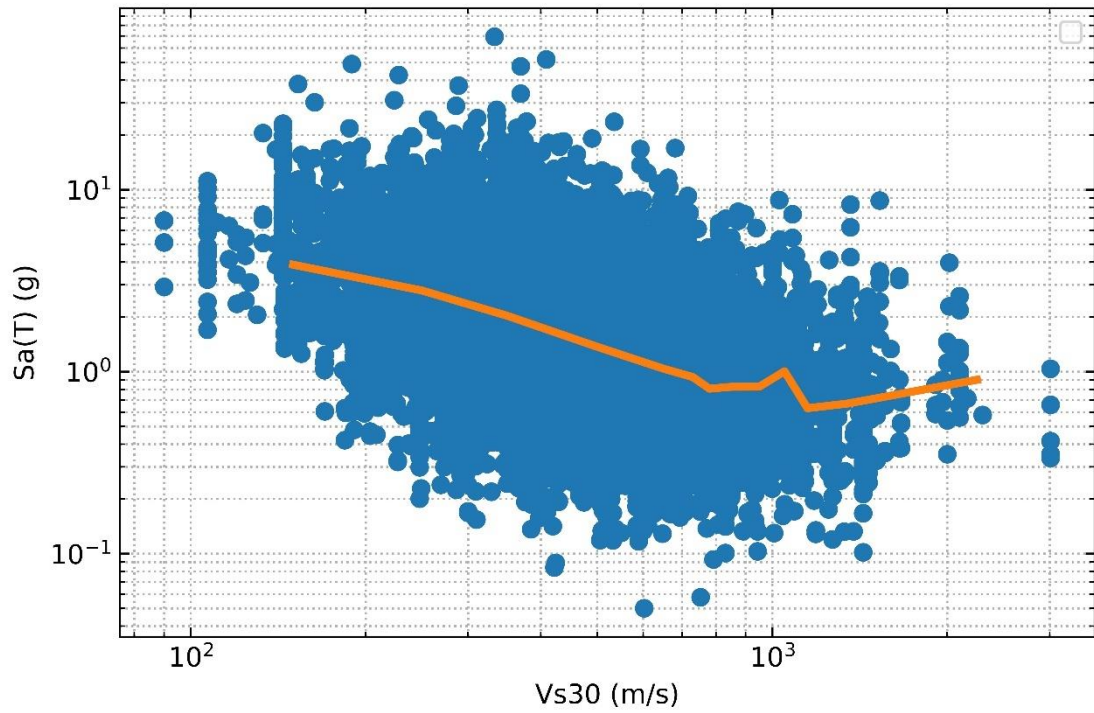


Figure B.24. V_{s30} scaling at 0.6s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

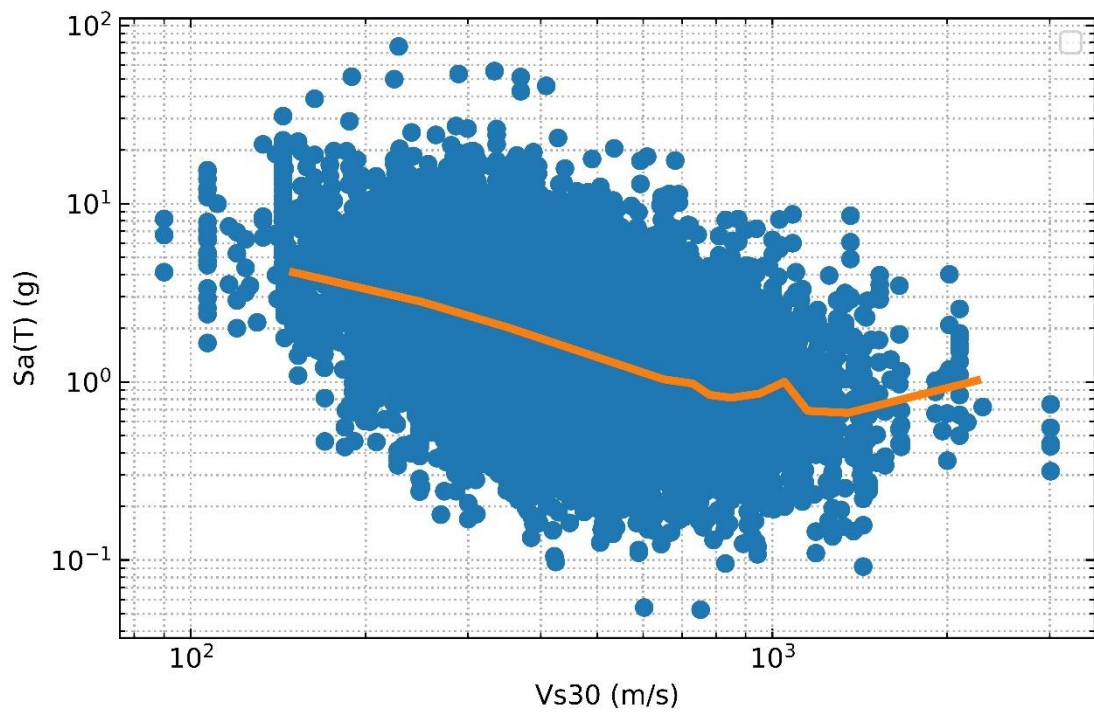


Figure B.25. V_{s30} scaling at 0.7s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

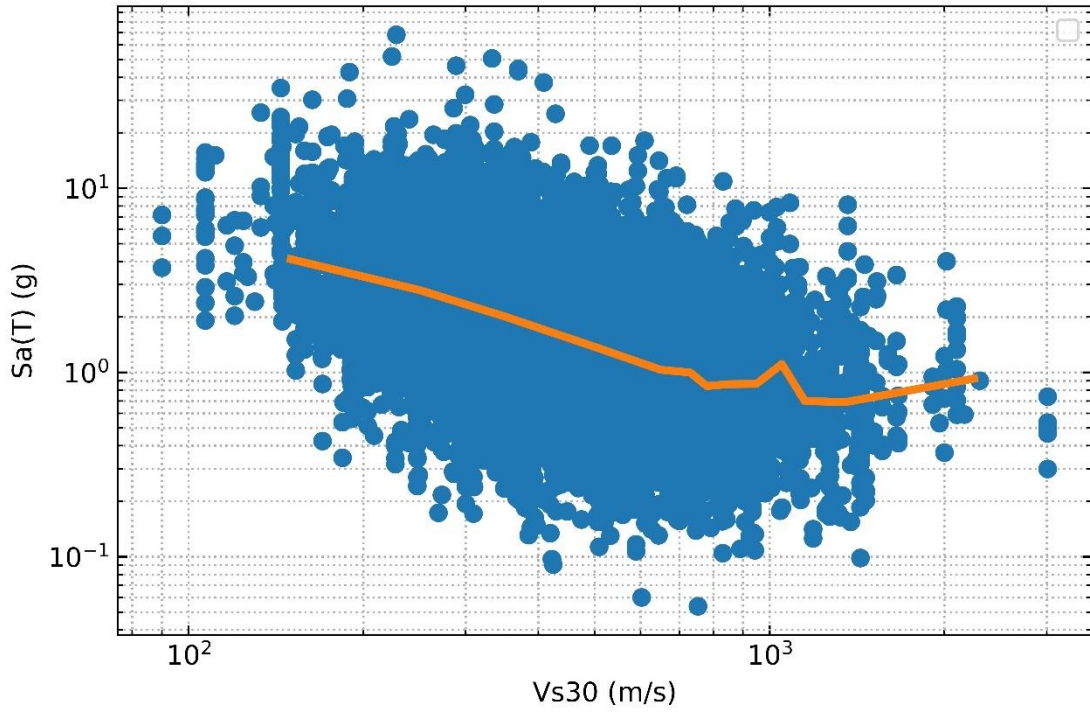


Figure B.26. V_{s30} scaling at 0.75s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

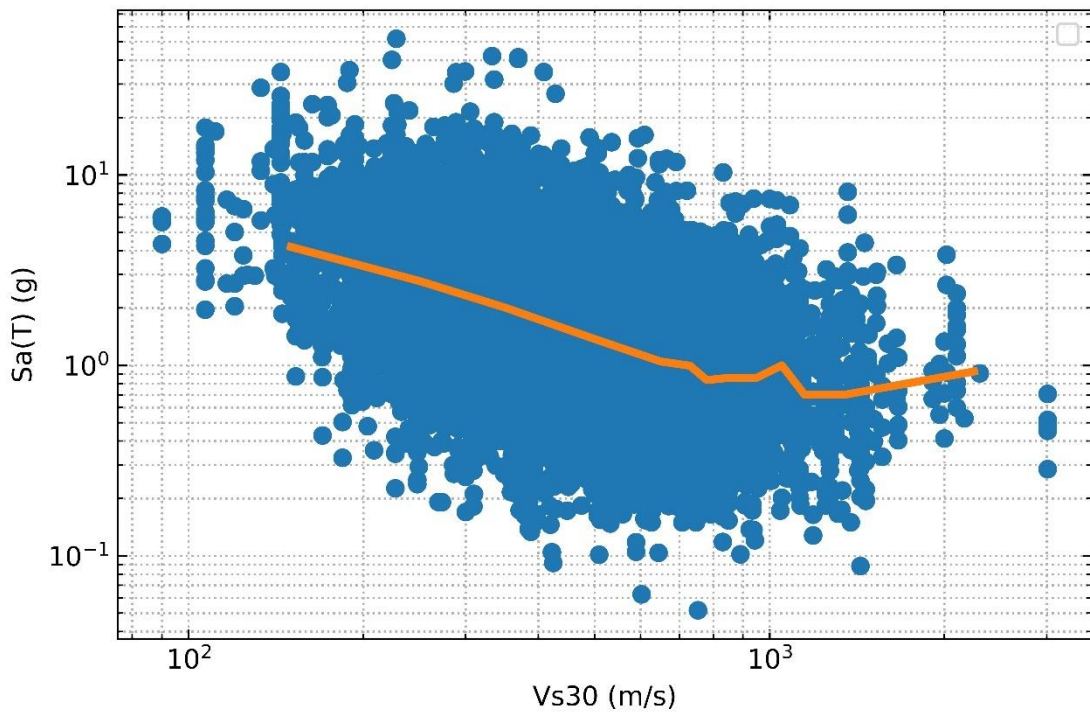


Figure B.27. V_{s30} scaling at 0.8s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

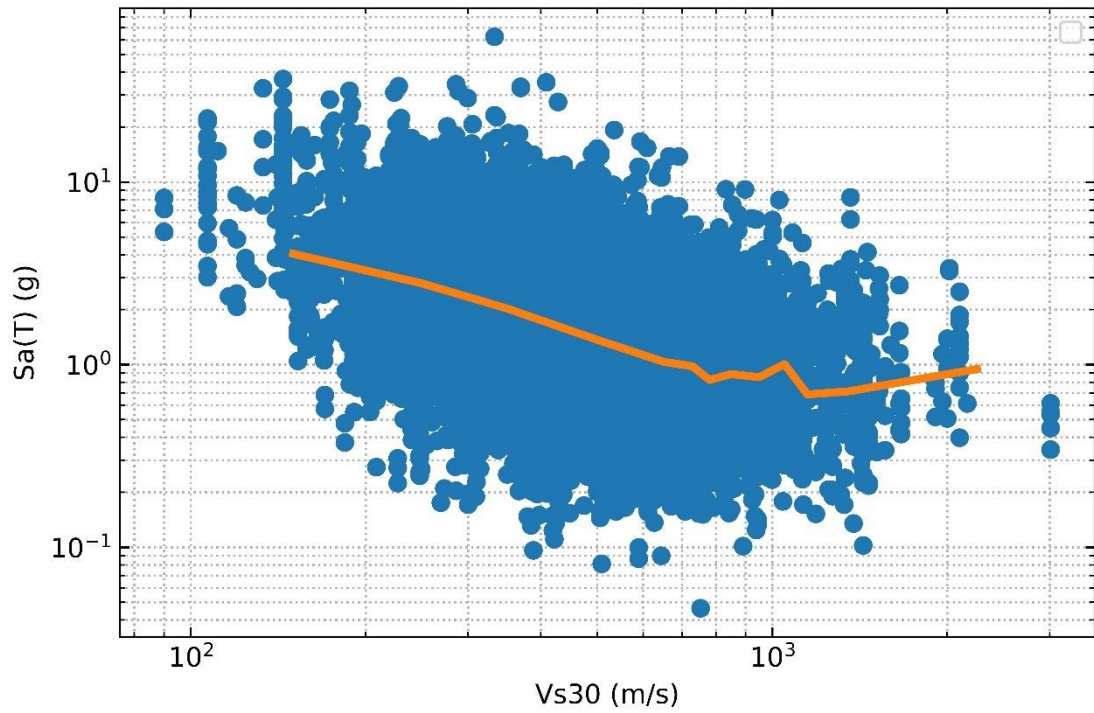


Figure B.28. V_{s30} scaling at 0.9s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

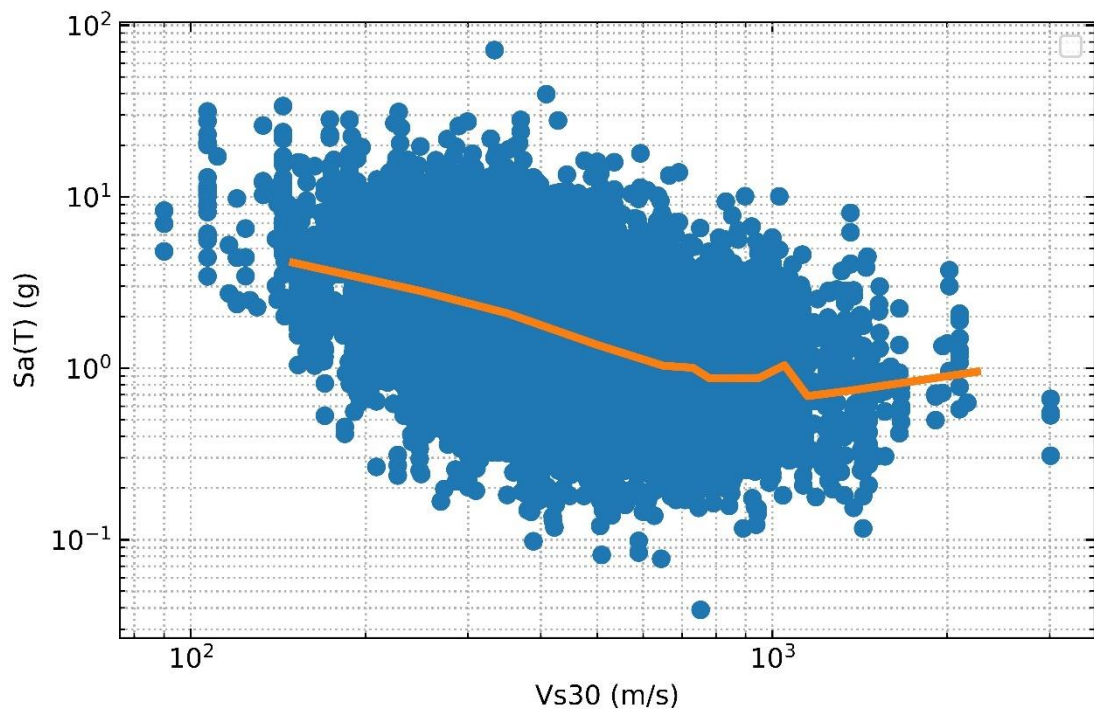


Figure B.29. V_{s30} scaling at 1s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

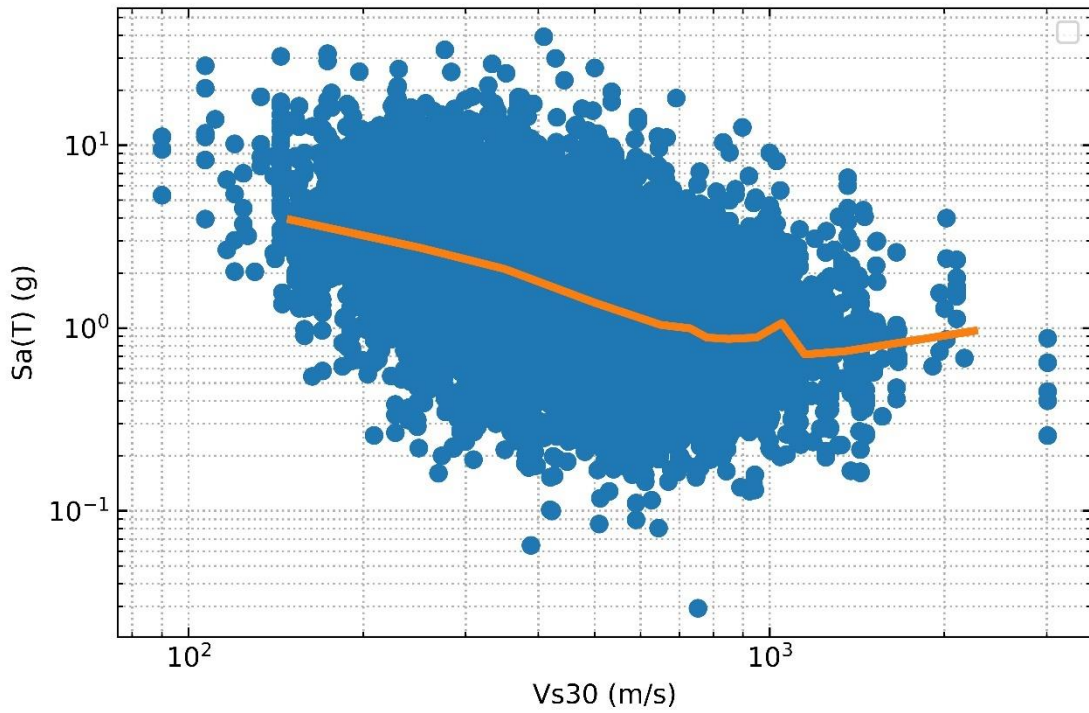


Figure B.30. V_{s30} scaling at 1.2s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

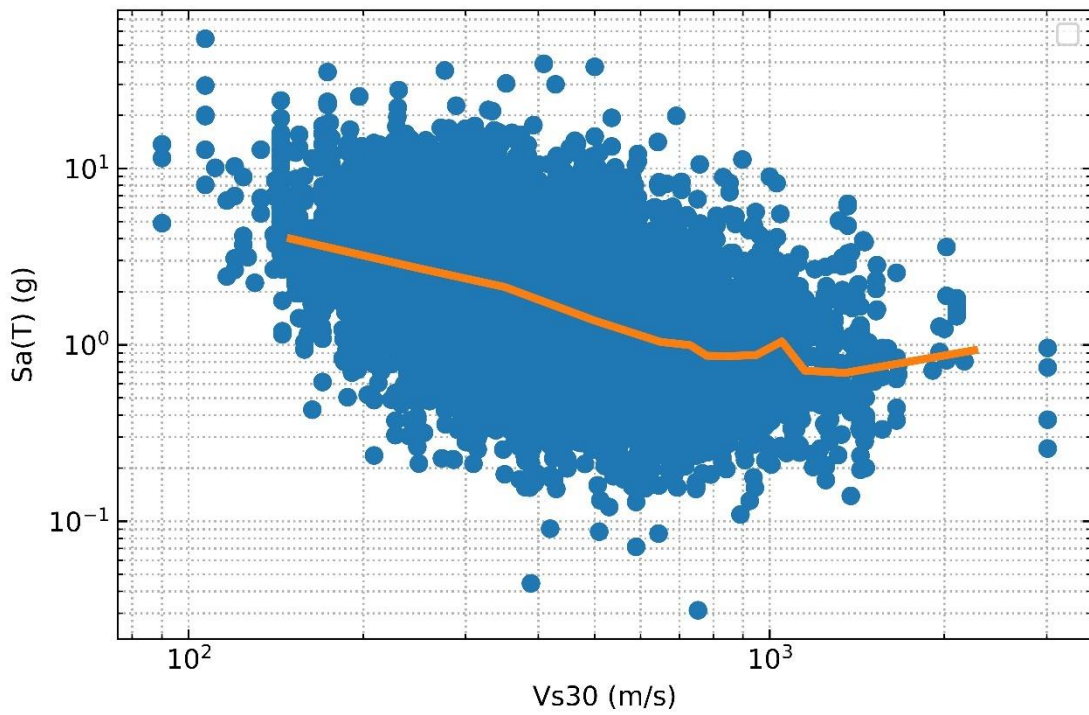


Figure B.31. V_{s30} scaling at 1.4s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

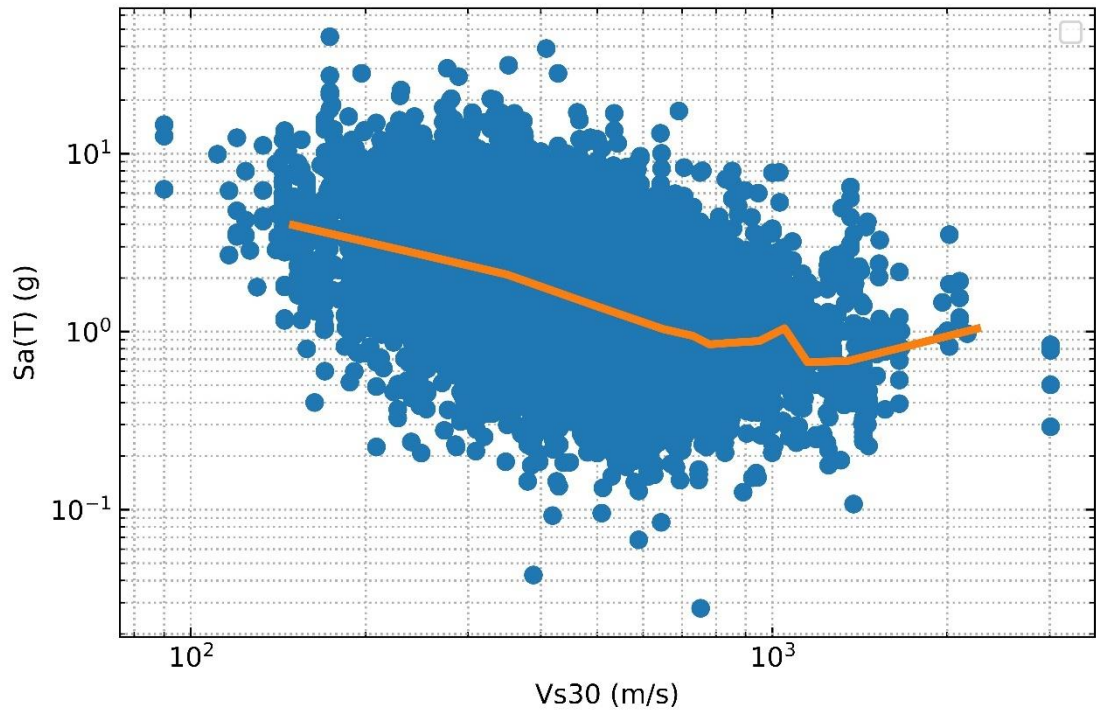


Figure B.32. V_{s30} scaling at 1.6s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

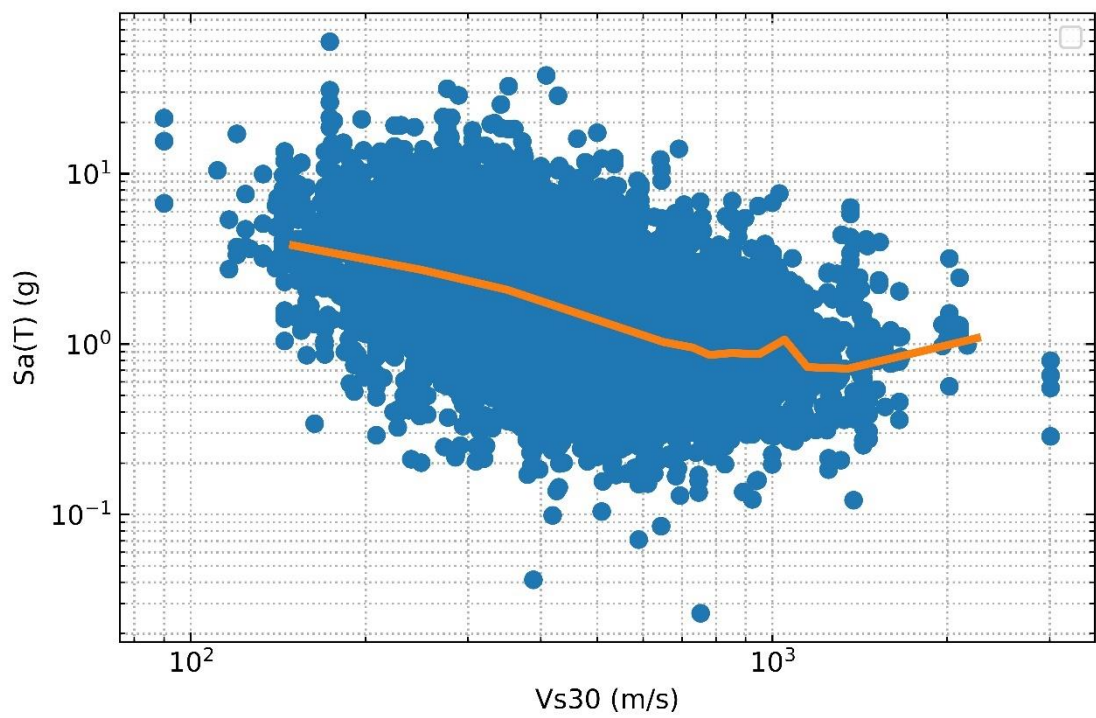


Figure B.33. V_{s30} scaling at 1.8s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

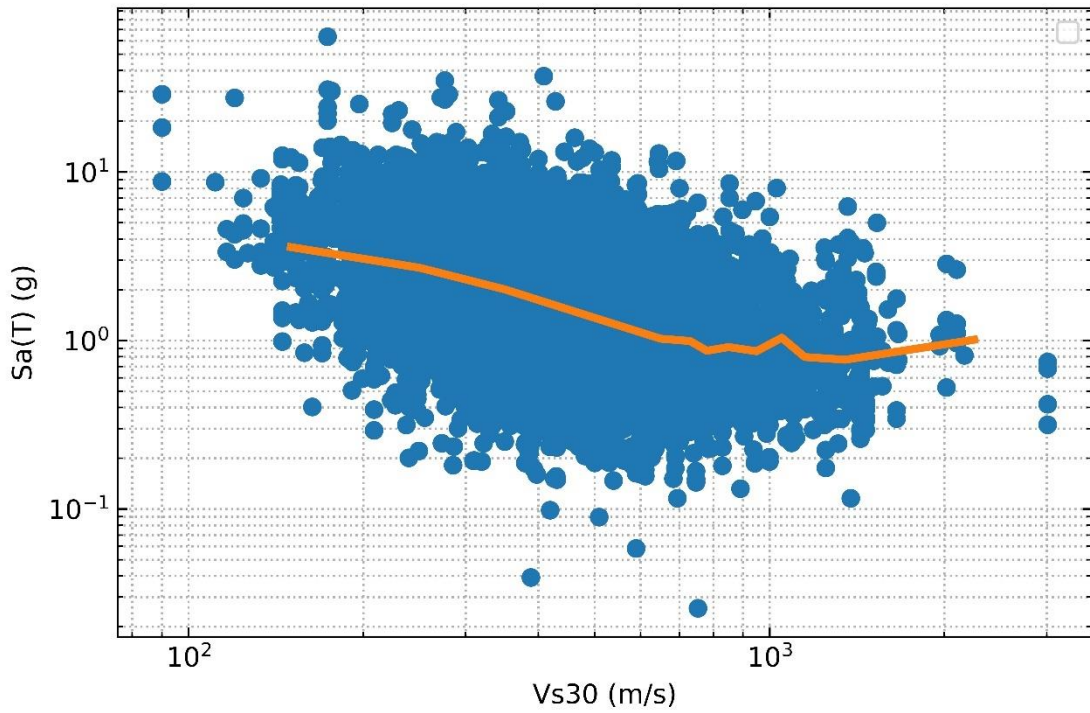


Figure B.34. V_{s30} scaling at 2s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

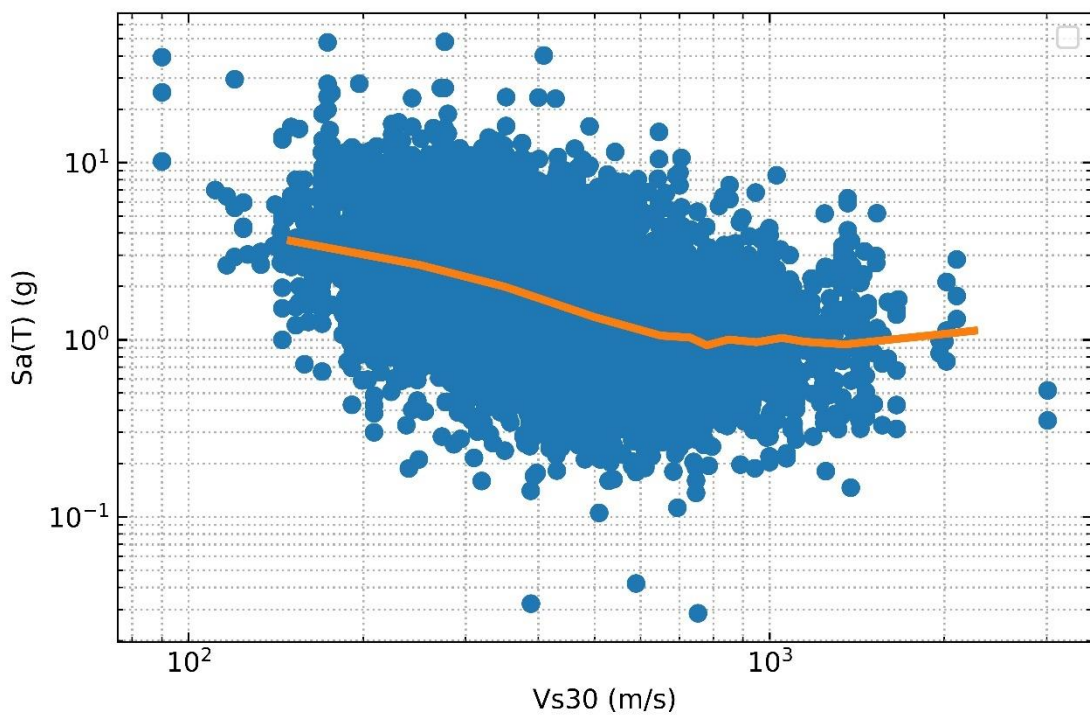


Figure B.35. V_{s30} scaling at 2.5s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

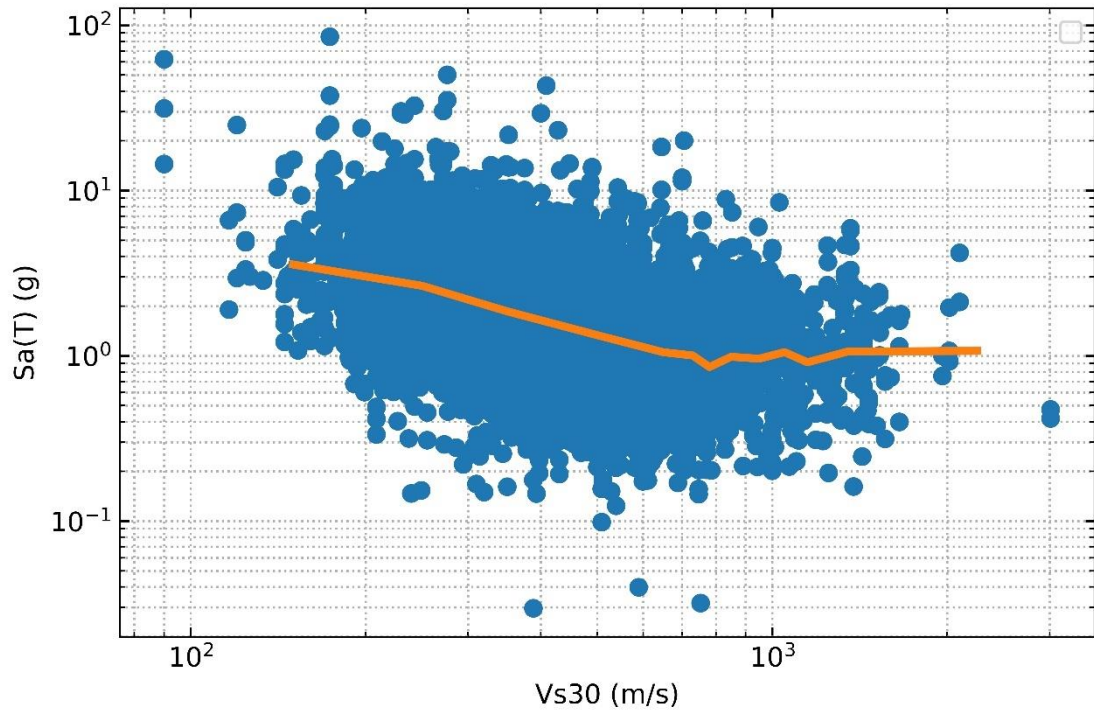


Figure B.36. V_{s30} scaling at 3s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

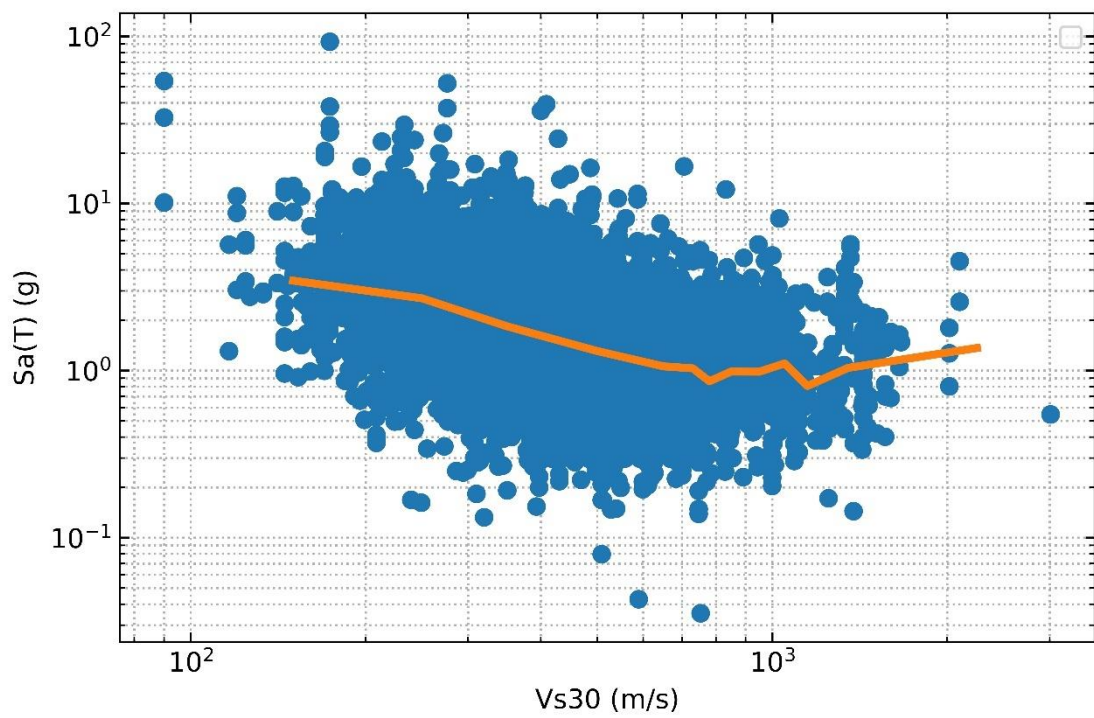


Figure B.37. V_{s30} scaling at 3.5s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

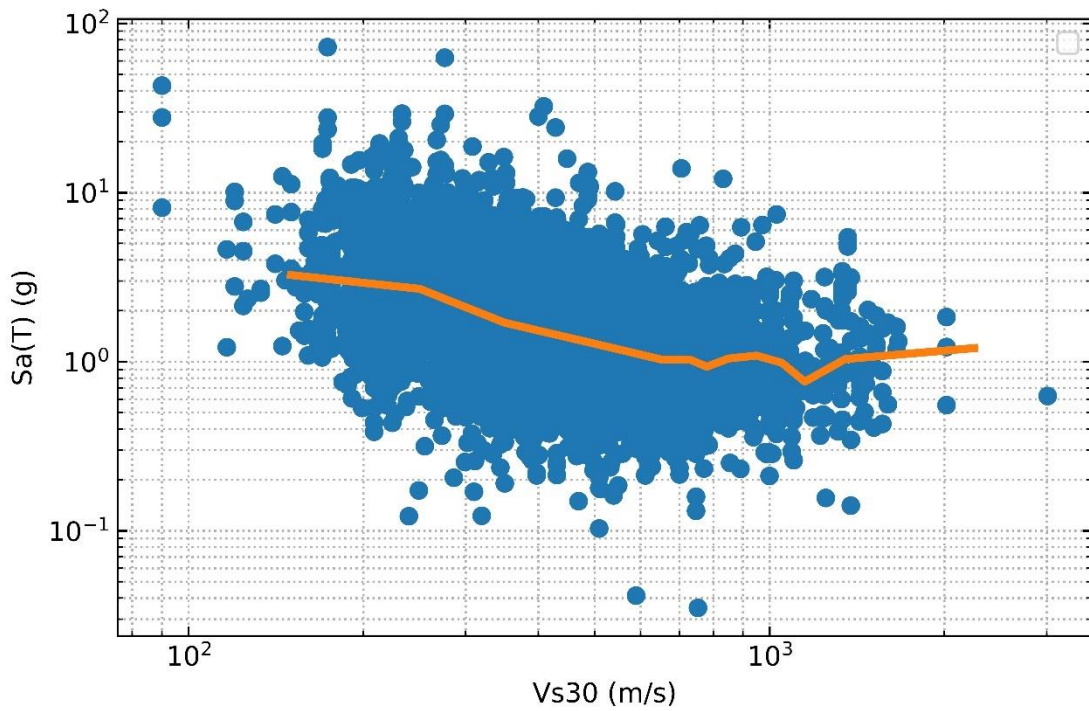


Figure B.38. V_{s30} scaling at 4s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

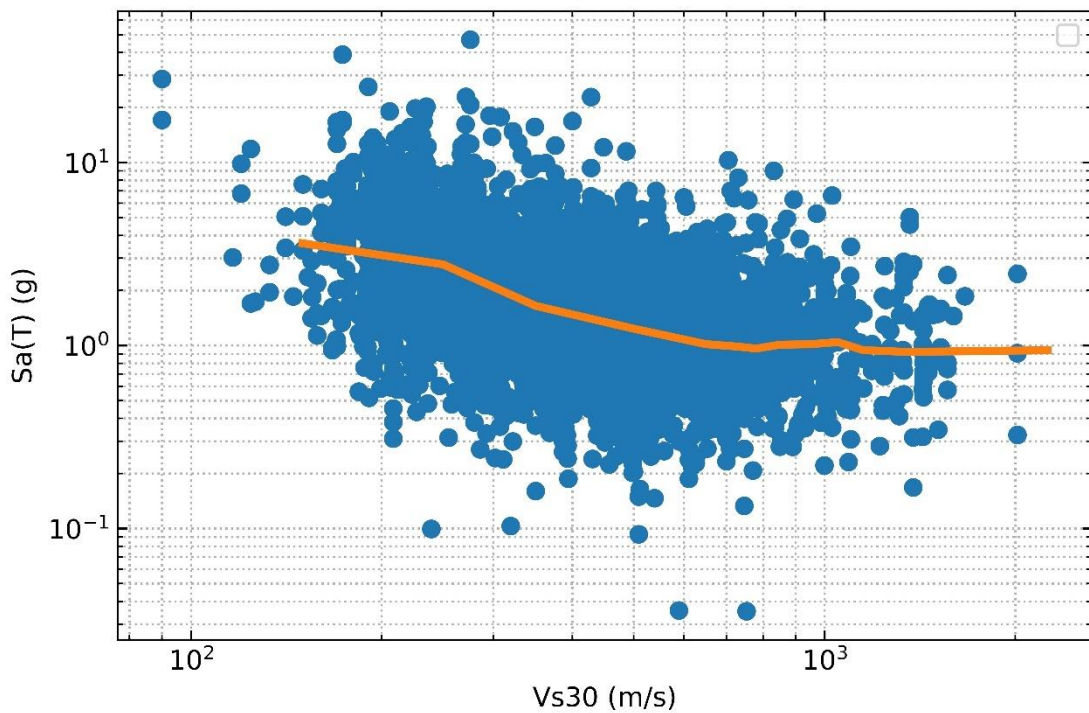


Figure B.39. V_{s30} scaling at 5s, all data are scaled to $M = 6$ and for strike-slip earthquake scenario.

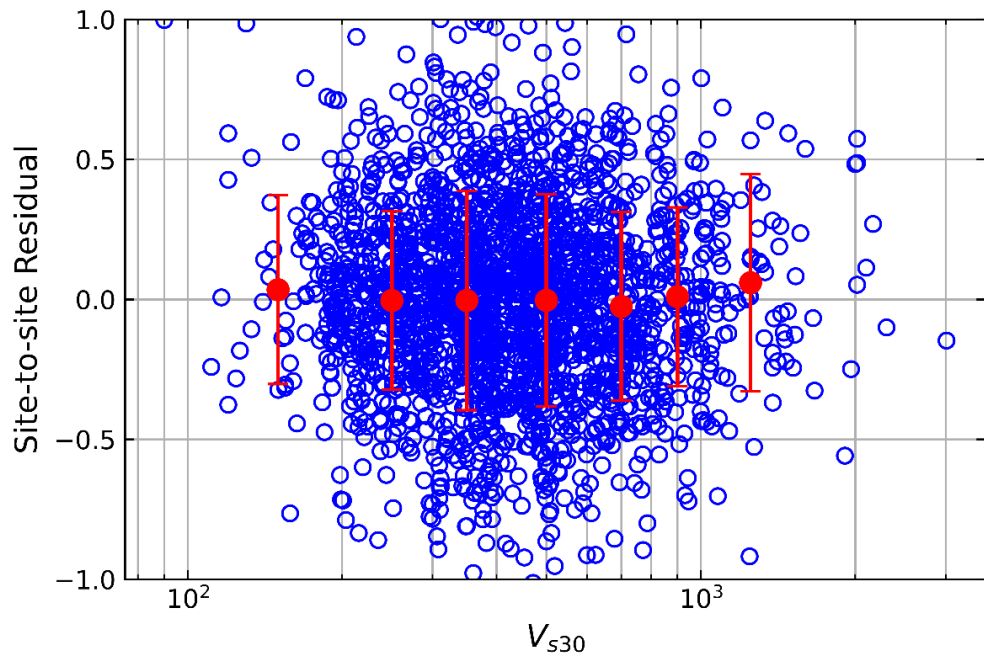


Figure B.40. Site-to-site standard deviation with V_{s30} for 0.01s.

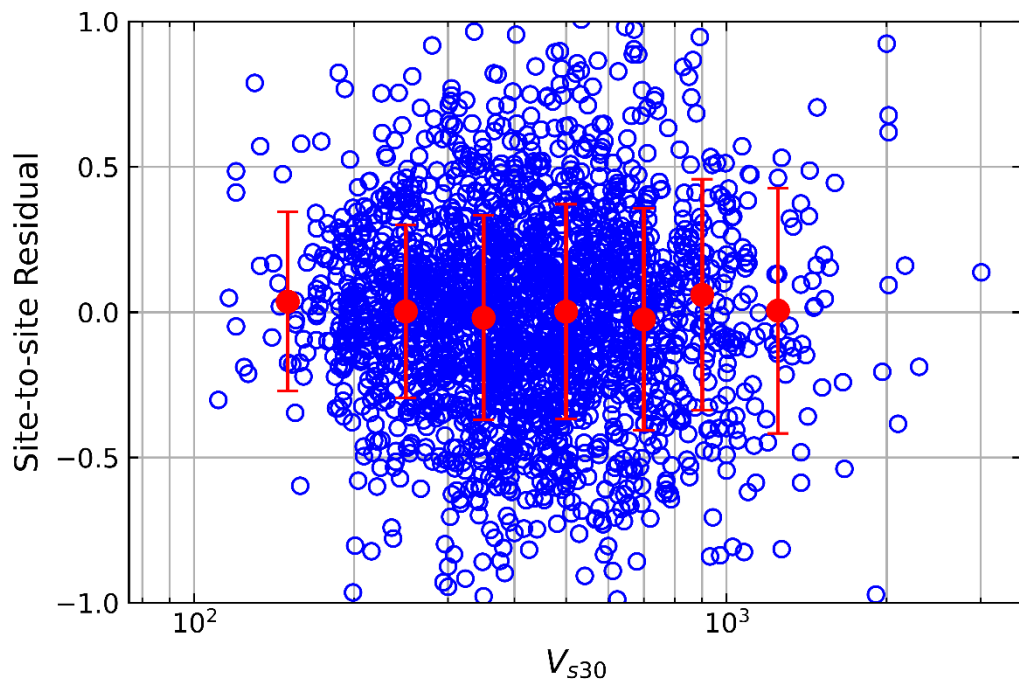


Figure B.41. Site-to-site standard deviation with V_{s30} for 0.025s.

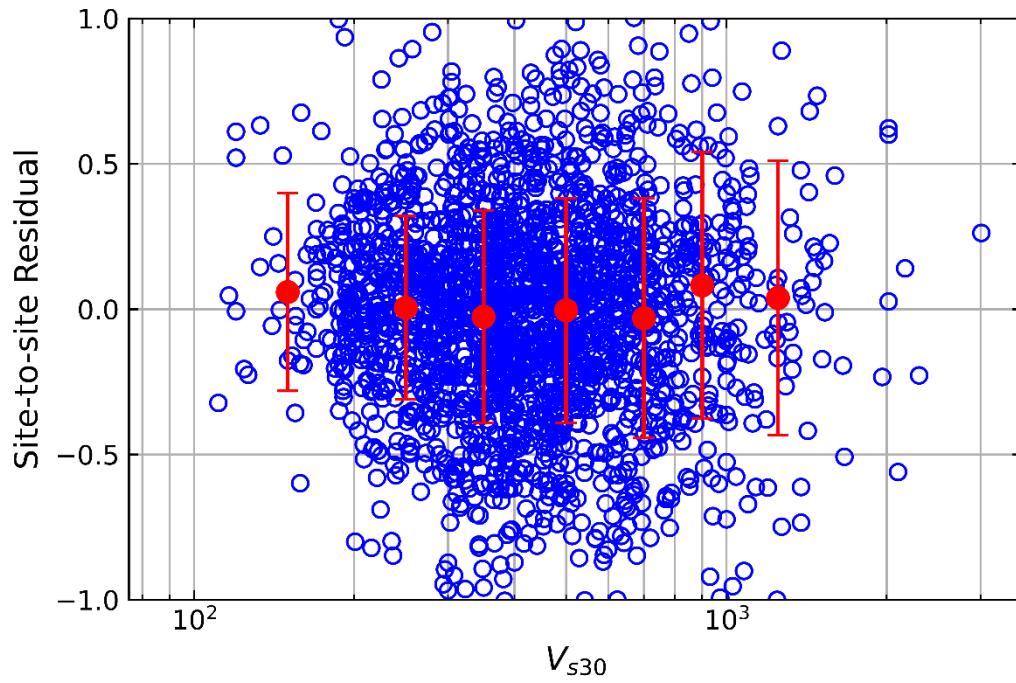


Figure B.42. Site-to-site standard deviation with V_{s30} for 0.04s.

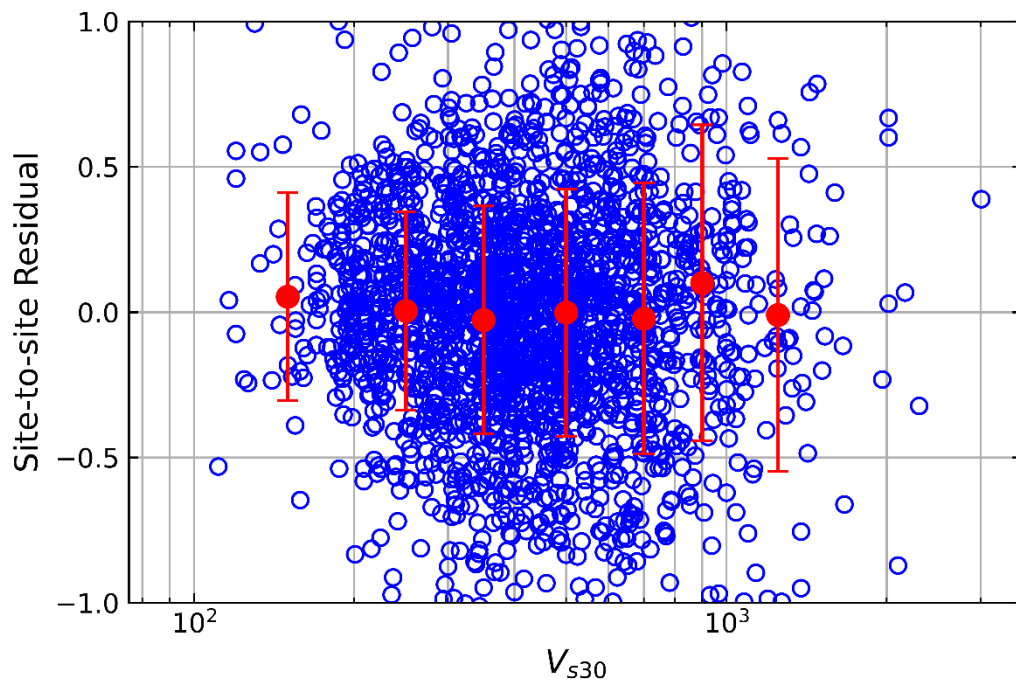


Figure B.43. Site-to-site standard deviation with V_{s30} for 0.05s.

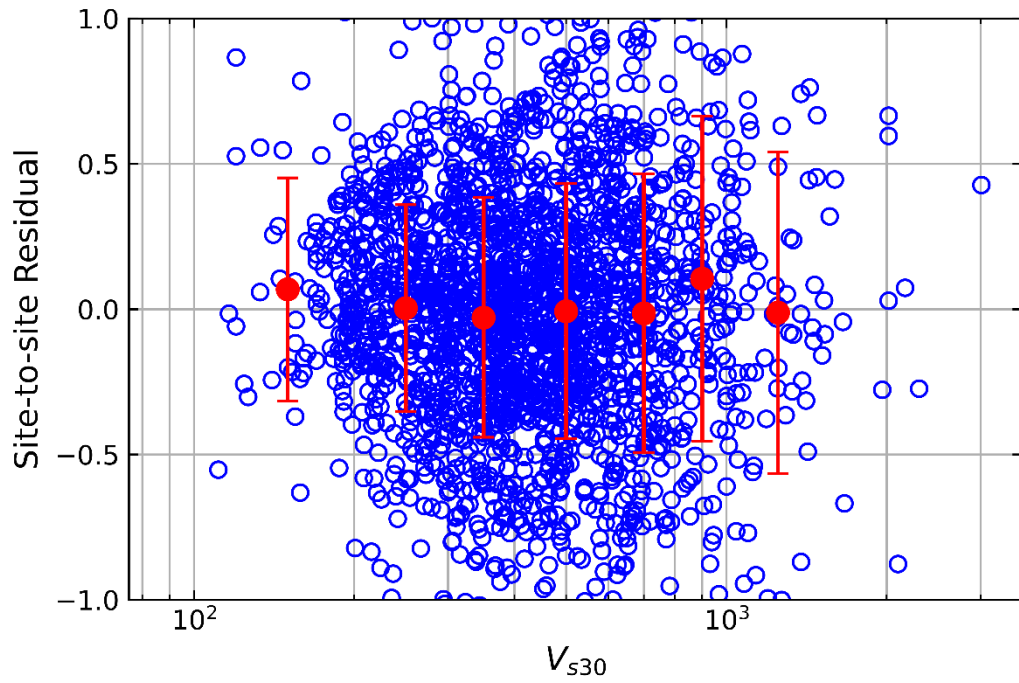


Figure B.44. Site-to-site standard deviation with V_{s30} for 0.07s.

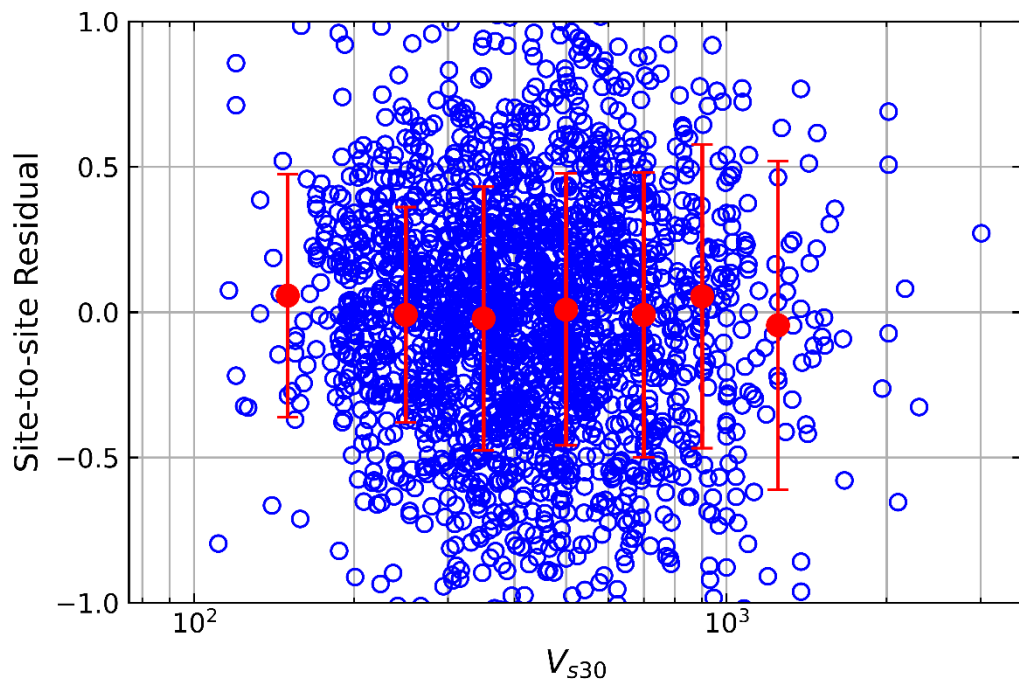


Figure B.45. Site-to-site standard deviation with V_{s30} for 0.1s.

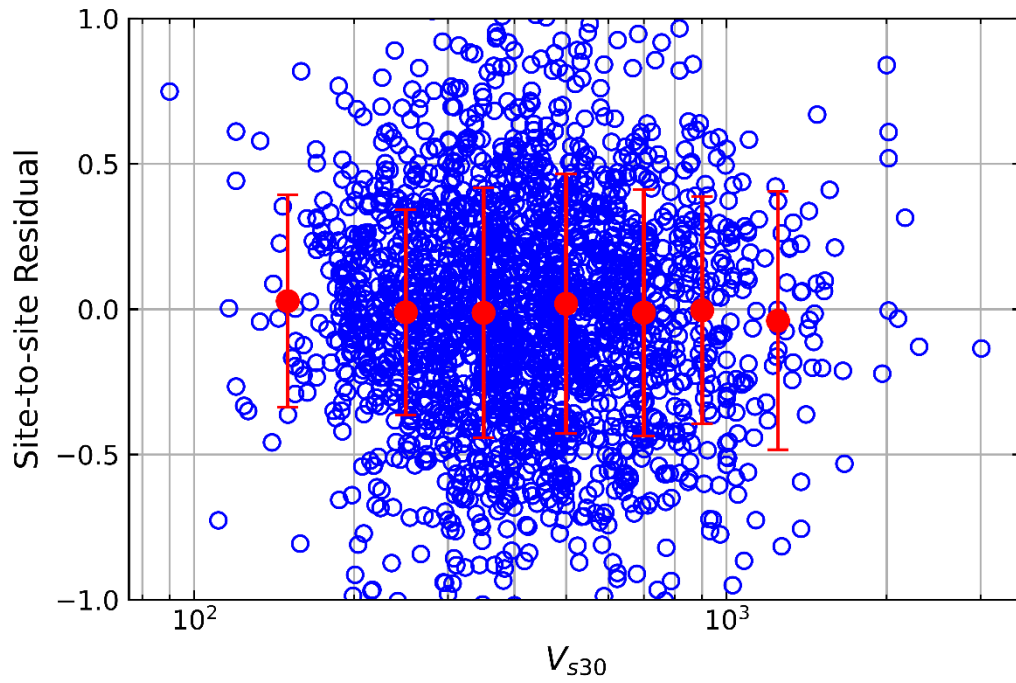


Figure B.46. Site-to-site standard deviation with V_{s30} for 0.15s.

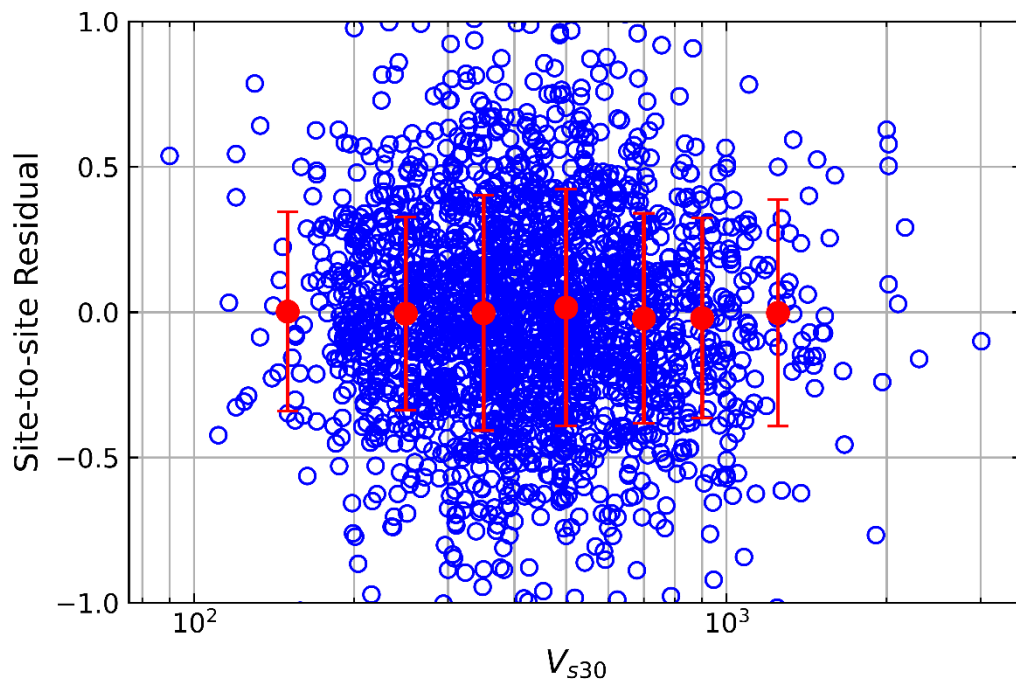


Figure B.47. Site-to-site standard deviation with V_{s30} for 0.2s.

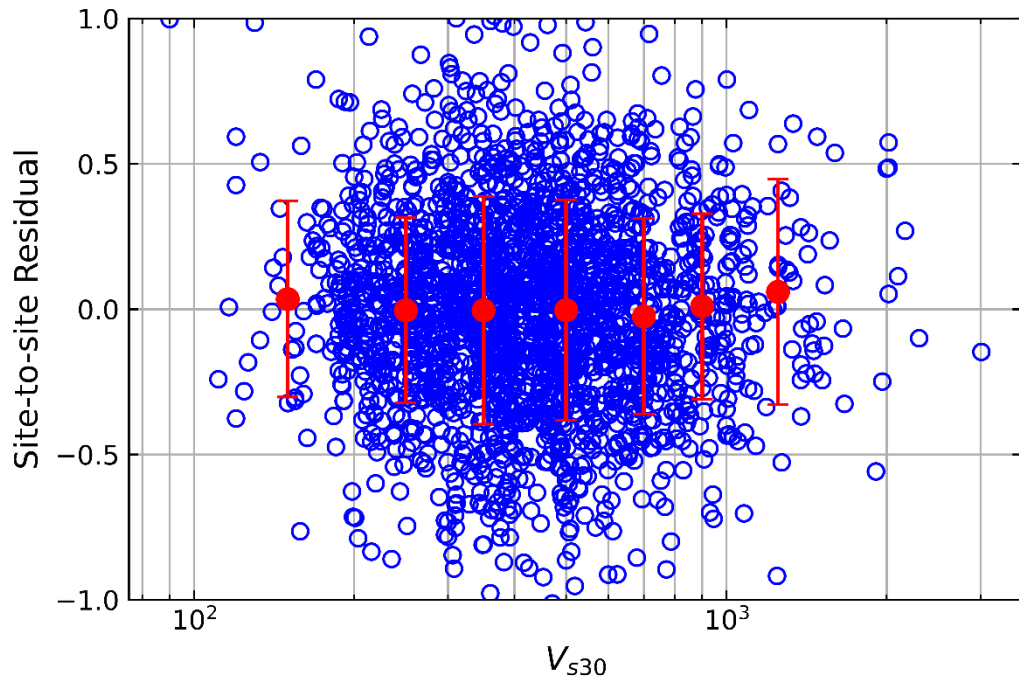


Figure B.48. Site-to-site standard deviation with V_{s30} for 0.25s.

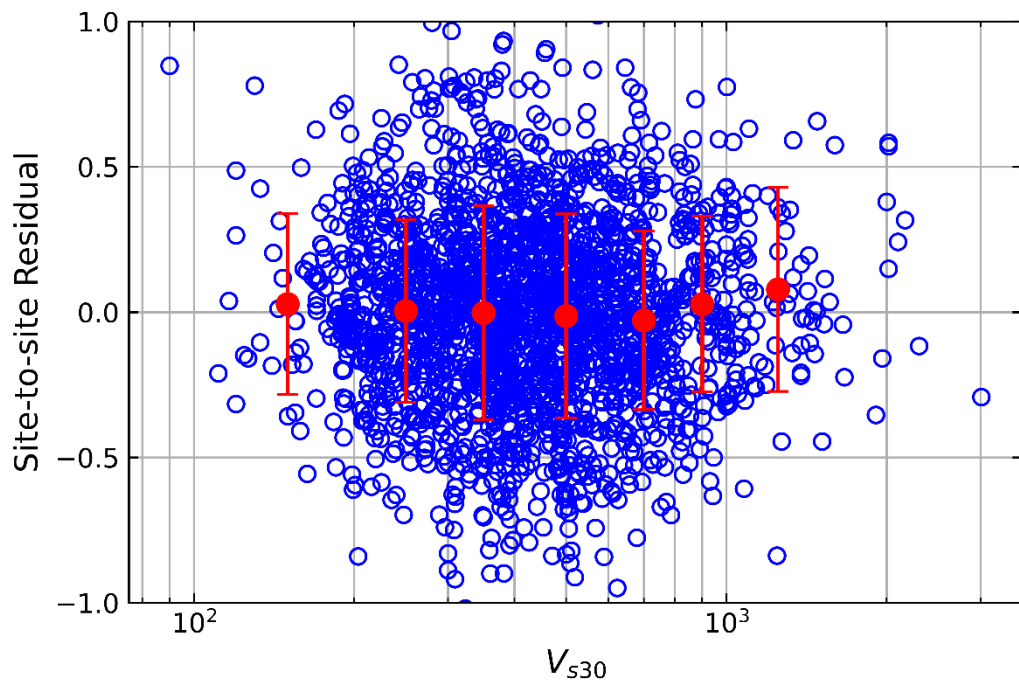


Figure B.49. Site-to-site standard deviation with V_{s30} for 0.3s.

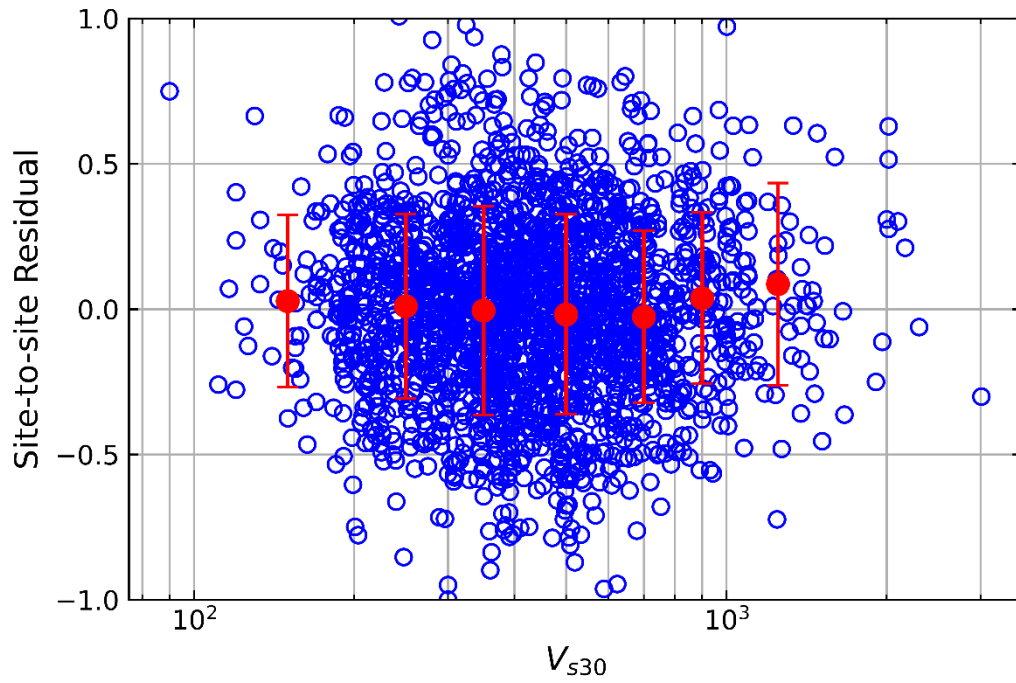


Figure B.50. Site-to-site standard deviation with V_{s30} for 0.35s.

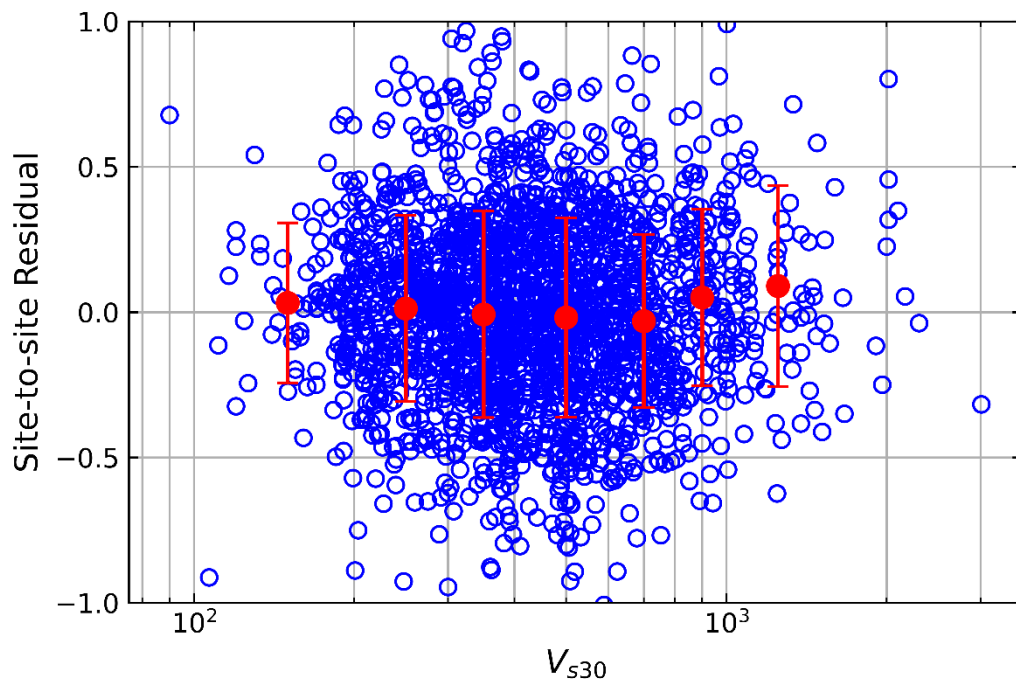


Figure B.51. Site-to-site standard deviation with V_{s30} for 0.4s.

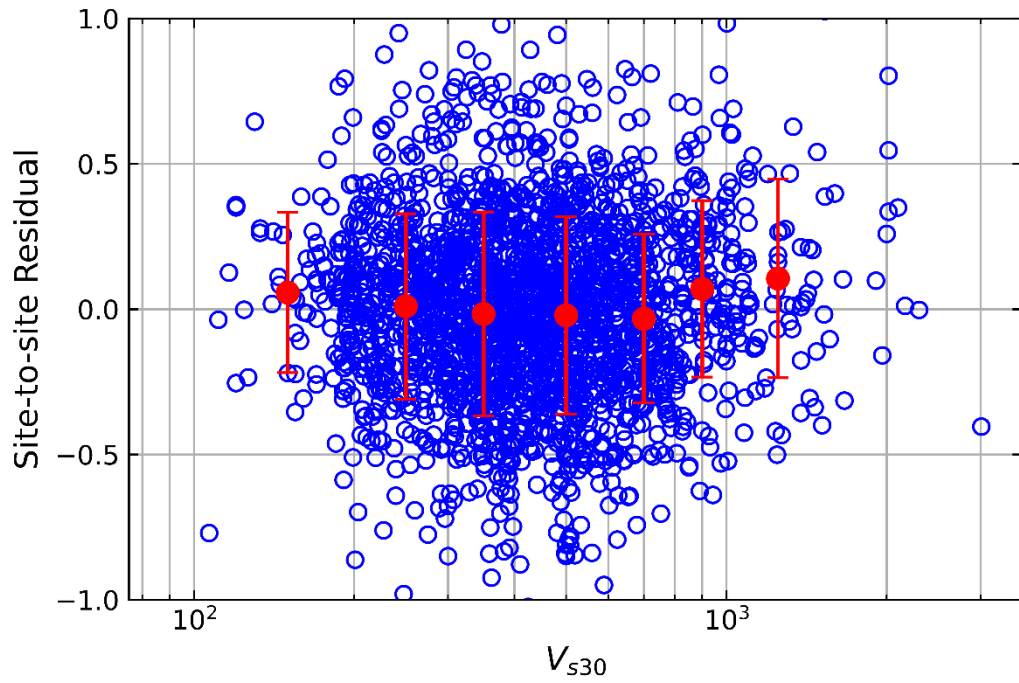


Figure B.52. Site-to-site standard deviation with V_{s30} for 0.45s.

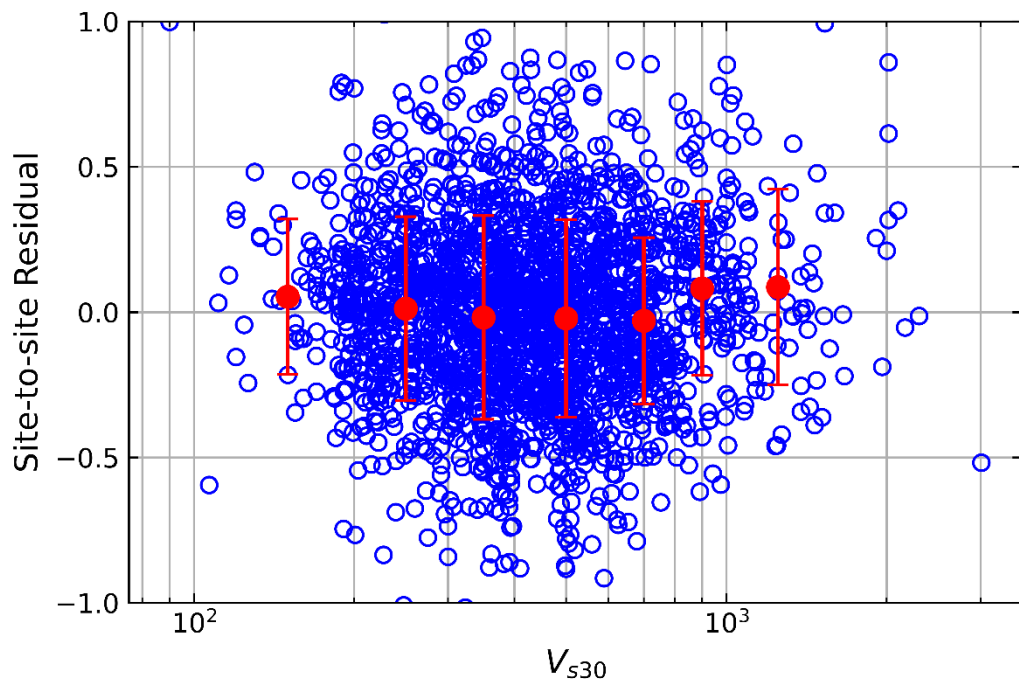


Figure B.53. Site-to-site standard deviation with V_{s30} for 0.5s.

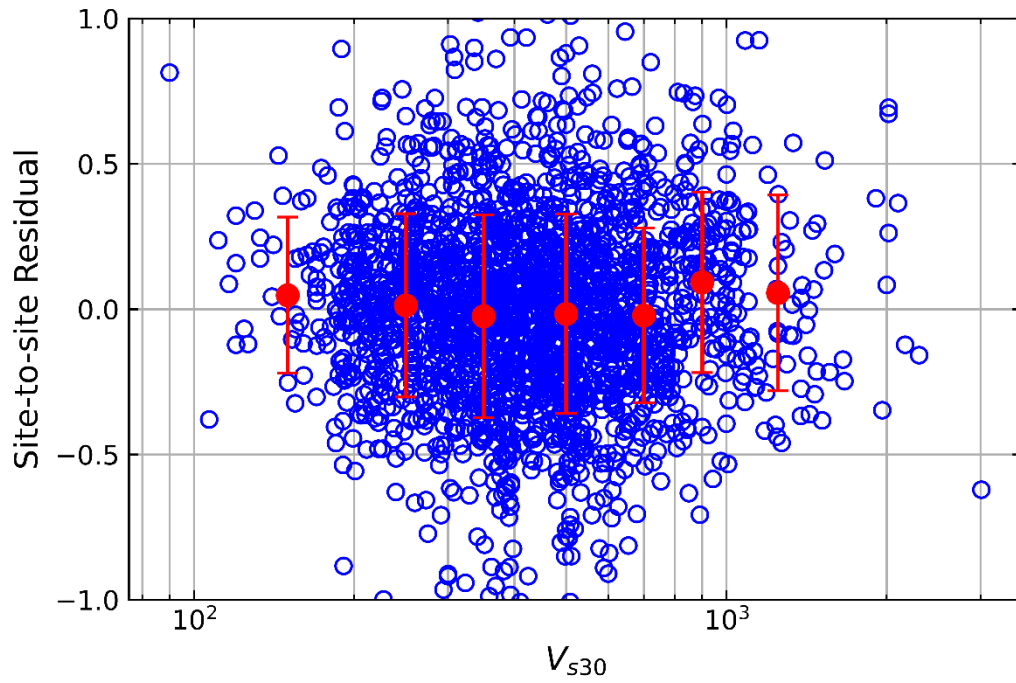


Figure B.54. Site-to-site standard deviation with V_{s30} for 0.6s.

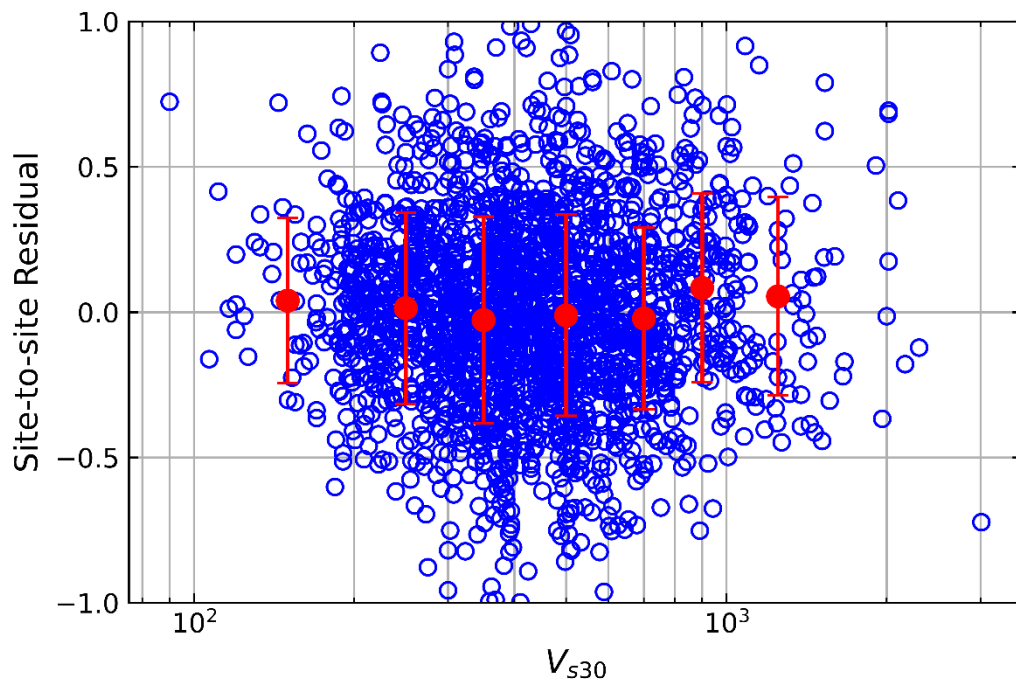


Figure B.55. Site-to-site standard deviation with V_{s30} for 0.7s.

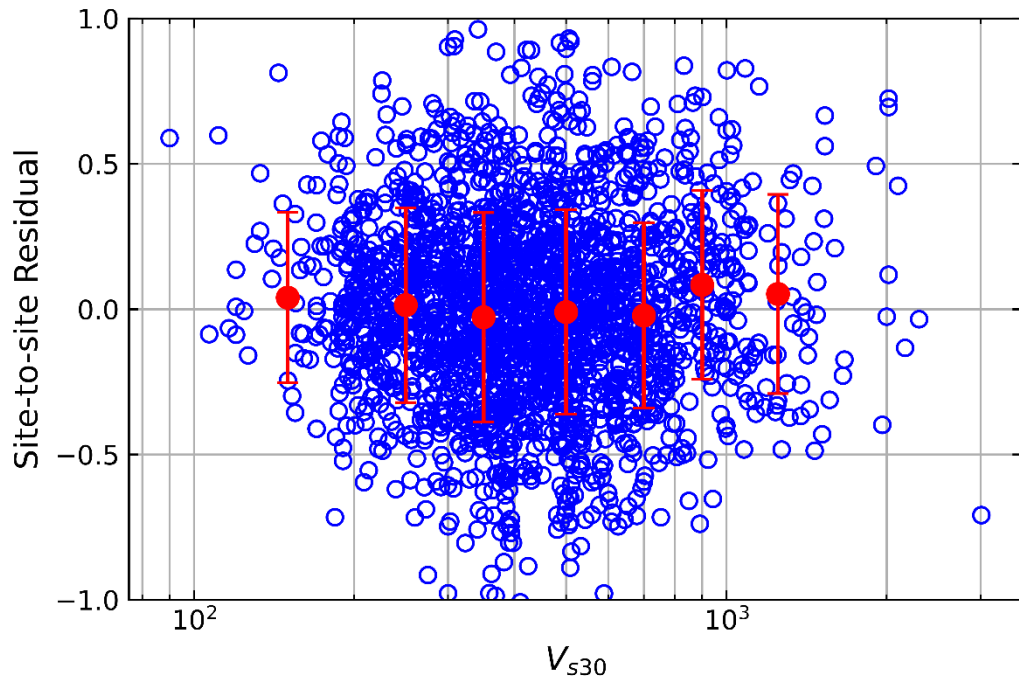


Figure B.56. Site-to-site standard deviation with V_{s30} for 0.75s.

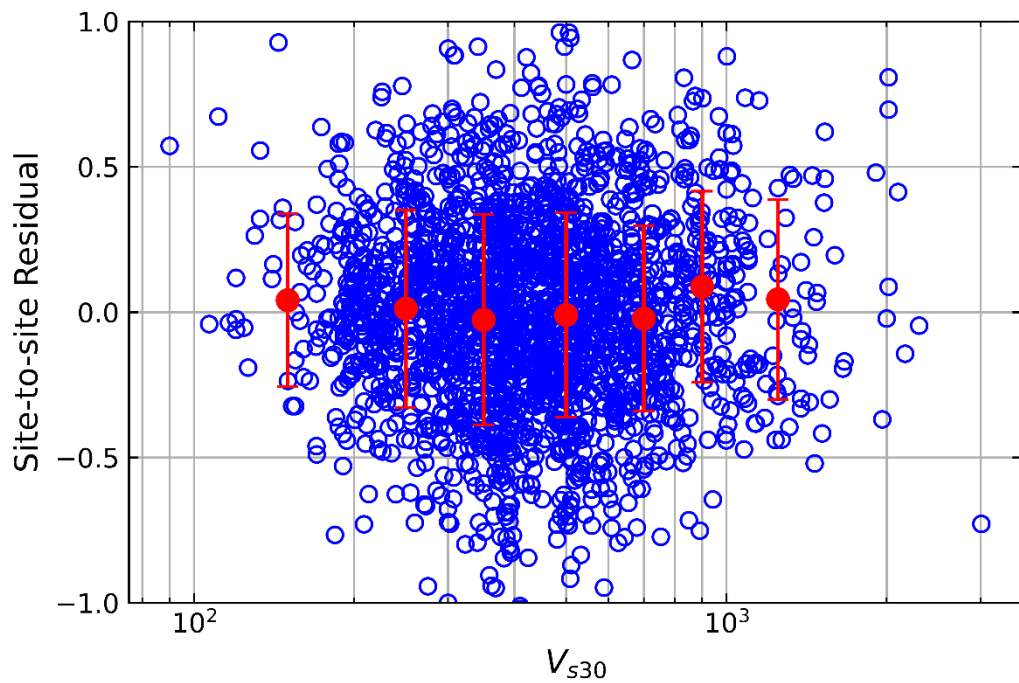


Figure B.57. Site-to-site standard deviation with V_{s30} for 0.8s.

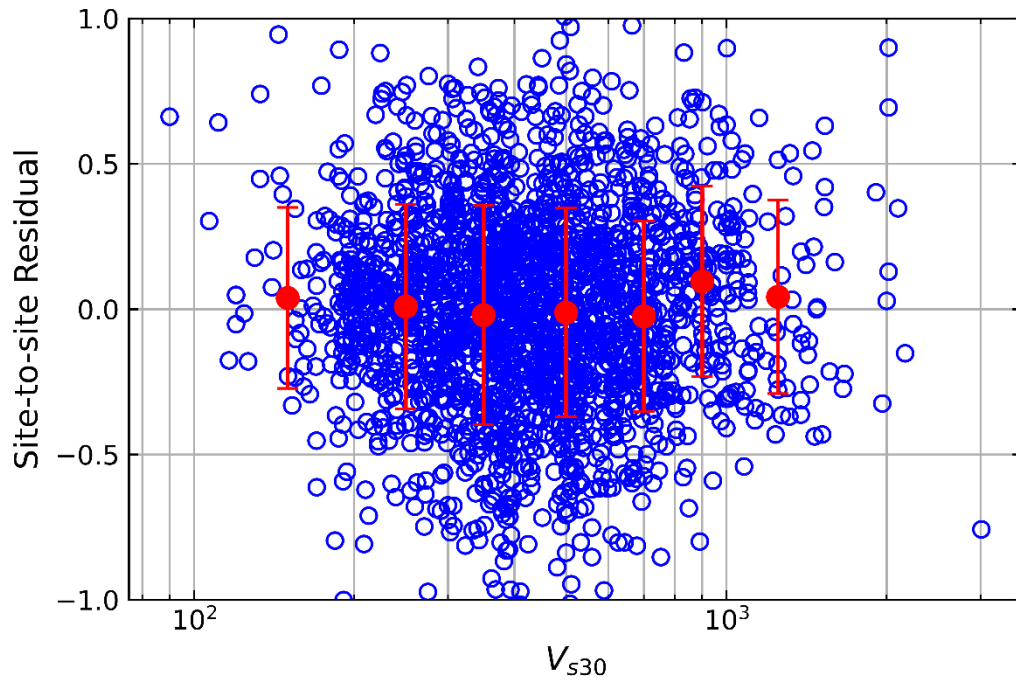


Figure B.58. Site-to-site standard deviation with V_{s30} for 0.9s.

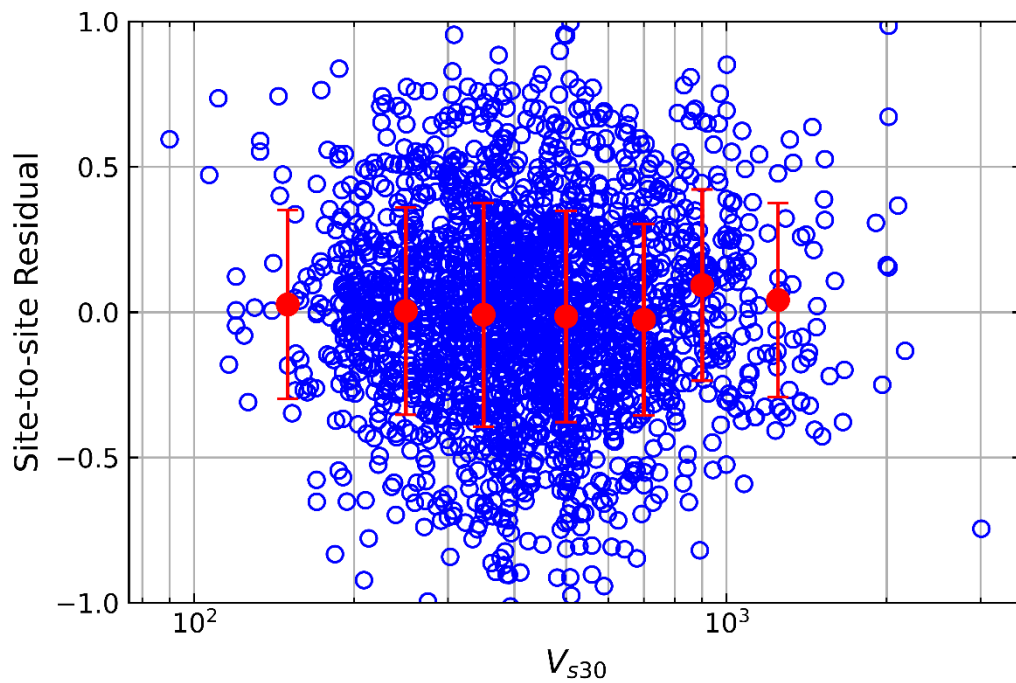


Figure B.59. Site-to-site standard deviation with V_{s30} for 1s.

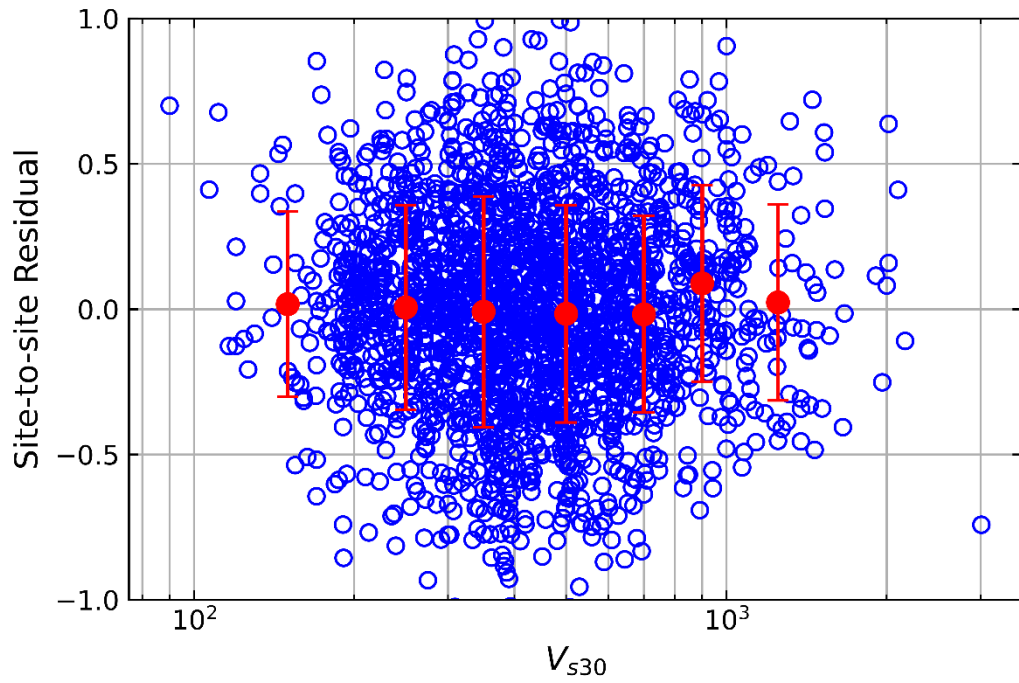


Figure B.60. Site-to-site standard deviation with V_{s30} for 1.2s.

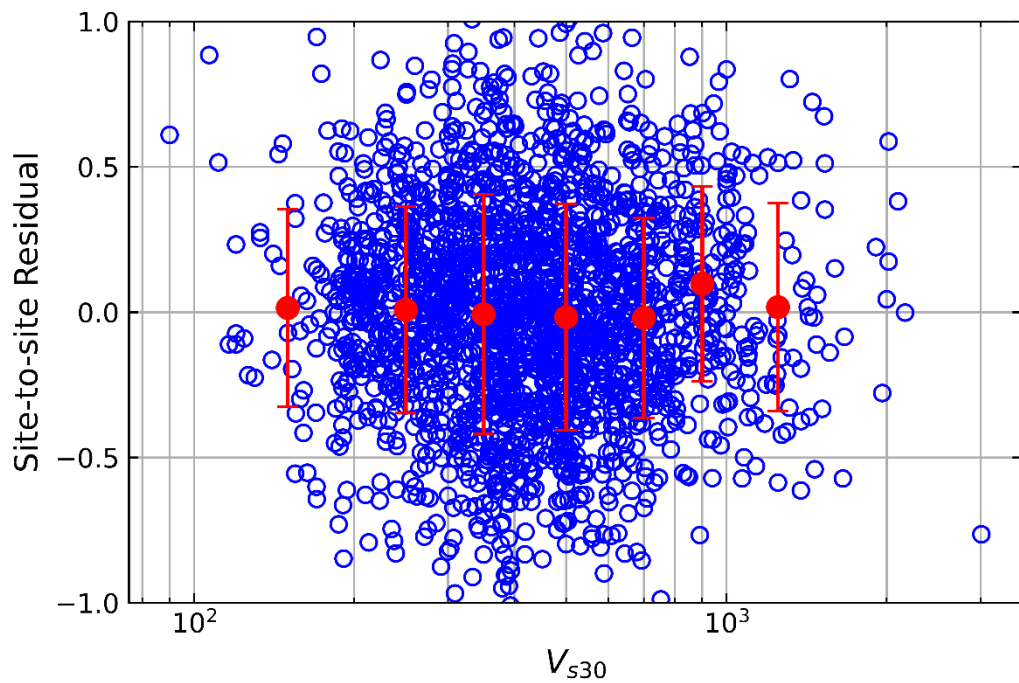


Figure B.61. Site-to-site standard deviation with V_{s30} for 1.4s.

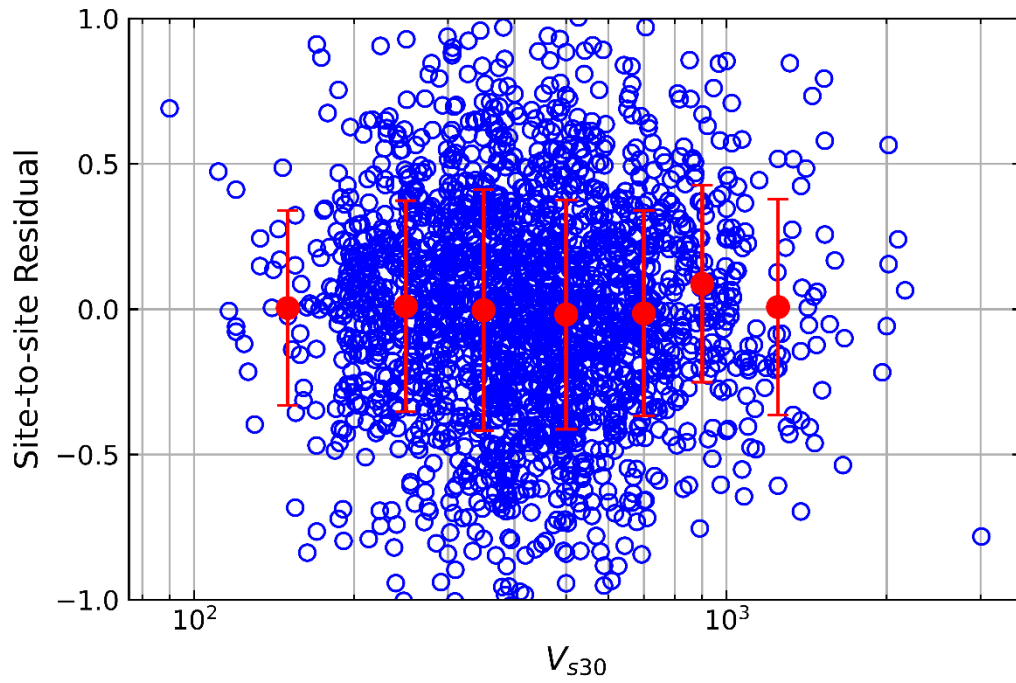


Figure B.62. Site-to-site standard deviation with V_{s30} for 1.6s.

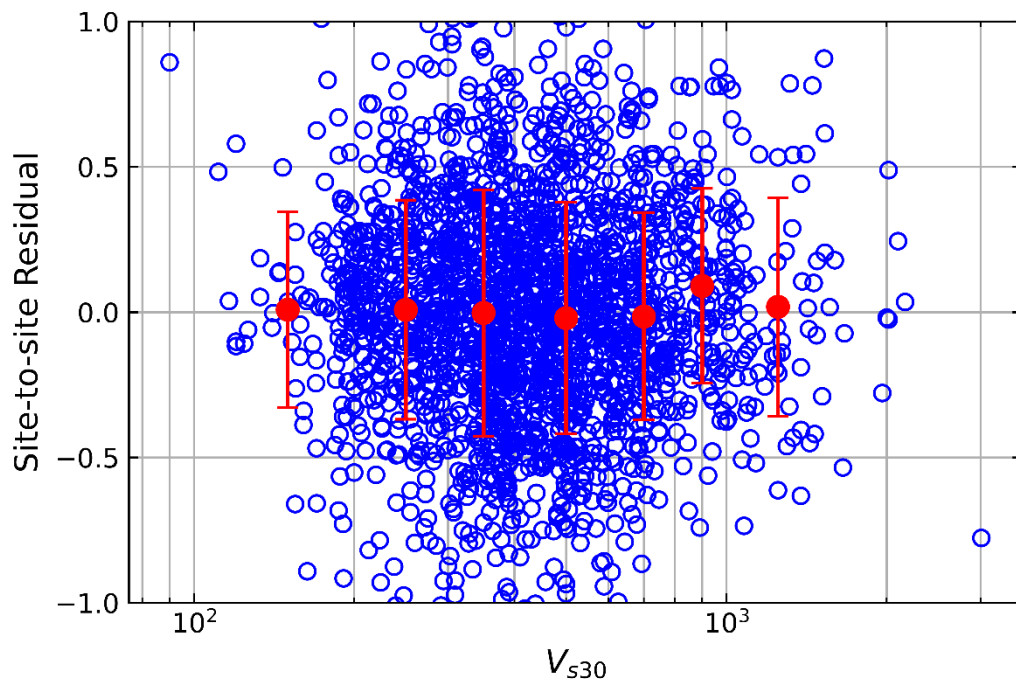


Figure B.63. Site-to-site standard deviation with V_{s30} for 1.8s.

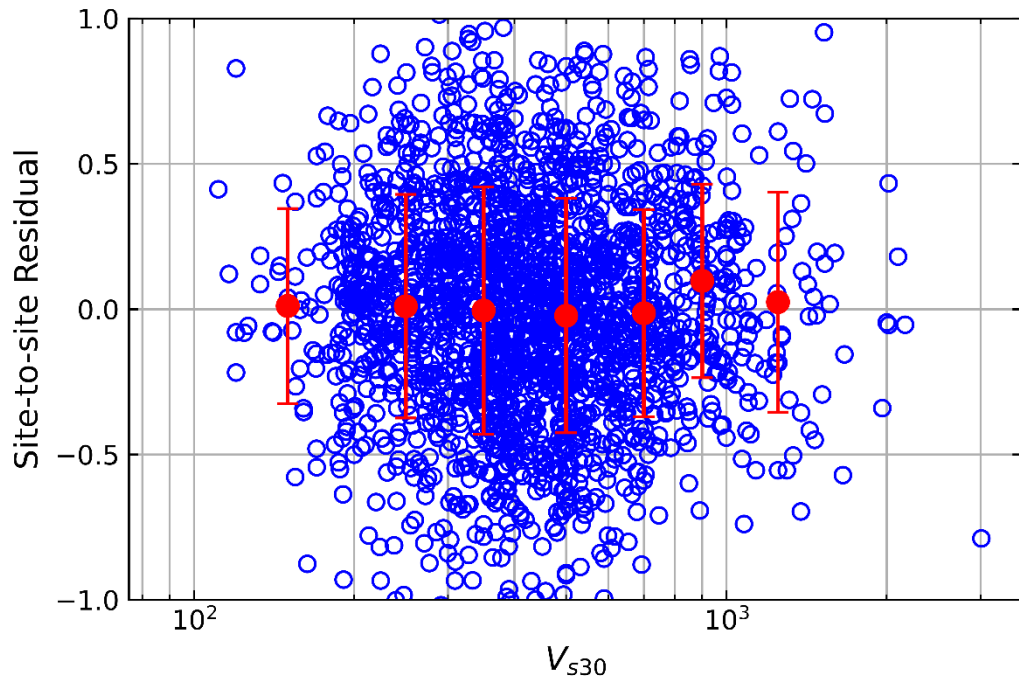


Figure B.64. Site-to-site standard deviation with V_{s30} for 2s.

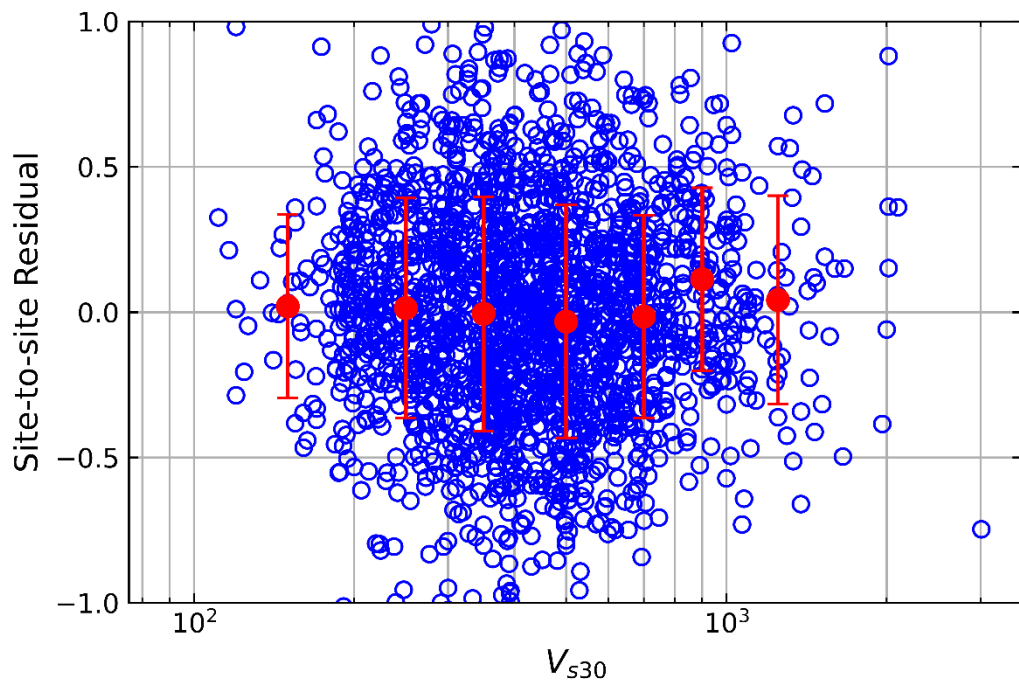


Figure B.65. Site-to-site standard deviation with V_{s30} for 2.5s.

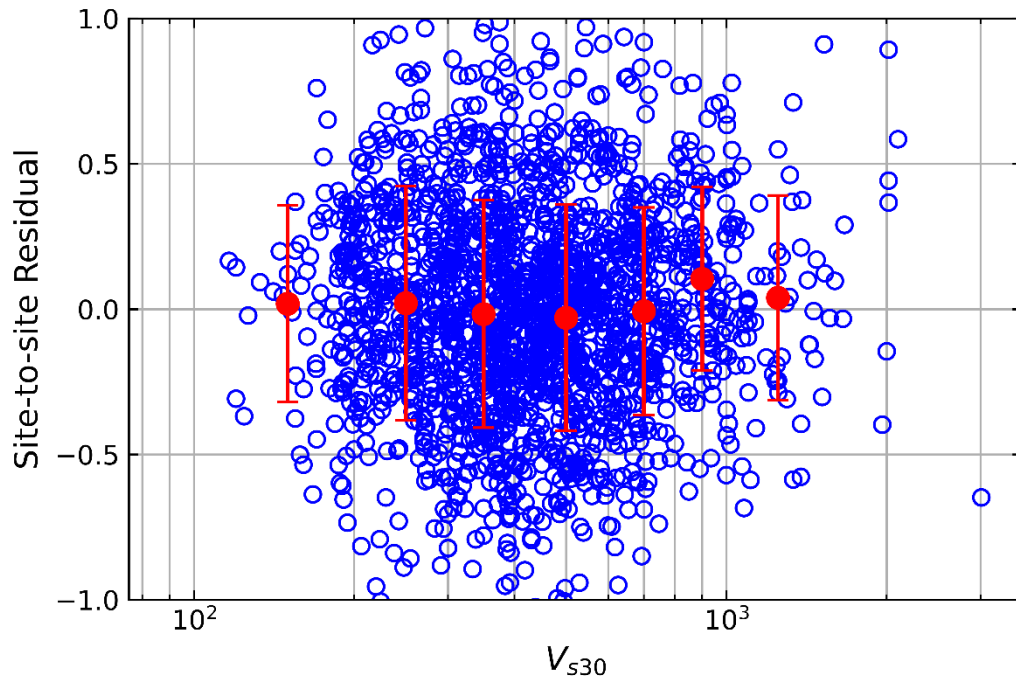


Figure B.66. Site-to-site standard deviation with V_{s30} for 3s.

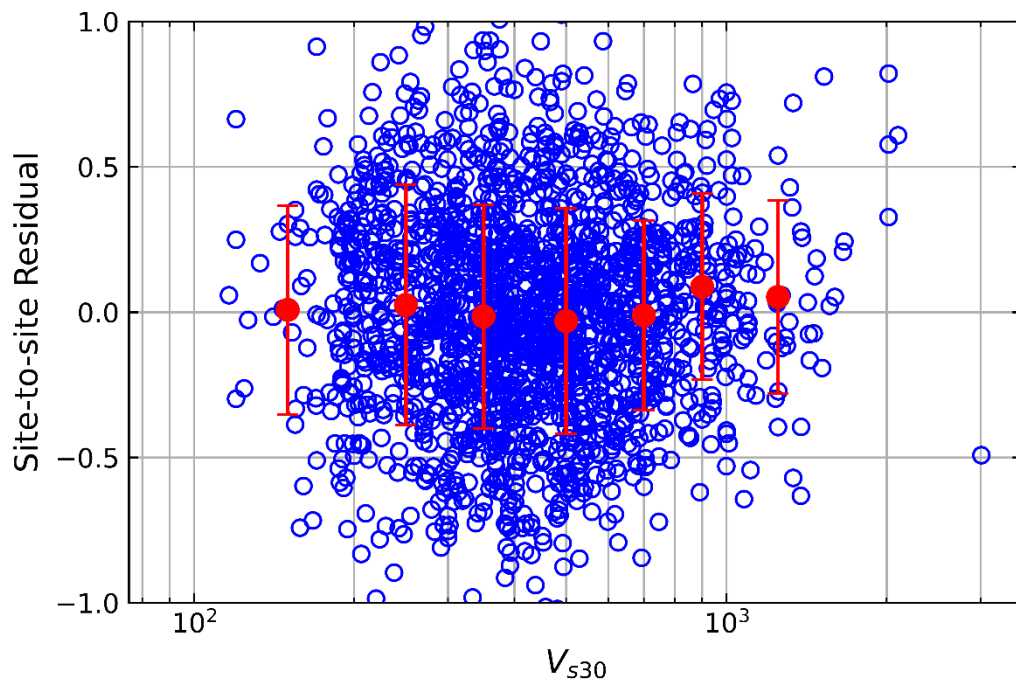


Figure B.67. Site-to-site standard deviation with V_{s30} for 3.5s.

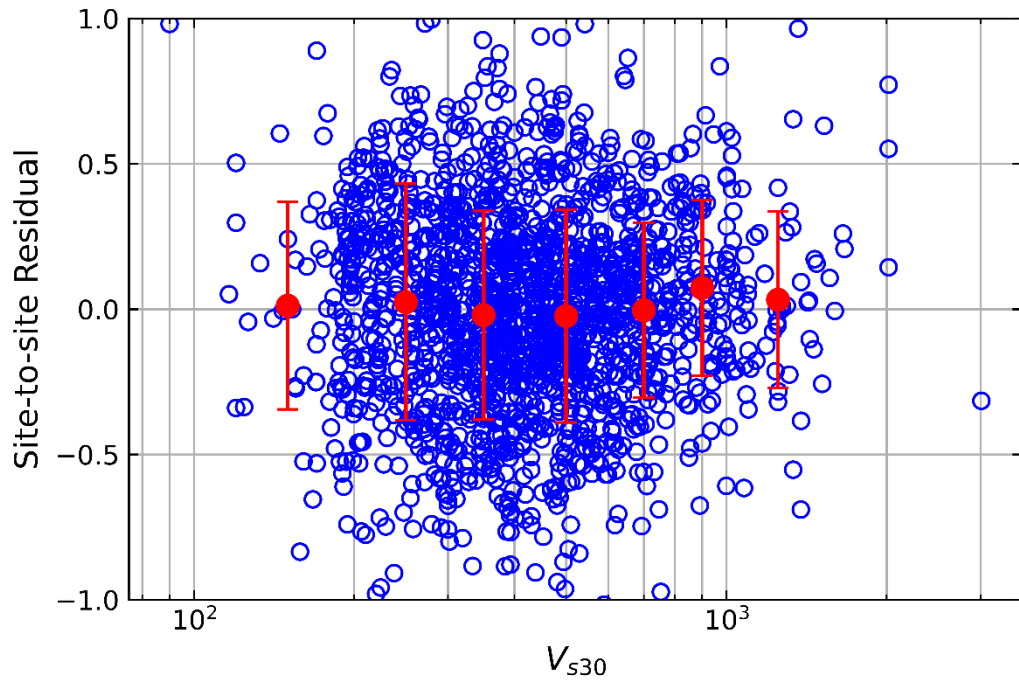


Figure B.68. Site-to-site standard deviation with V_{s30} for 4s.

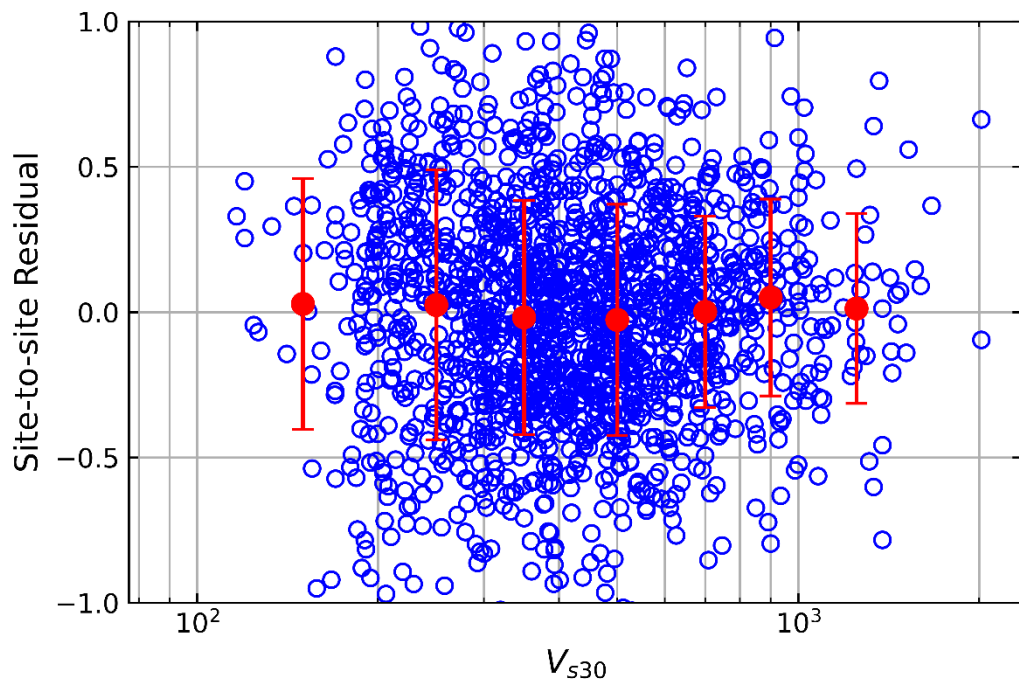


Figure B.69. Site-to-site standard deviation with V_{s30} for 5s.

APPENDIX C- Between-Event Standard Deviation Model

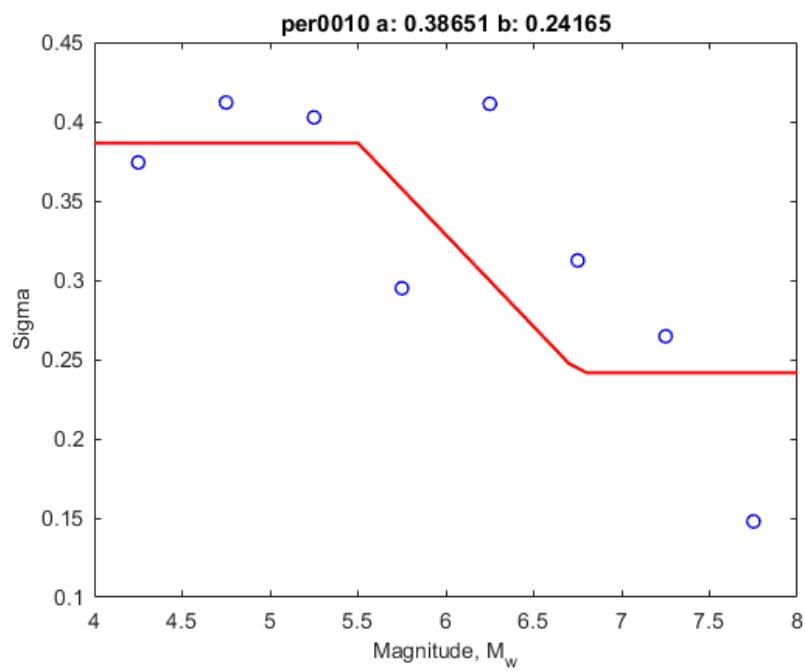


Figure C.1. Between-event standard deviation model for 0.01s.

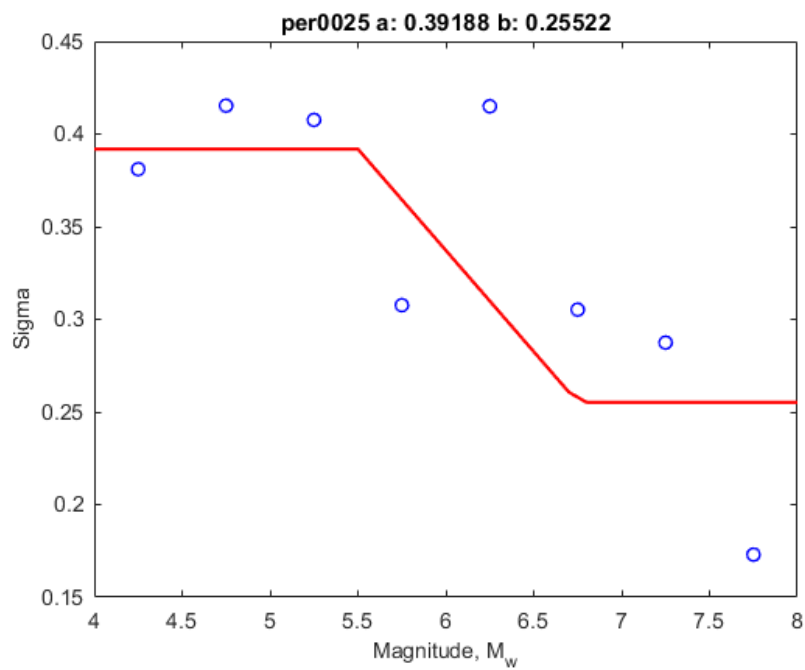


Figure C.2. Between-event standard deviation model for 0.025s.

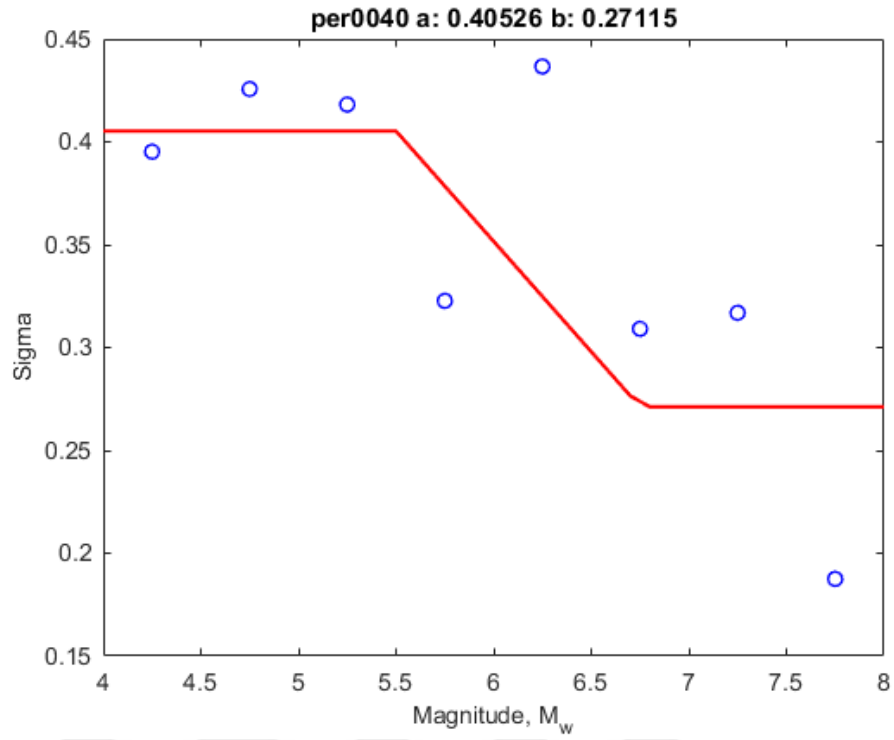


Figure C.3. Between-event standard deviation model for 0.04s.

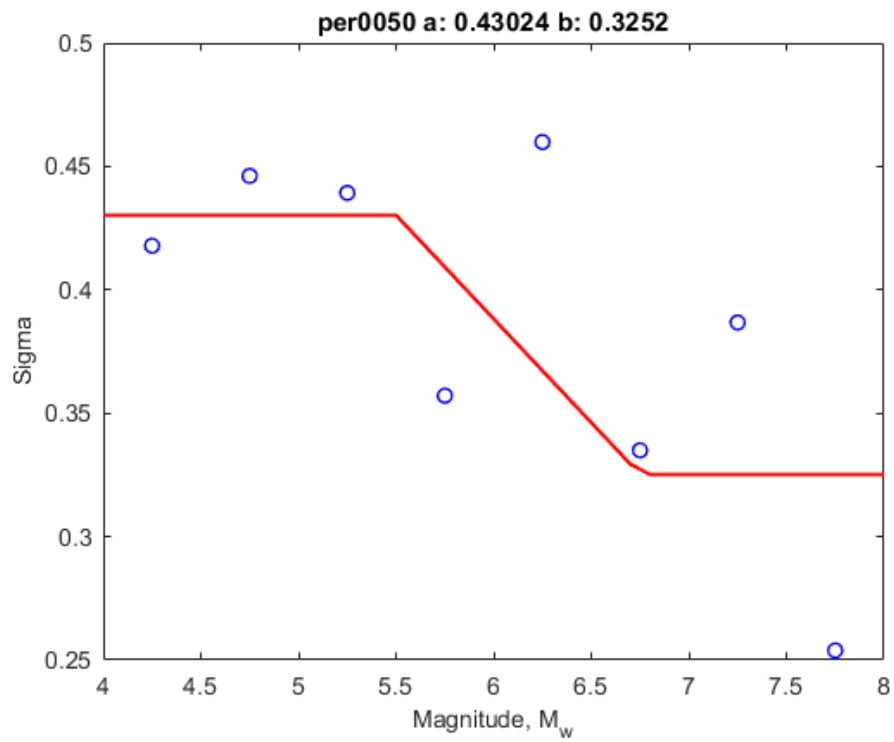


Figure C.4. Between-event standard deviation model for 0.05s.

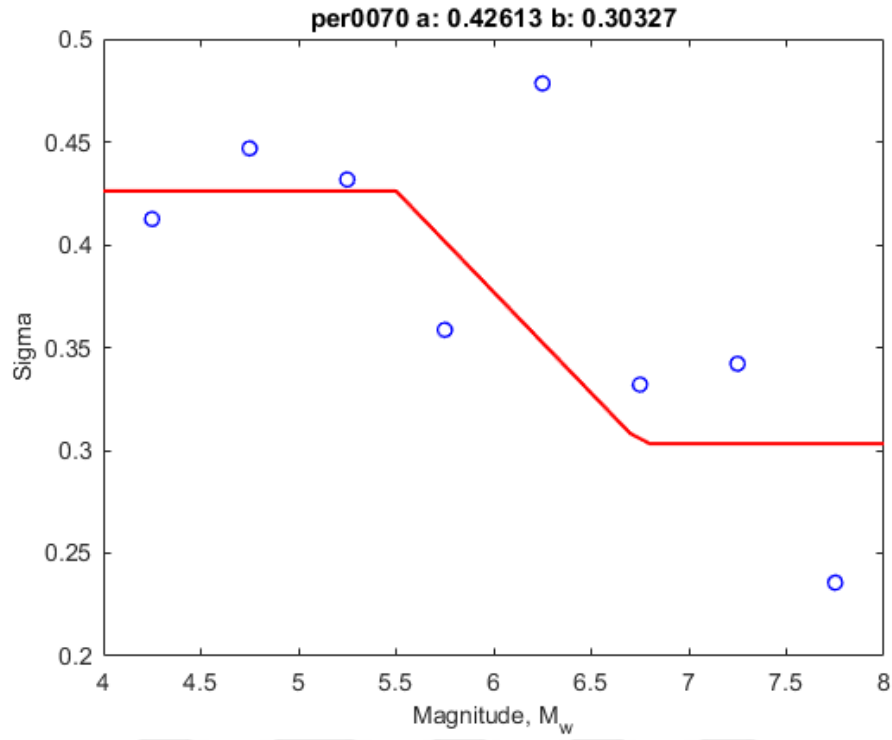


Figure C.5. Between-event standard deviation model for 0.07s.

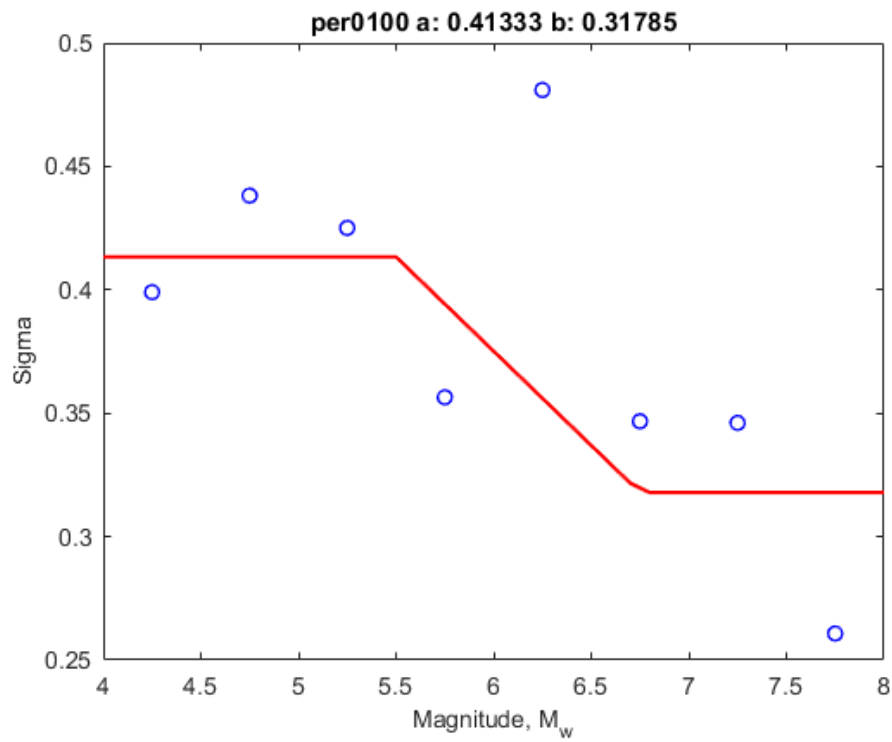


Figure C.6. Between-event standard deviation model for 0.1s.

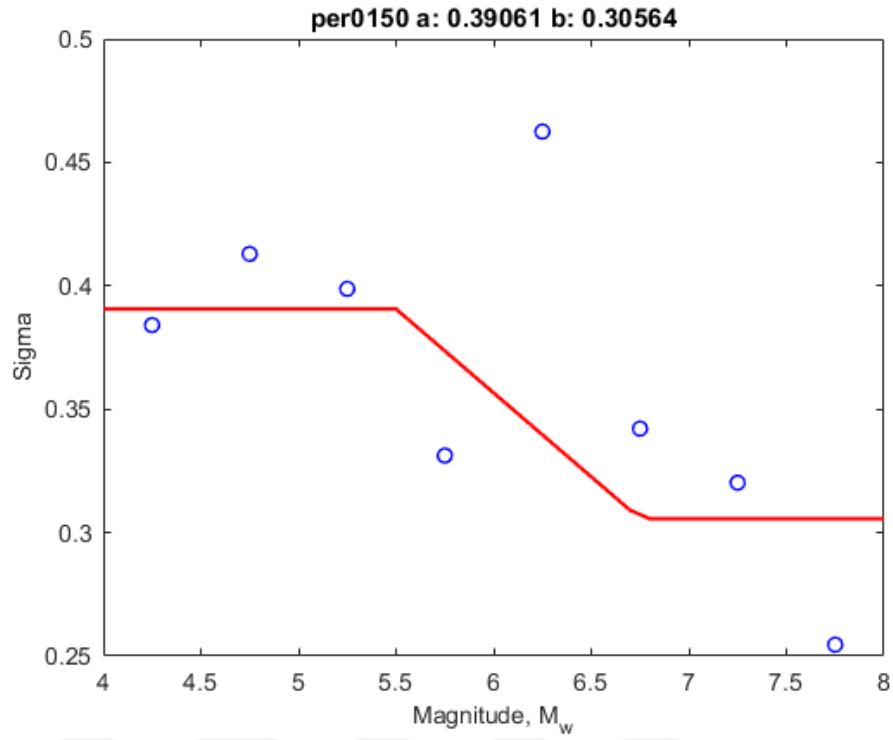


Figure C.7. Between-event standard deviation model for 0.15s.

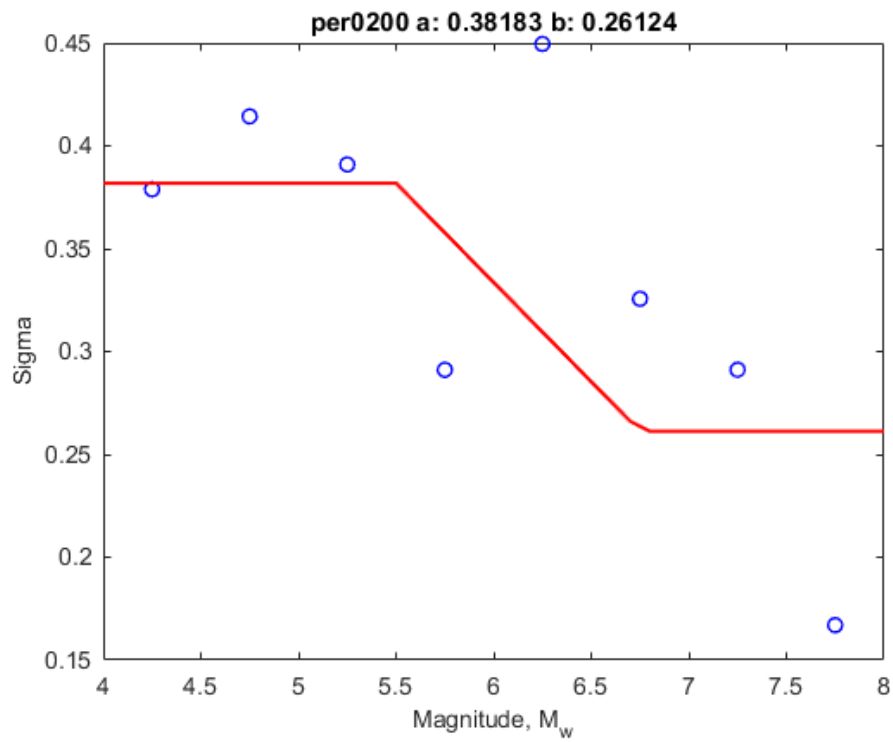


Figure C.8. Between-event standard deviation model for 0.2s.

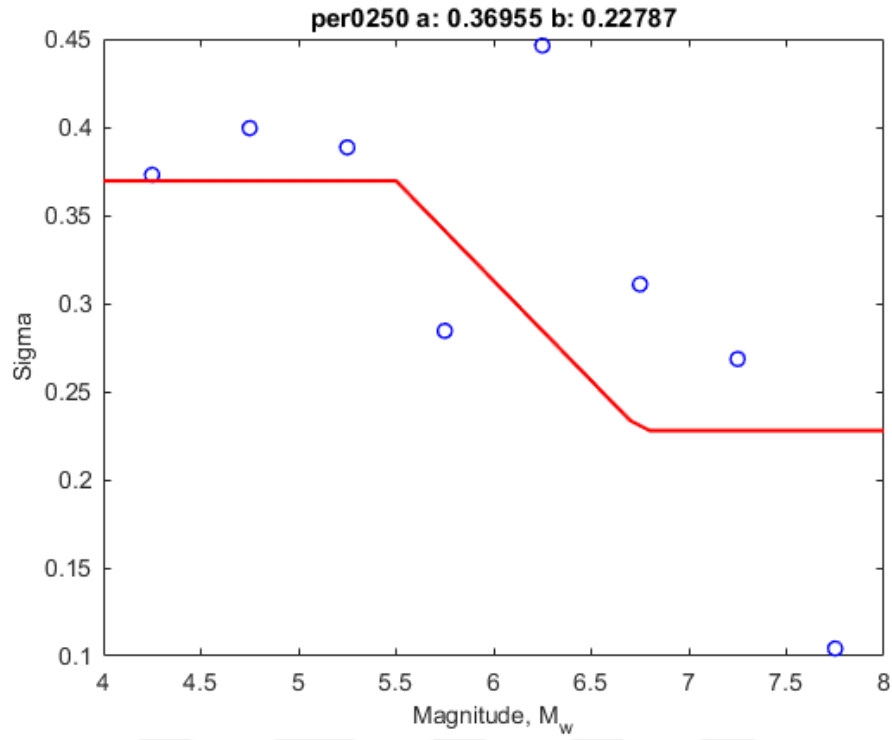


Figure C.9. Between-event standard deviation model for 0.25s.

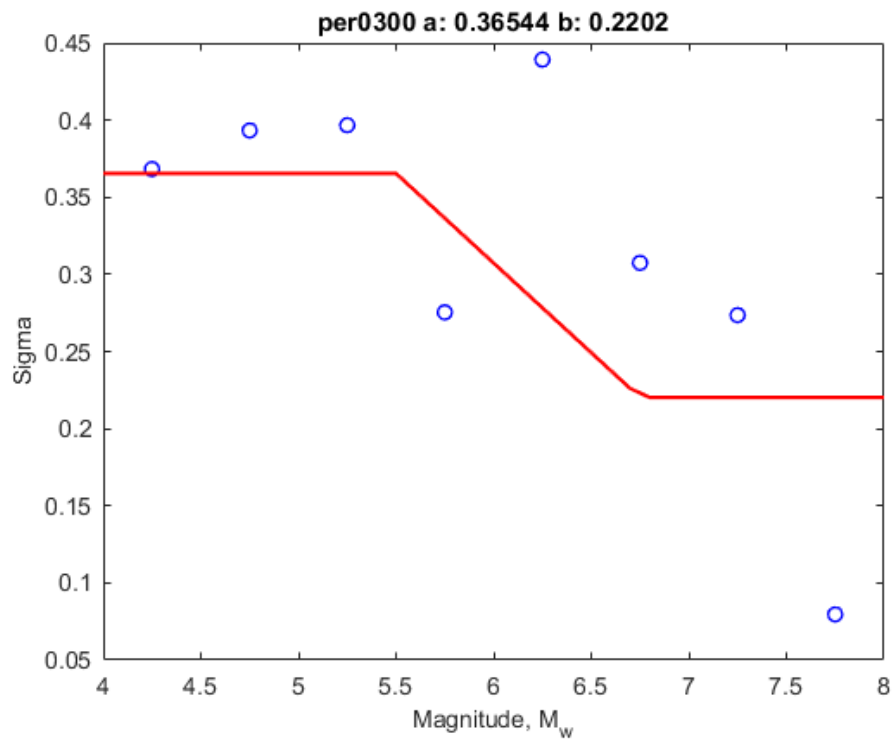


Figure C.10. Between-event standard deviation model for 0.030s.

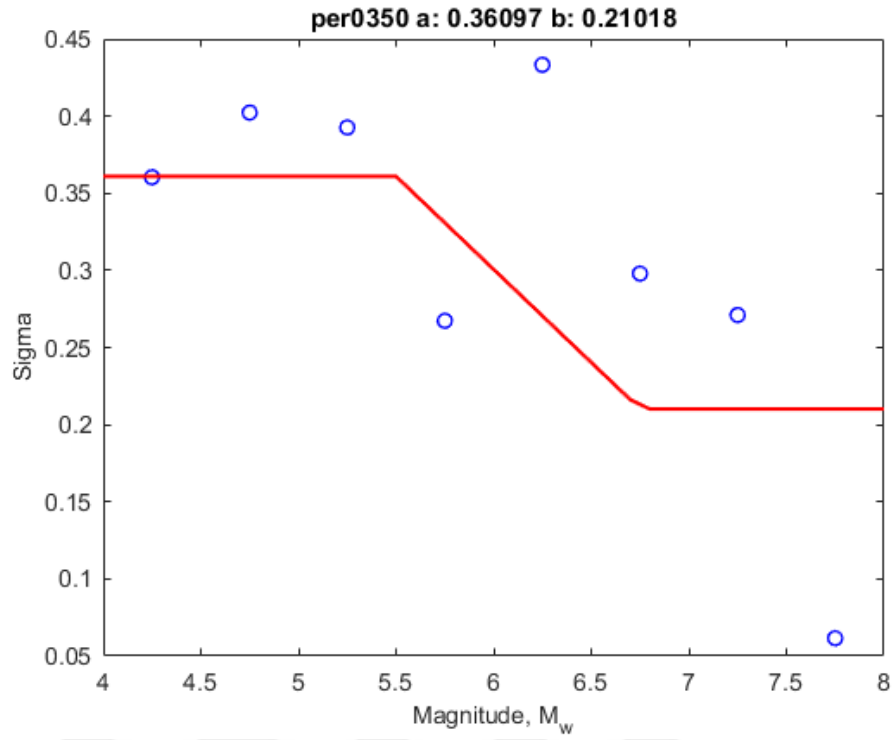


Figure C.11. Between-event standard deviation model for 0.035s.

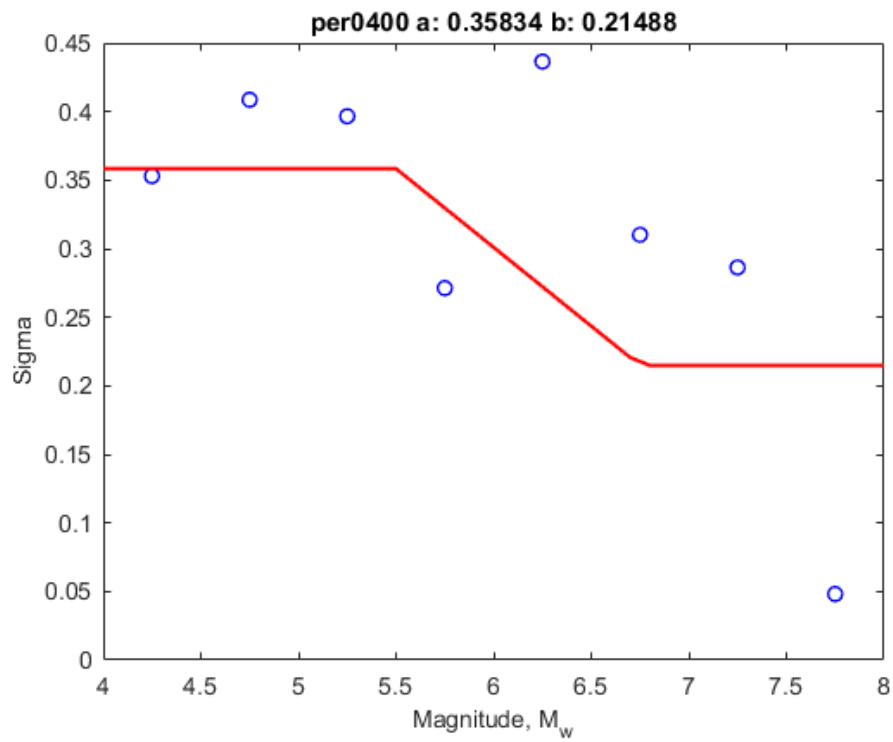


Figure C.12. Between-event standard deviation model for 0.4s.

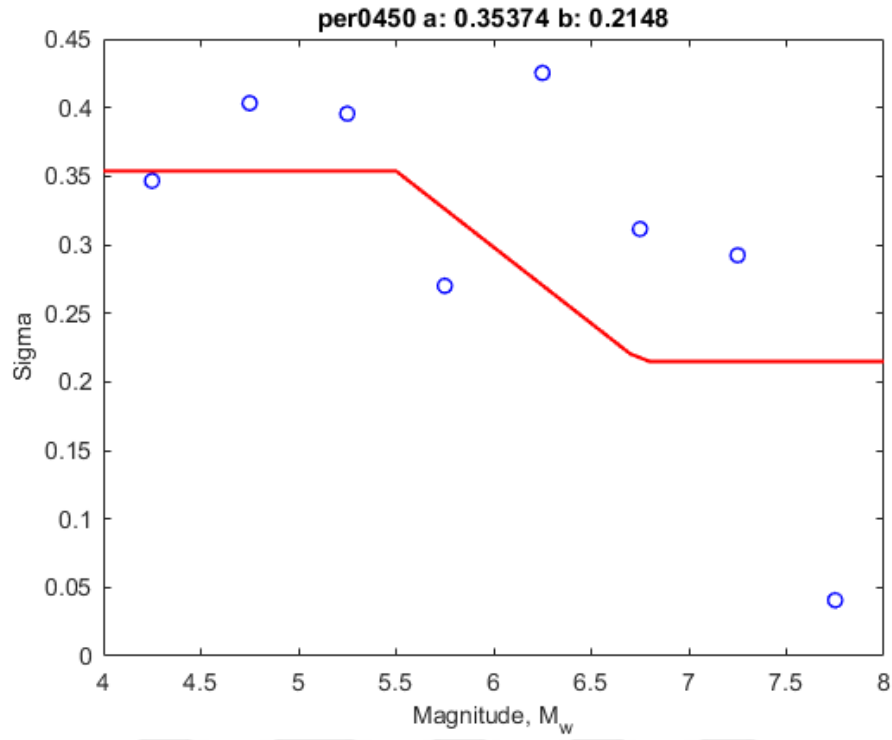


Figure C.13. Between-event standard deviation model for 0.45s

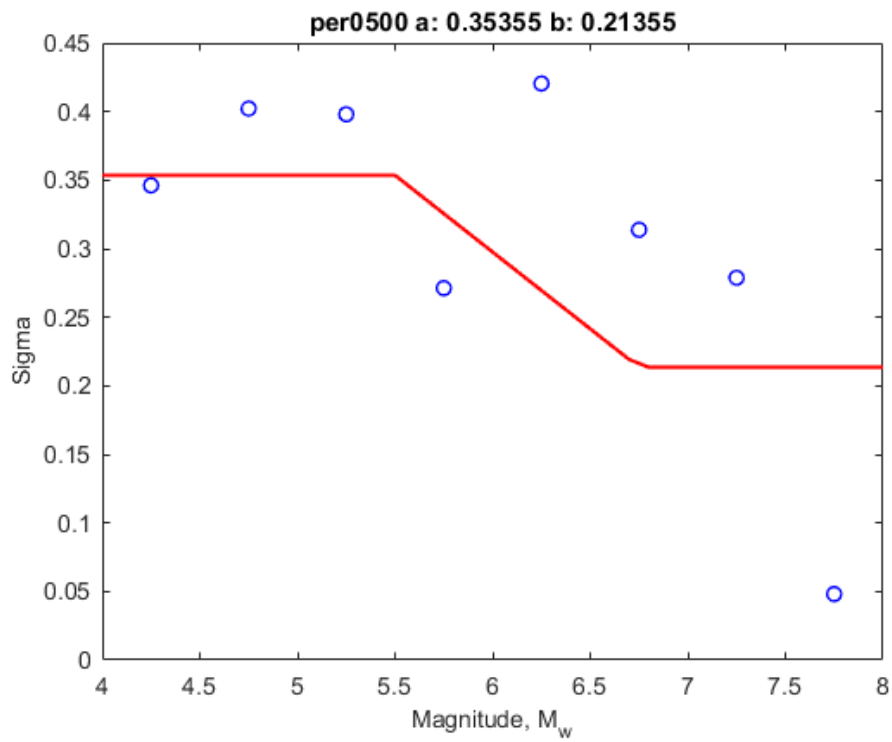


Figure C.14. Between-event standard deviation model for 0.5s.

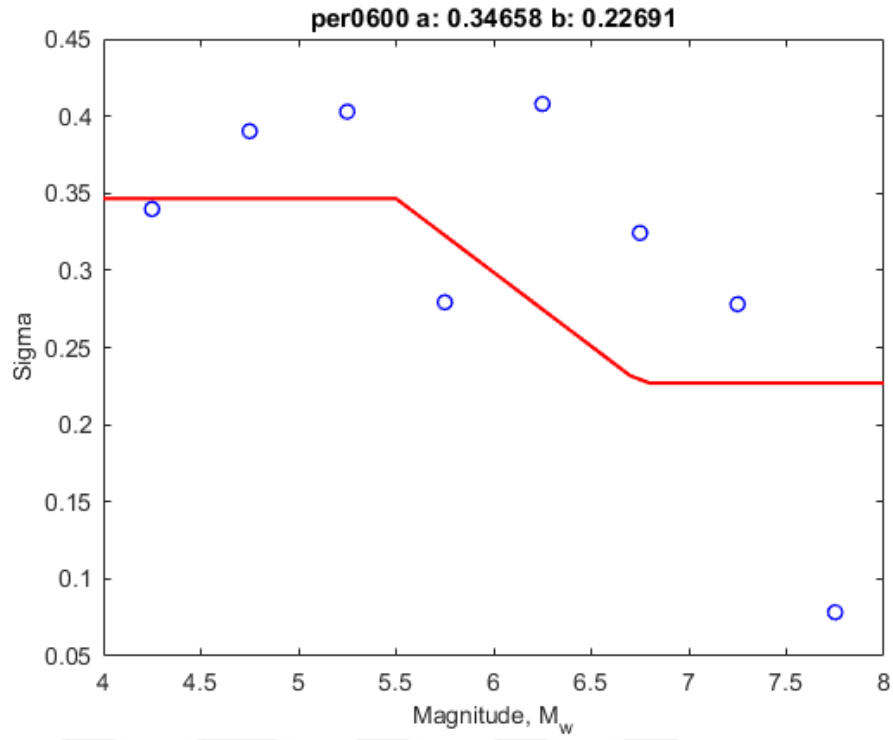


Figure C.15. Between-event standard deviation model for 0.6s.

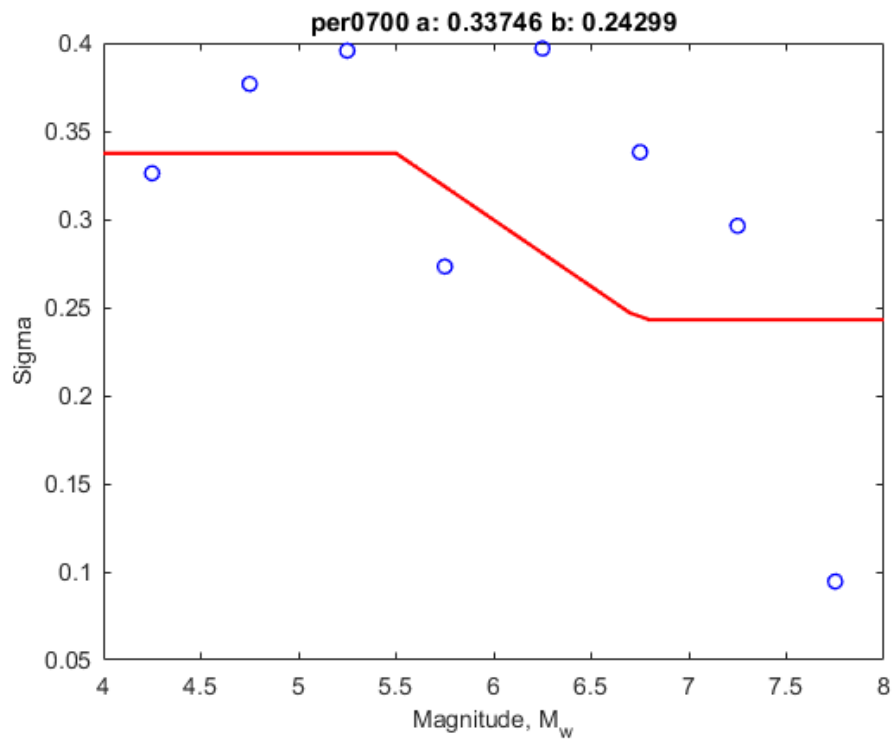


Figure C.16. Between-event standard deviation model for 0.7s.

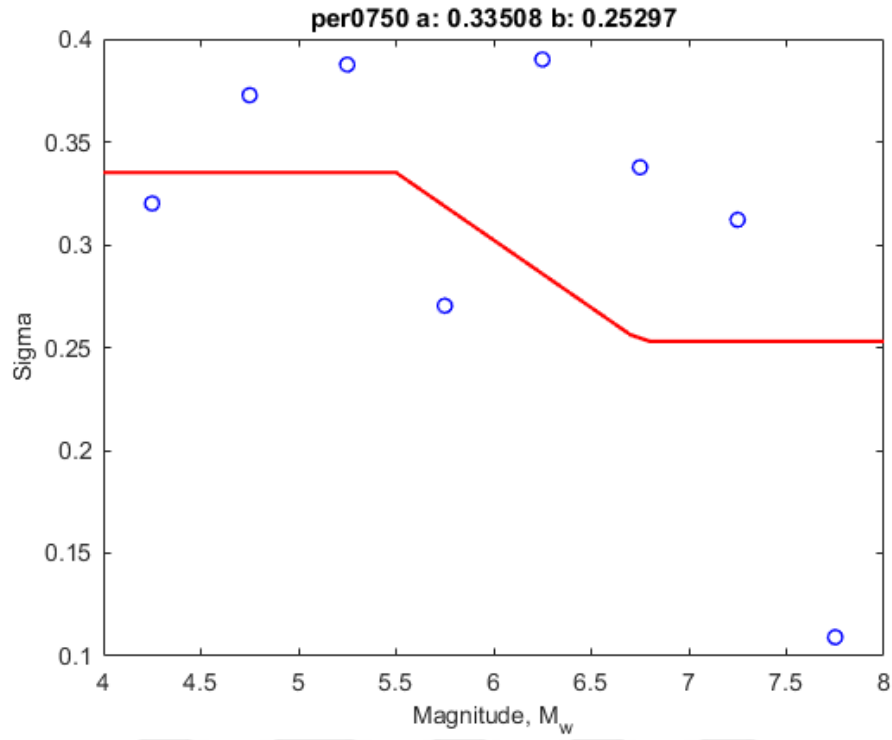


Figure C.17. Between-event standard deviation model for 0.75s.

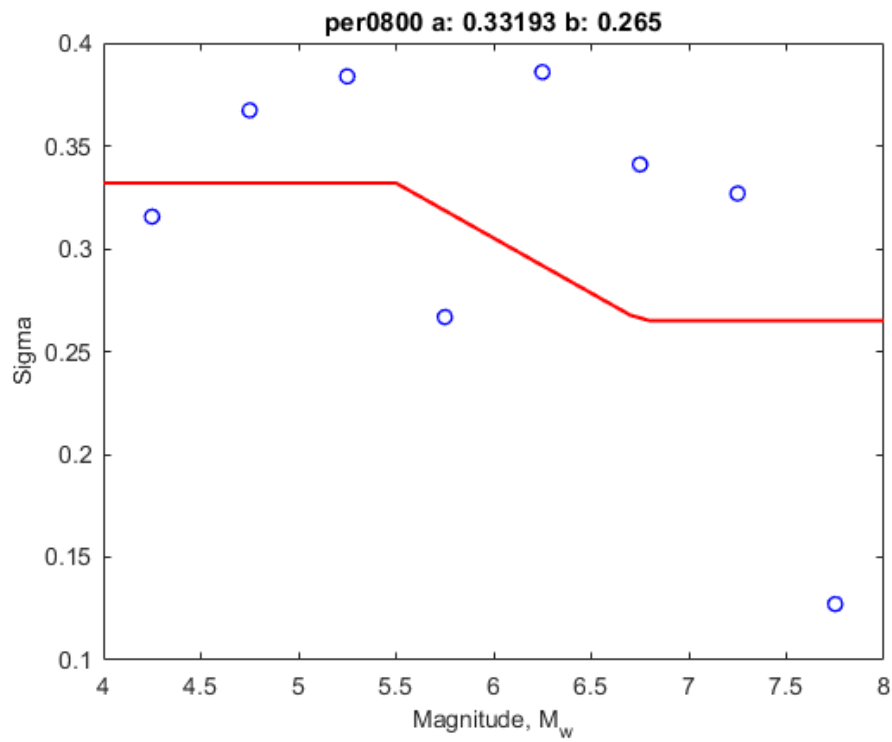


Figure C.18. Between-event standard deviation model for 0.8s.

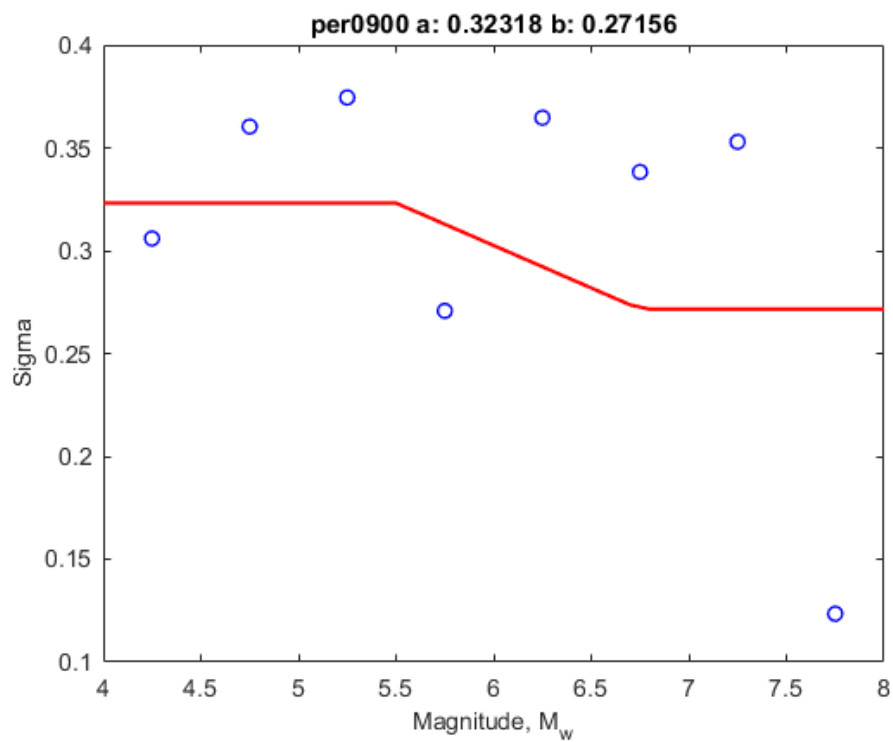


Figure C.19. Between-event standard deviation model for 0.9s.

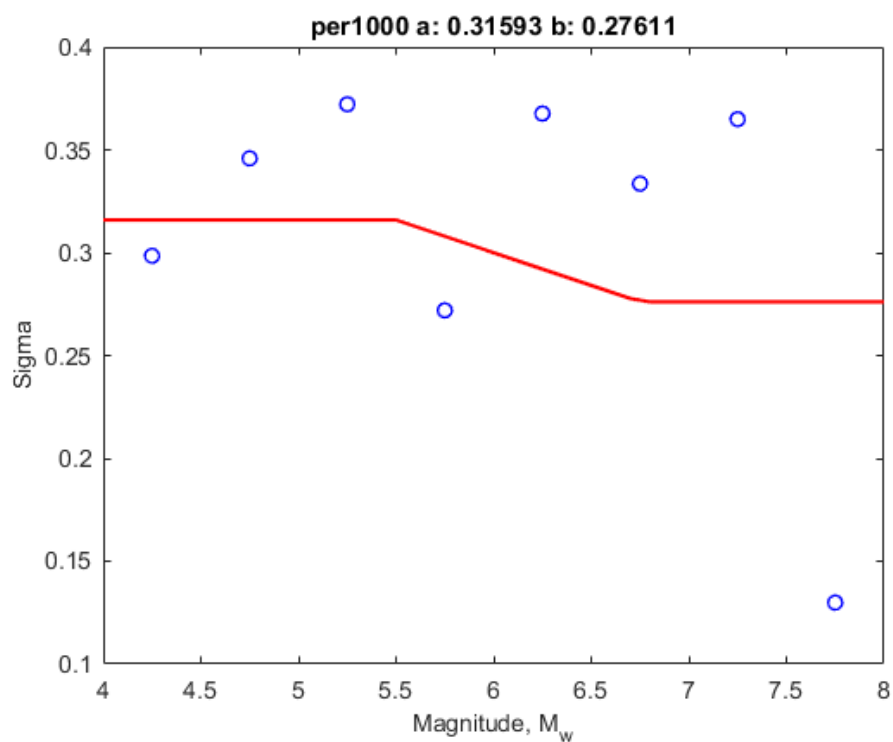


Figure C.20. Between-event standard deviation model for 1s.

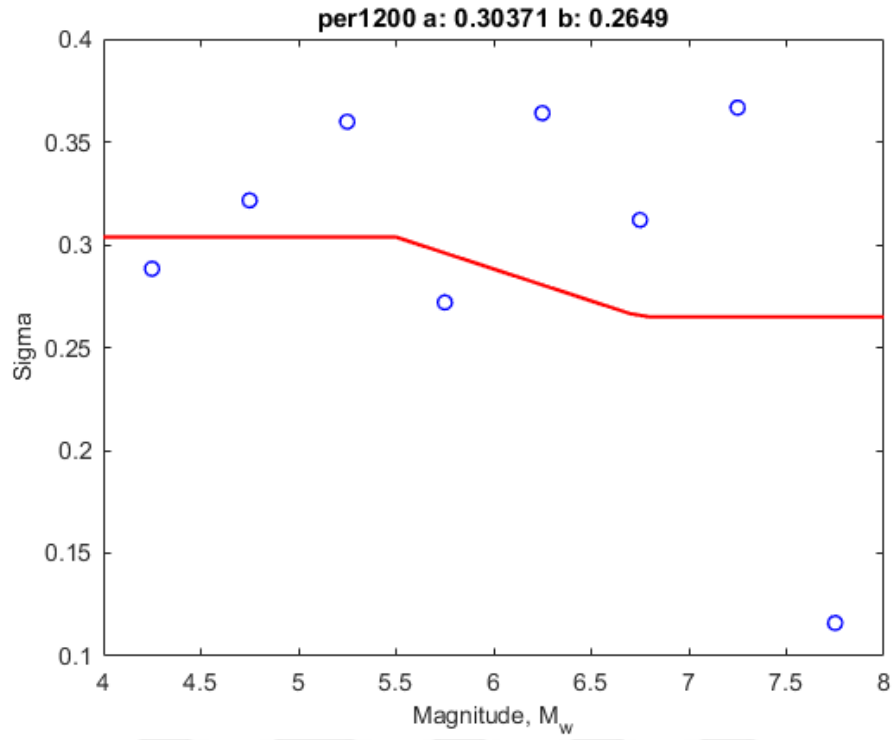


Figure C.21. Between-event standard deviation model for 1.2s.

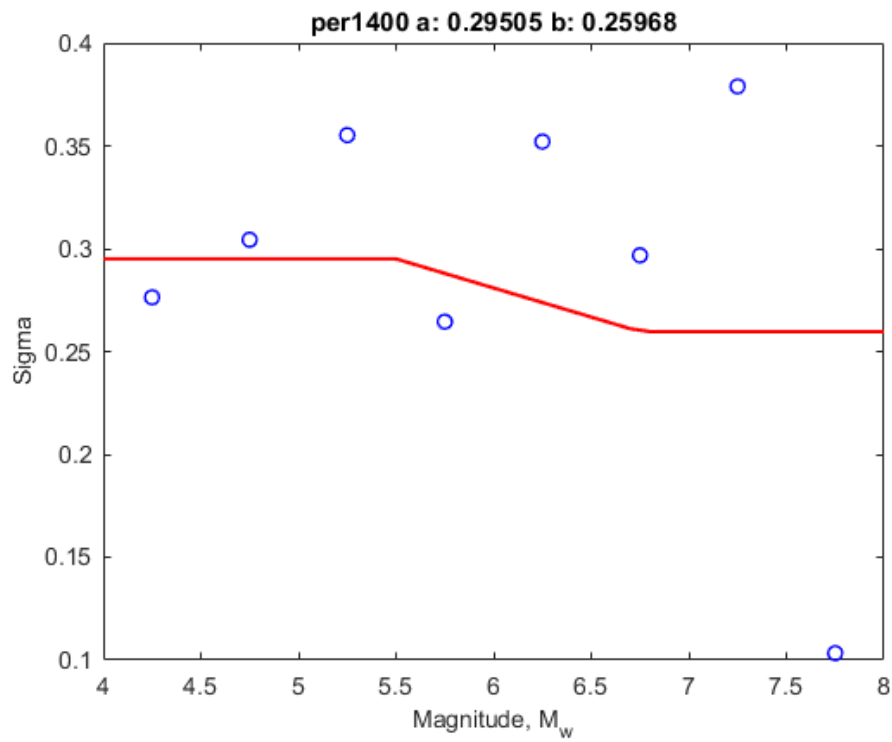


Figure C.22. Between-event standard deviation model for 1.4s.

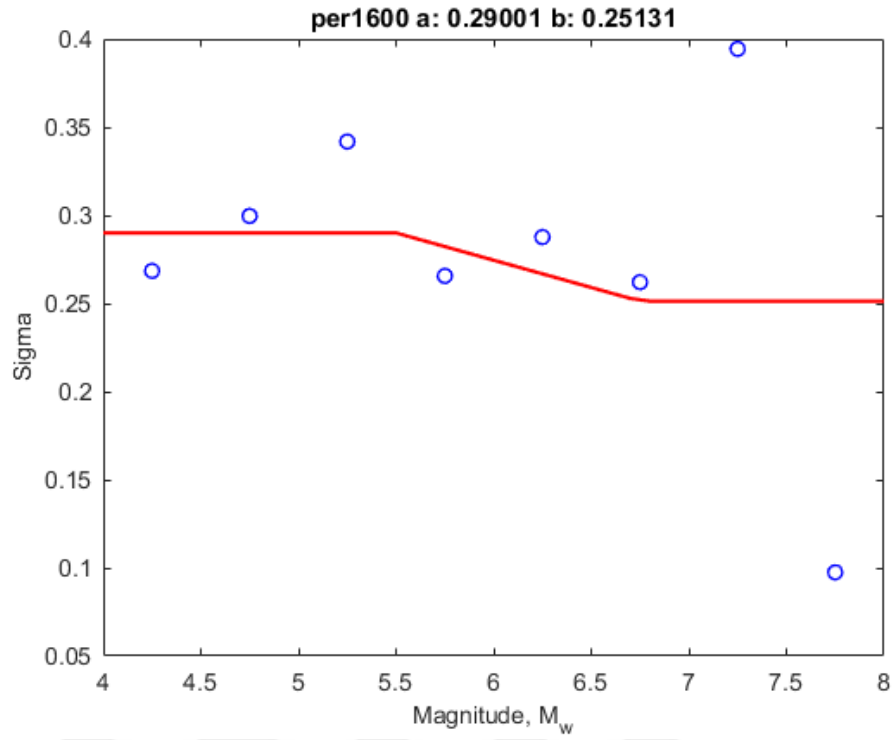


Figure C.23. Between-event standard deviation model for 1.6s.

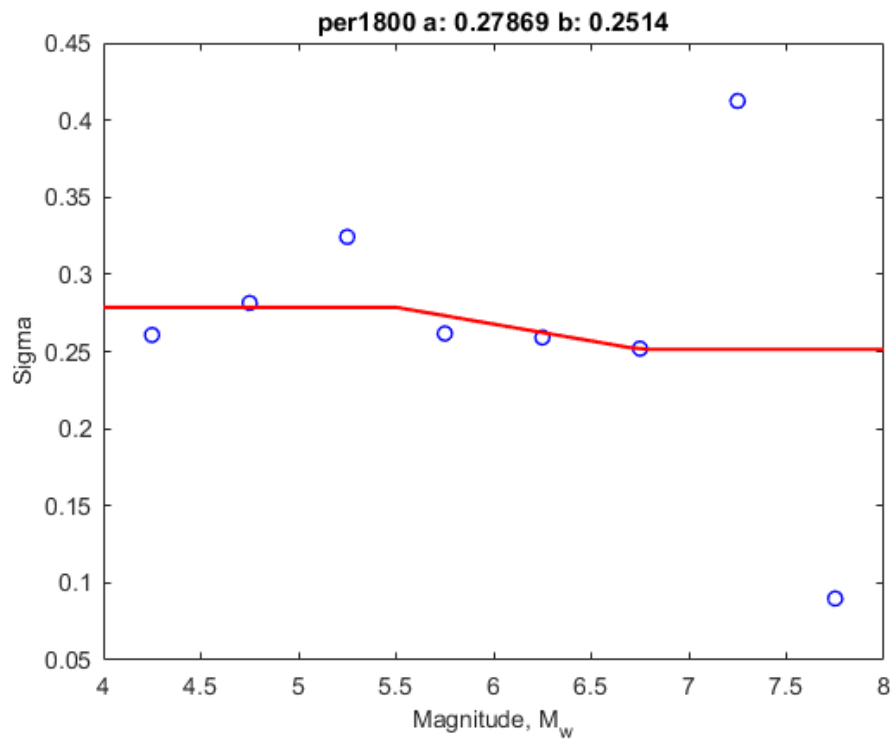


Figure C.24. Between-event standard deviation model for 1.8s.

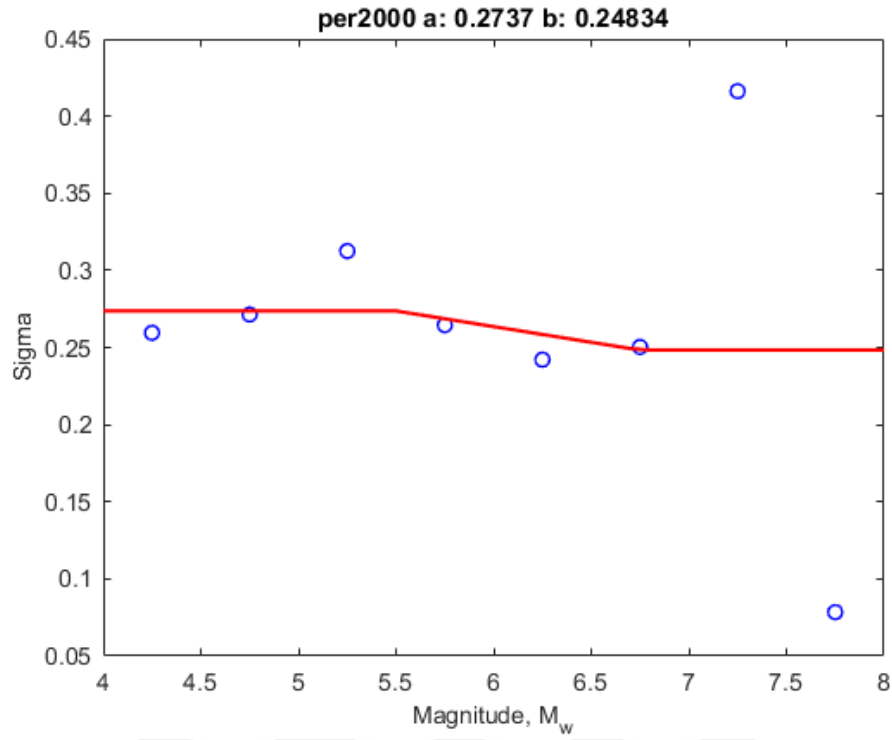


Figure C.25. Between-event standard deviation model for 2s.

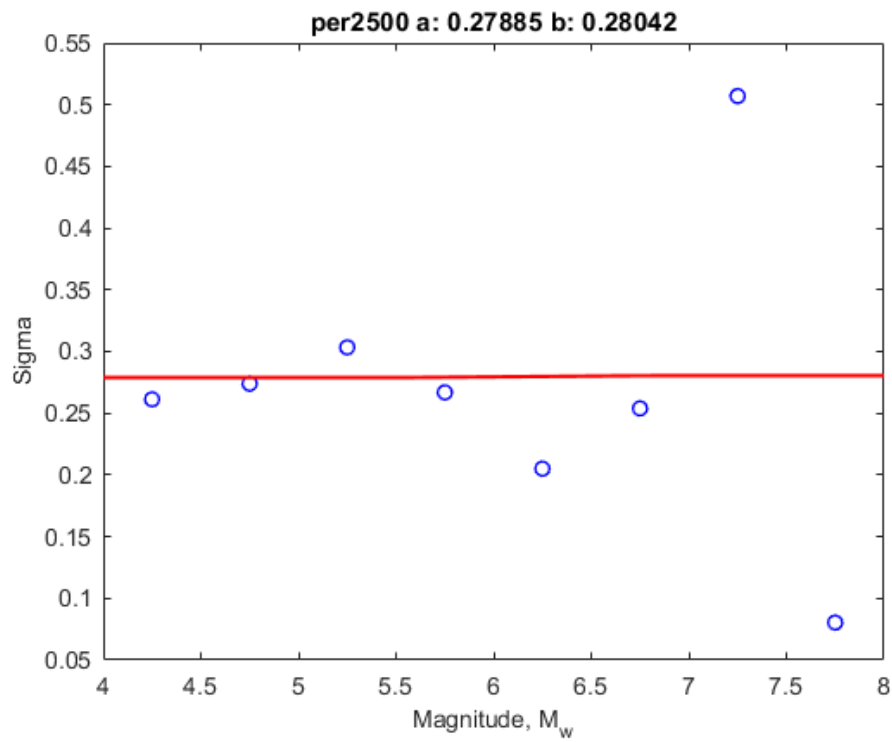


Figure C.26. Between-event standard deviation model for 2.5s.

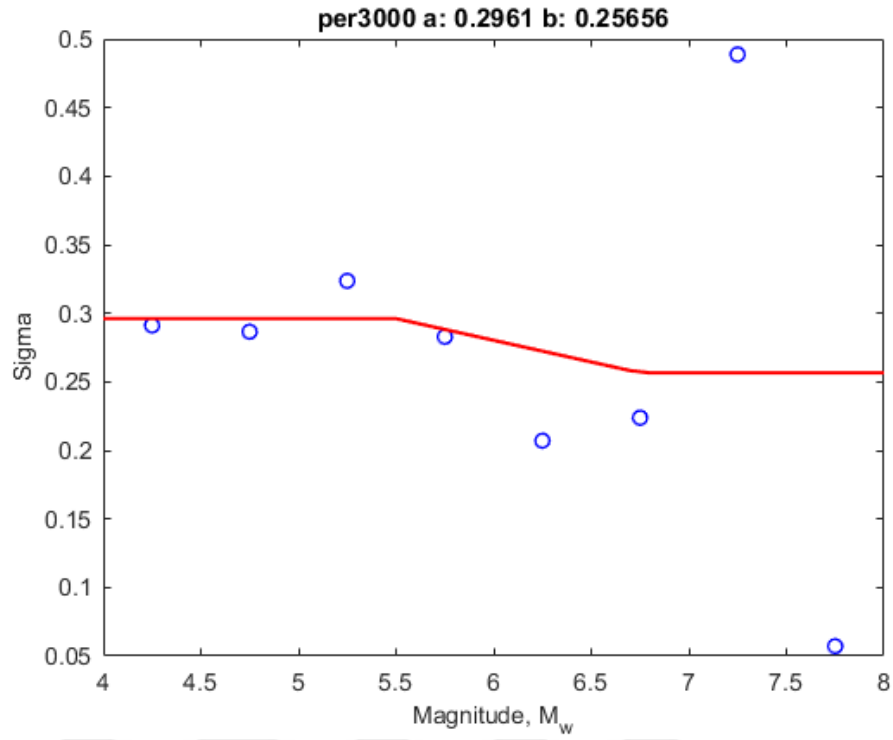


Figure C.27. Between-event standard deviation model for 3s.

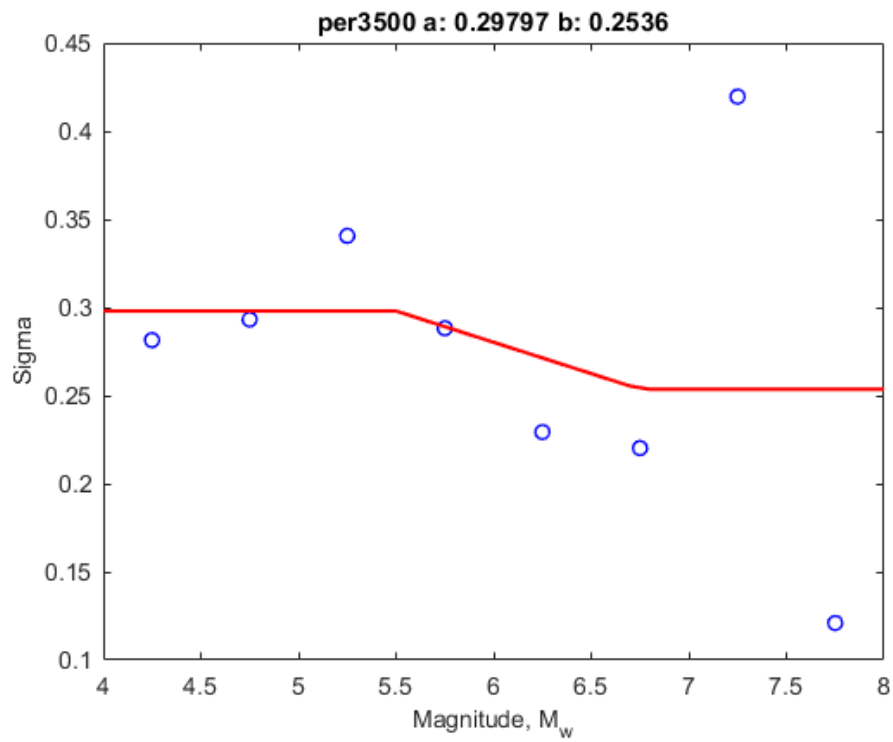


Figure C.28. Between-event standard deviation model for 3.5s.

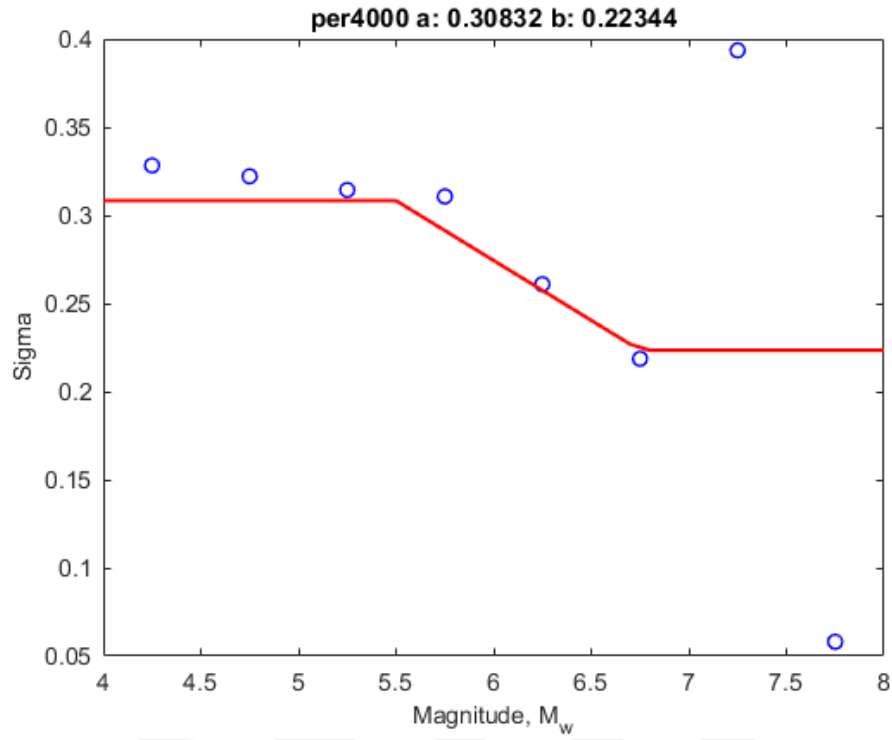


Figure C.29. Between-event standard deviation model for 4s.

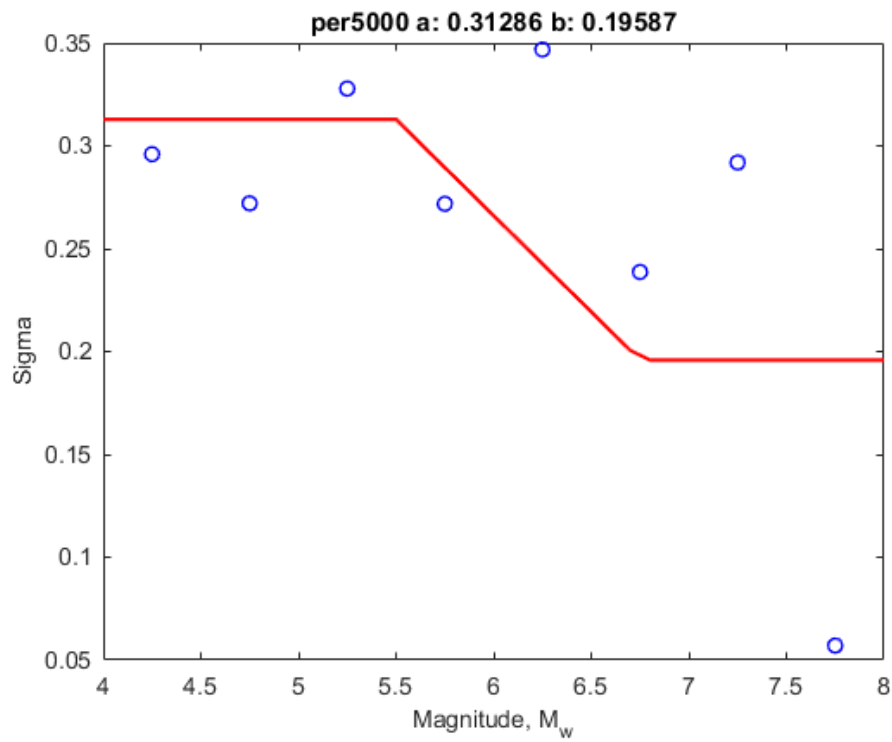


Figure C.30. Between-event standard deviation model for 5s.

APPENDIX D- Single-Site Within-Event Standard Deviation Standard Deviation Model

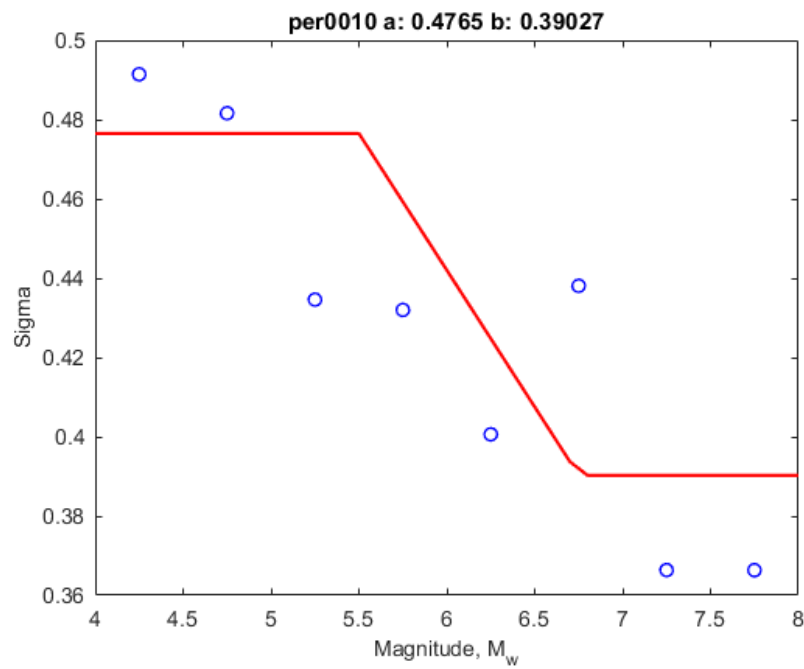


Figure D.1. Single-site within-event standard deviation model for 0.01s.

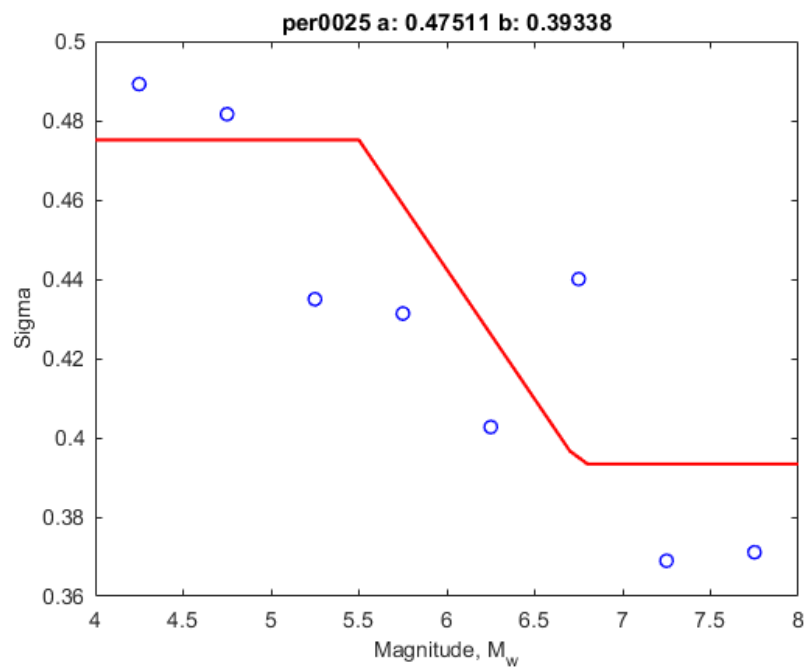


Figure D.2. Single-site within-event standard deviation model for 0.025s.

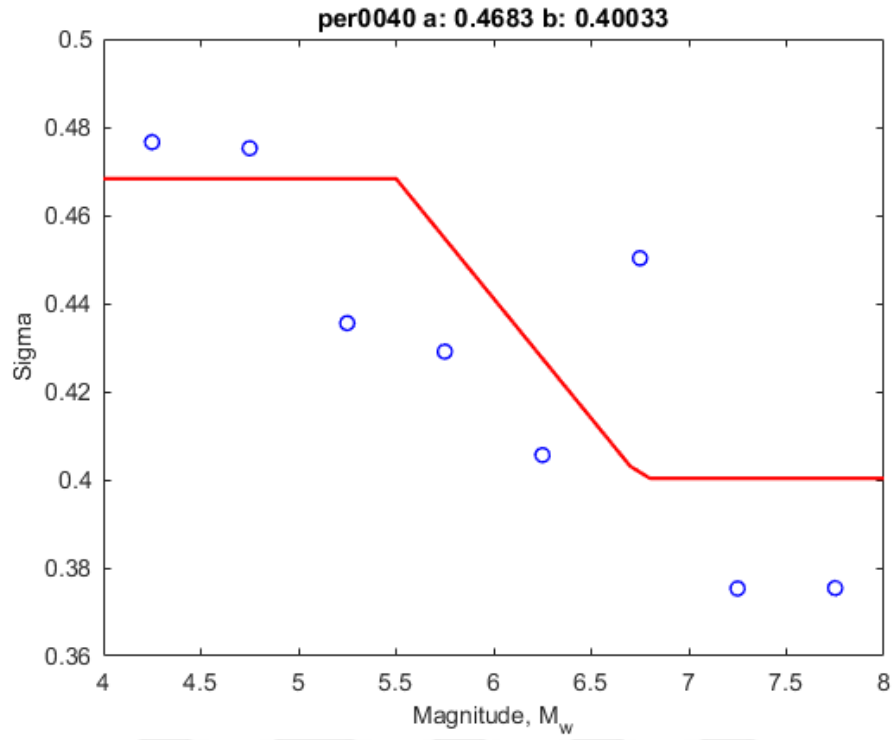


Figure D.3. Single-site within-event standard deviation model for 0.04s.

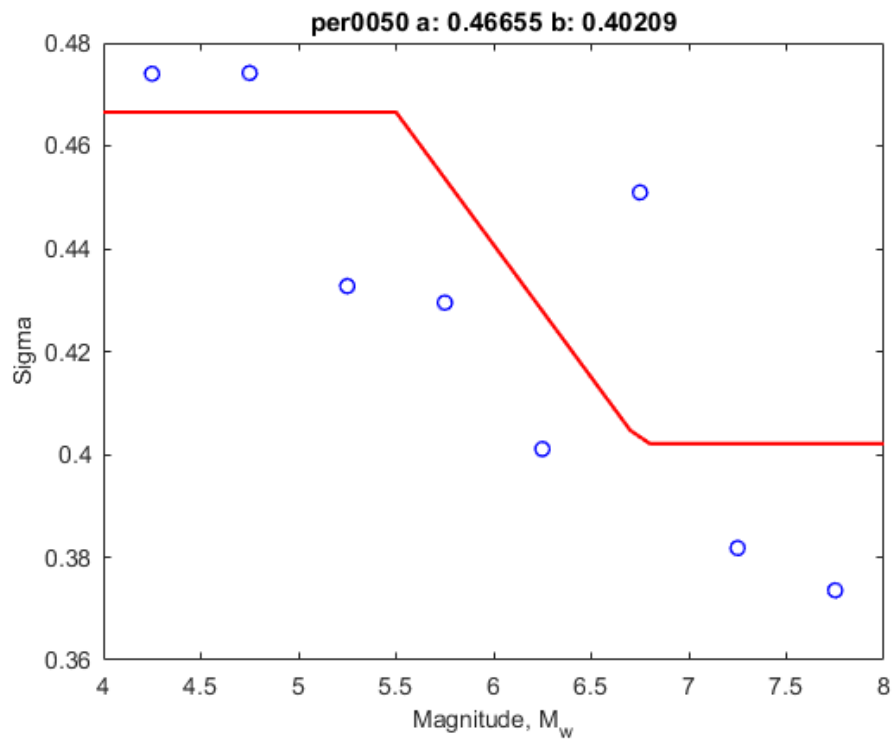


Figure D.4. Single-site within-event standard deviation model for 0.05s.

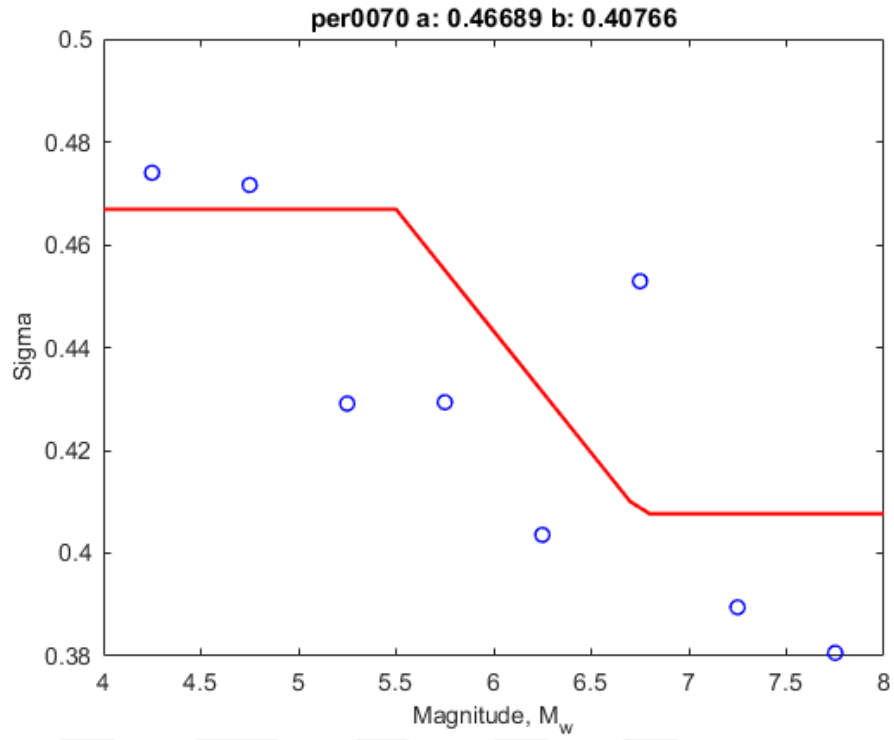


Figure D.5. Single-site within-event standard deviation model for 0.07s.

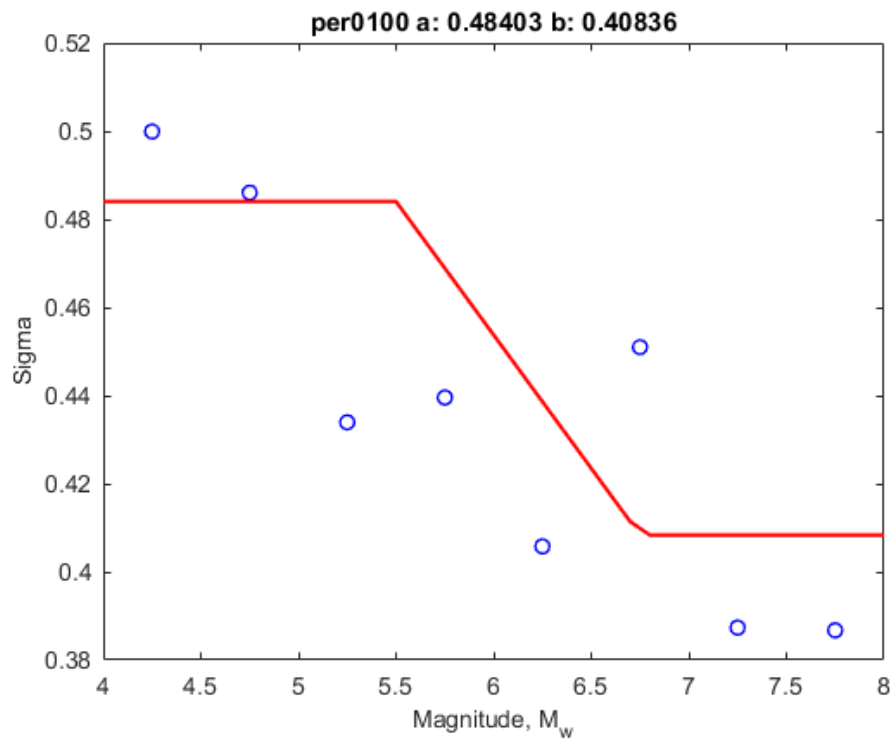


Figure D.6. Single-site within-event standard deviation model for 0.1s.

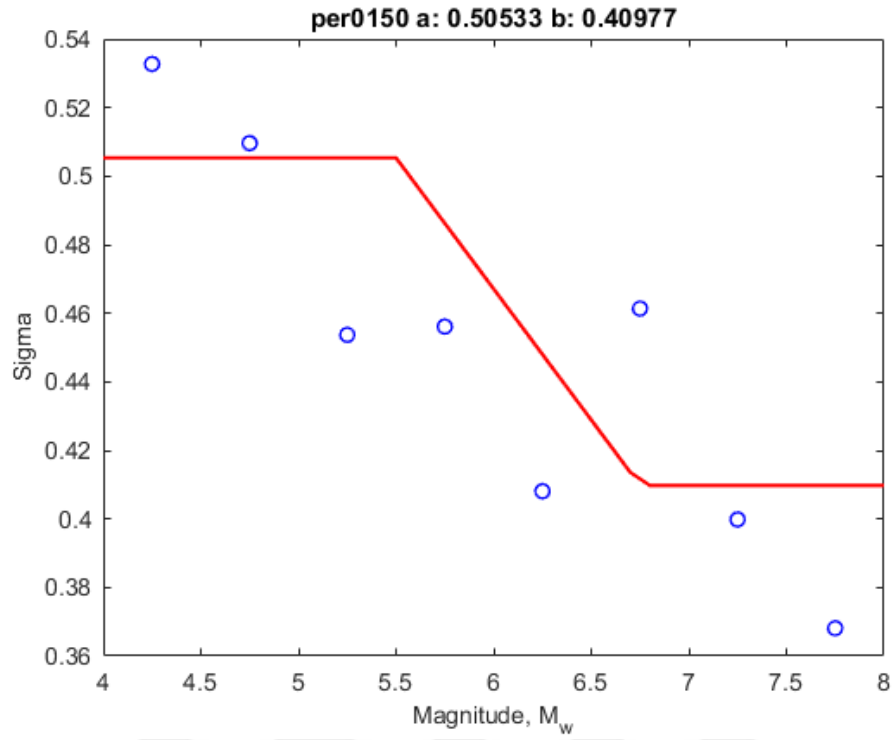


Figure D.7. Single-site within-event standard deviation model for 0.15s.

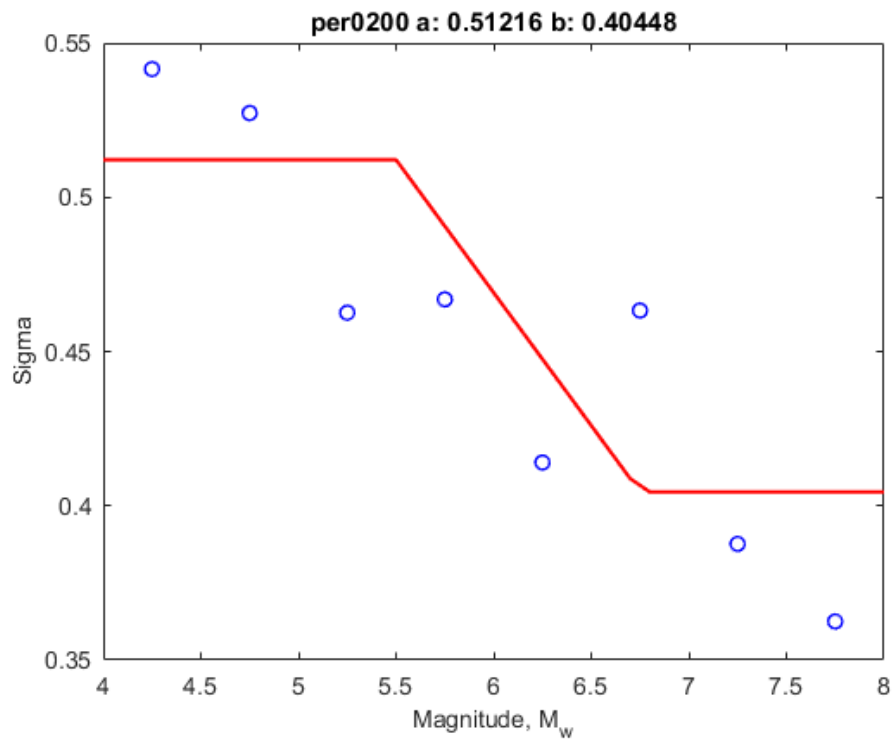


Figure D.8. Single-site within-event standard deviation model for 0.2s.

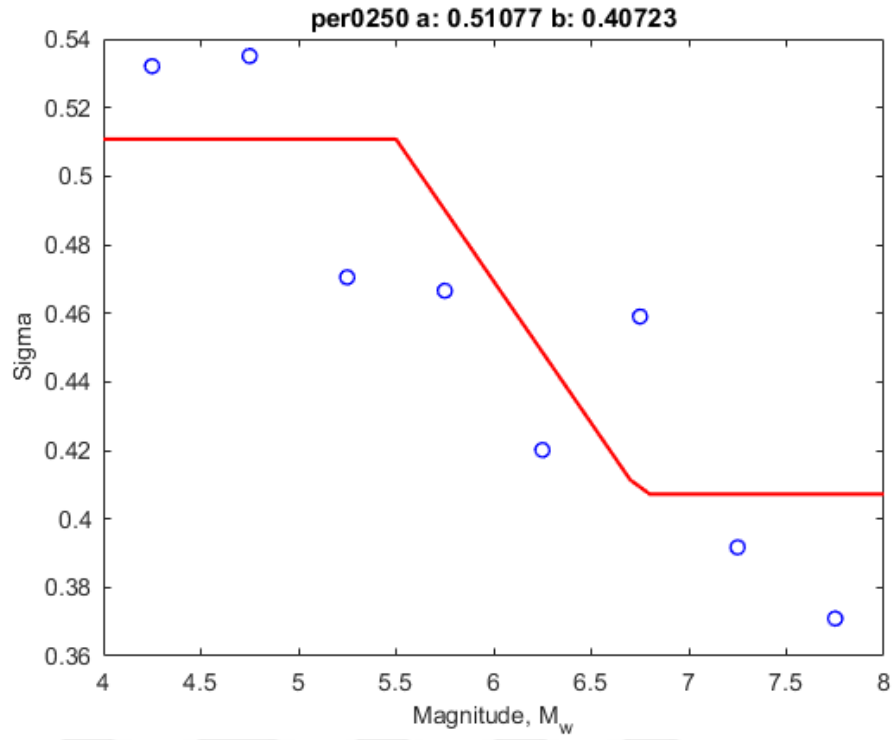


Figure D.9. Single-site within-event standard deviation model for 0.25s.

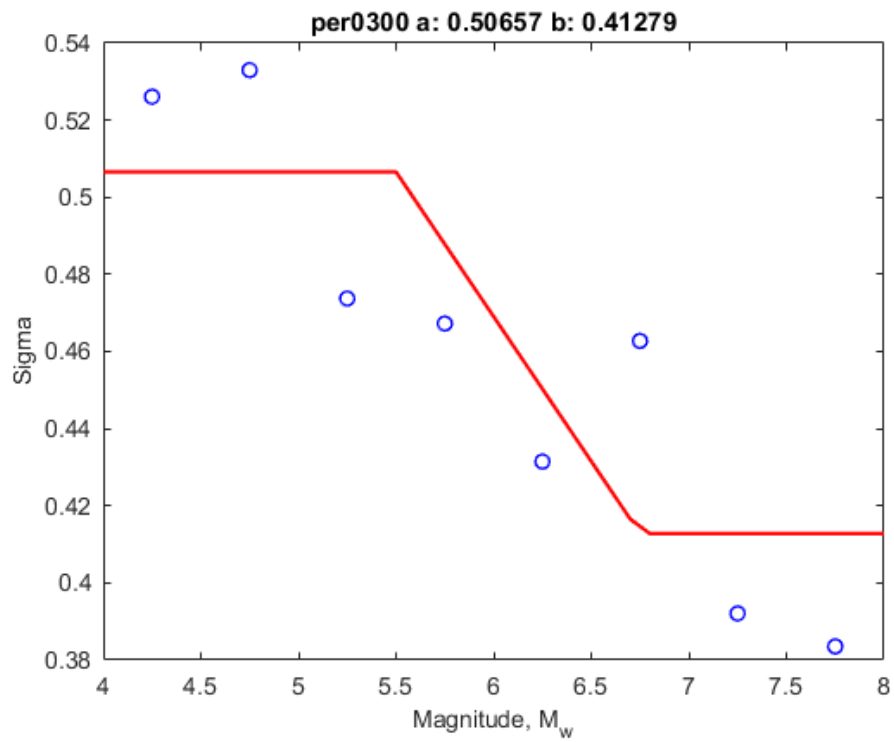


Figure D.10. Single-site within-event standard deviation model for 0.3s.

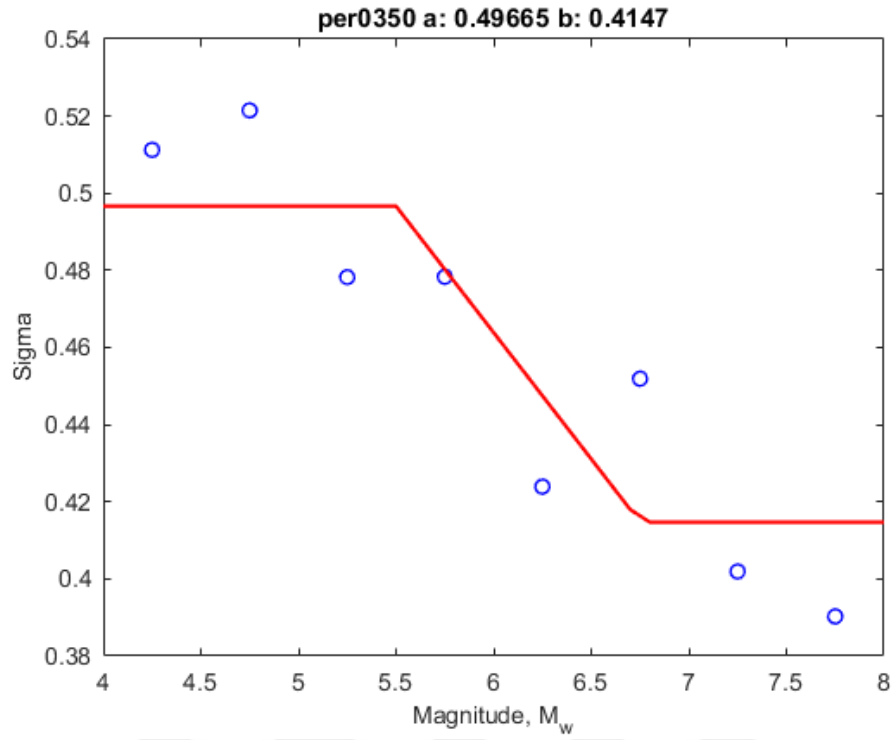


Figure D.11. Single-site within-event standard deviation model for 0.35s.

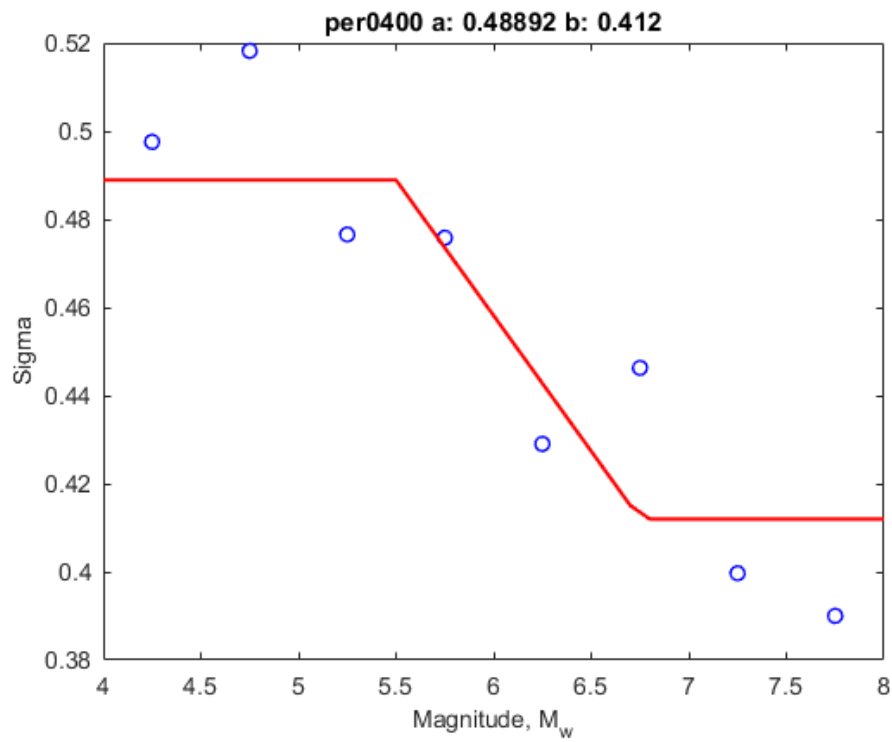


Figure D.12. Single-site within-event standard deviation model for 0.4s.

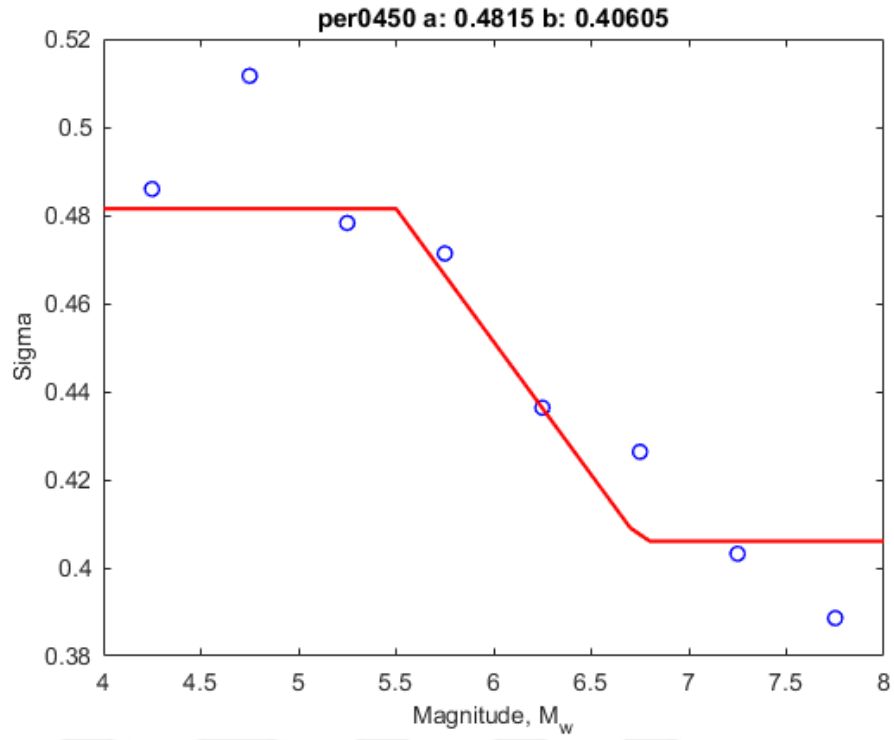


Figure D.13. Single-site within-event standard deviation model for 0.45s.

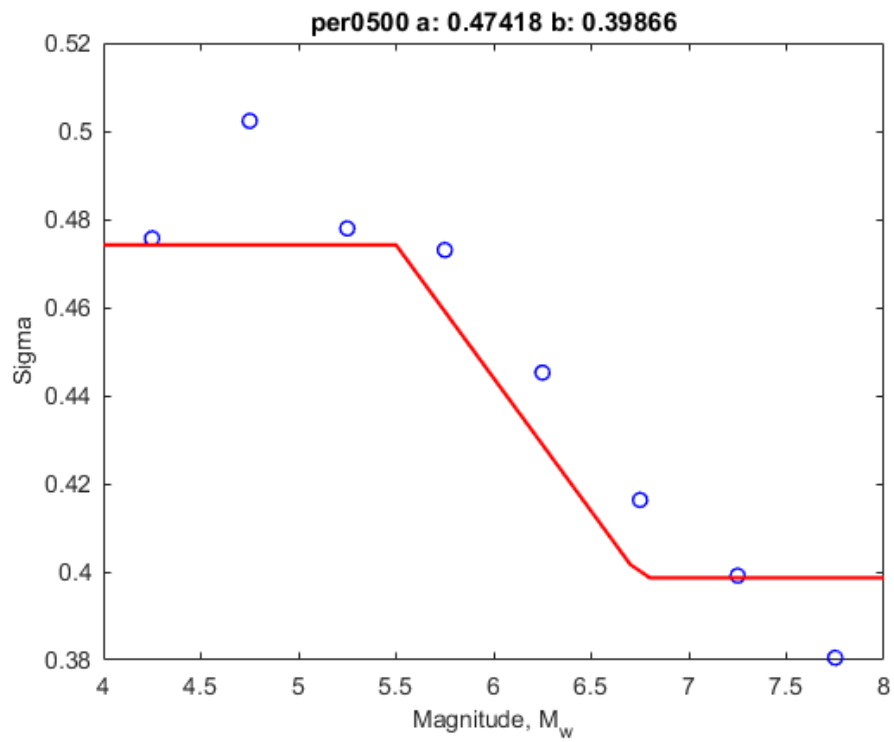


Figure D.14. Single-site within-event standard deviation model for 0.5s.

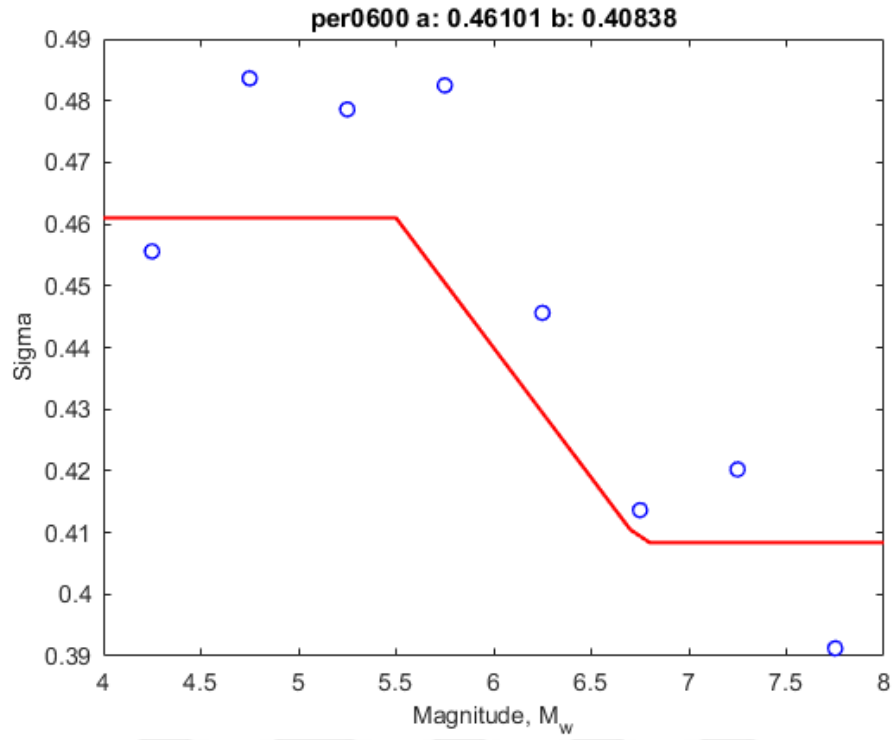


Figure D.15. Single-site within-event standard deviation model for 0.6s.

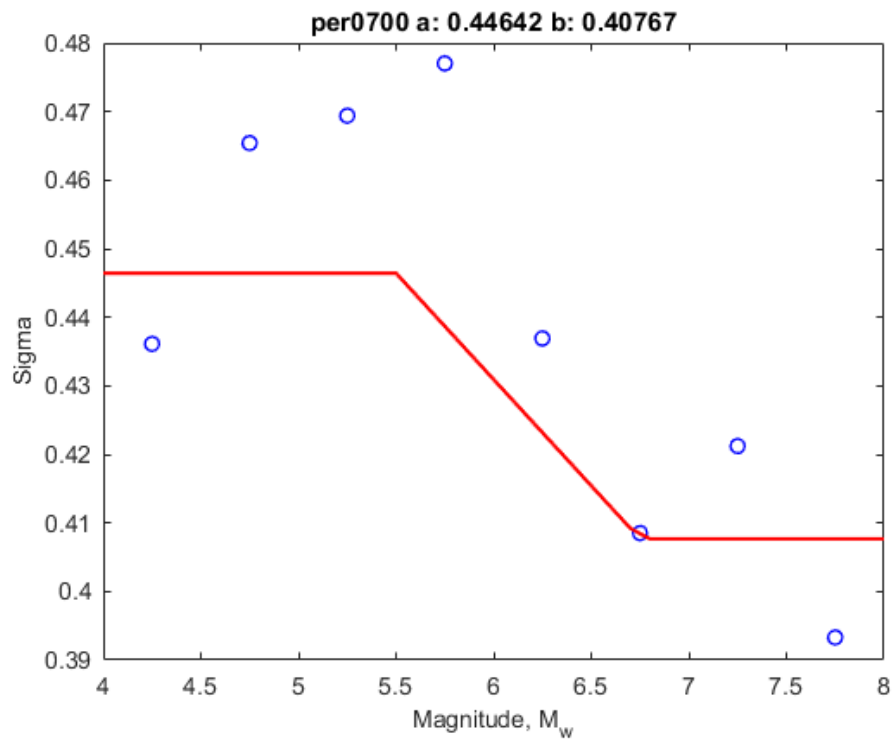


Figure D.16. Single-site within-event standard deviation model for 0.7s.

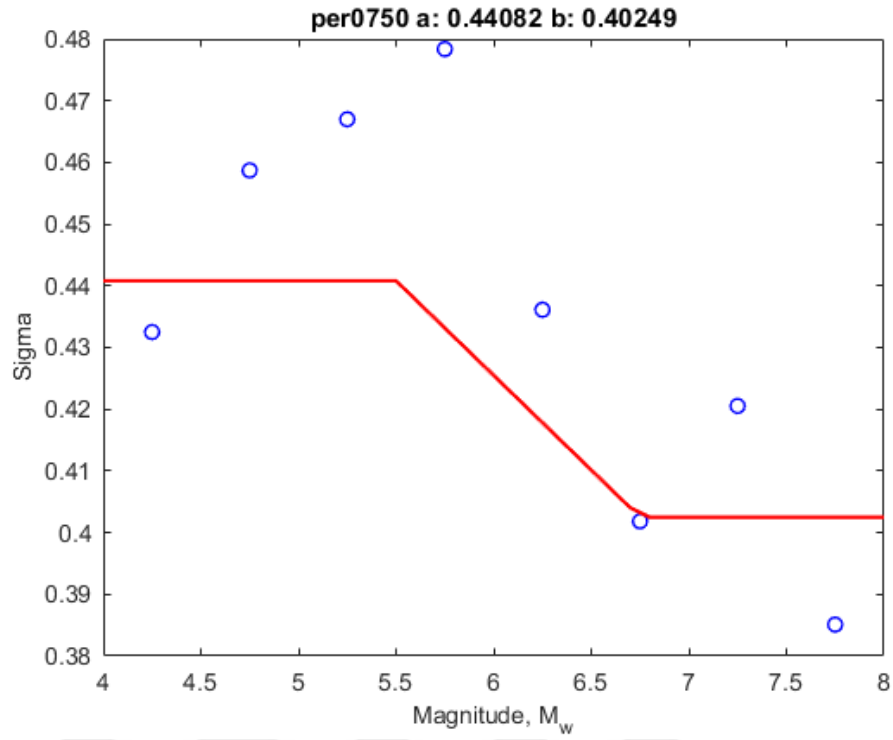


Figure D.17. Single-site within-event standard deviation model for 0.75s.

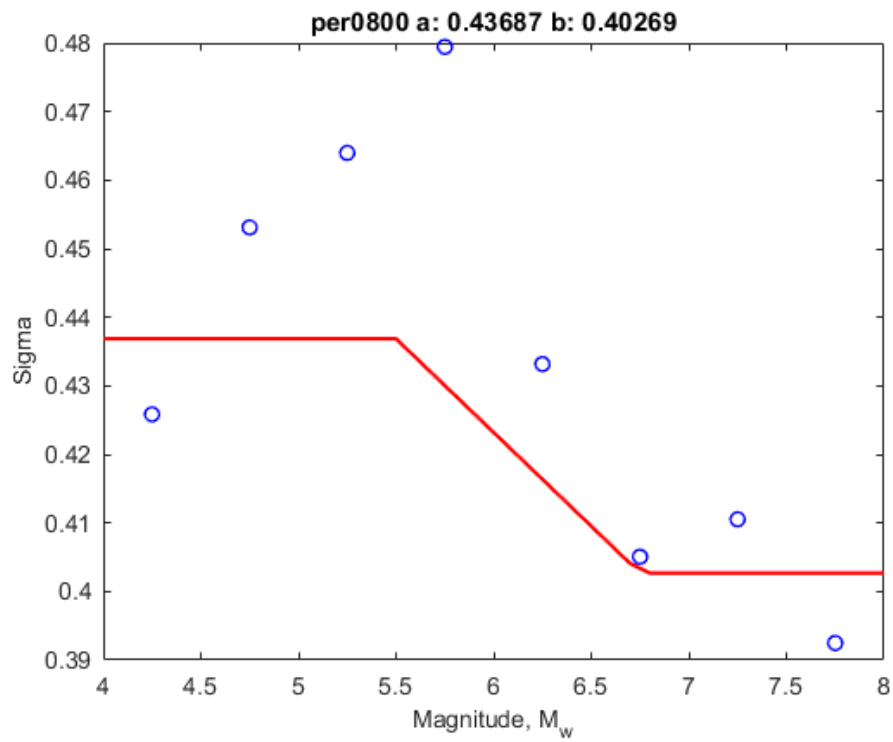


Figure D.18. Single-site within-event standard deviation model for 0.8s.

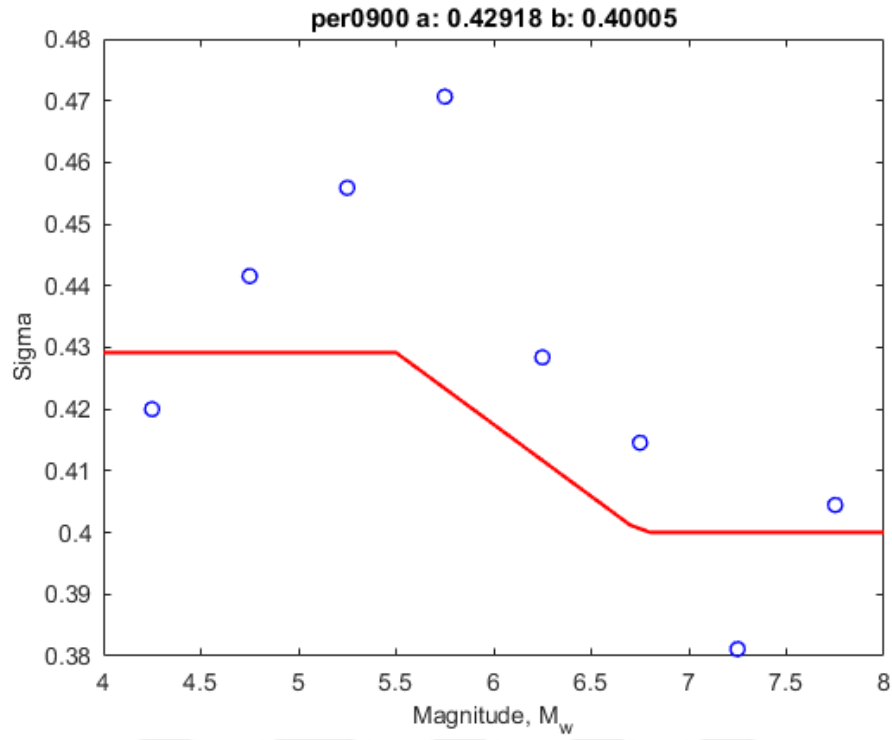


Figure D.19. Single-site within-event standard deviation model for 0.9s.

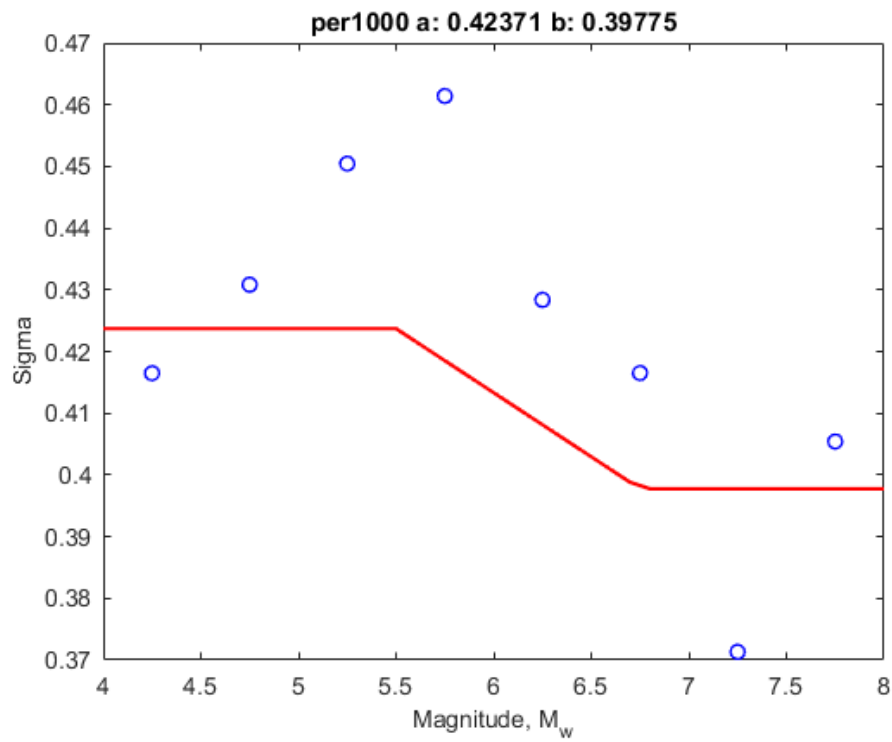


Figure D.20. Single-site within-event standard deviation model for 1s.

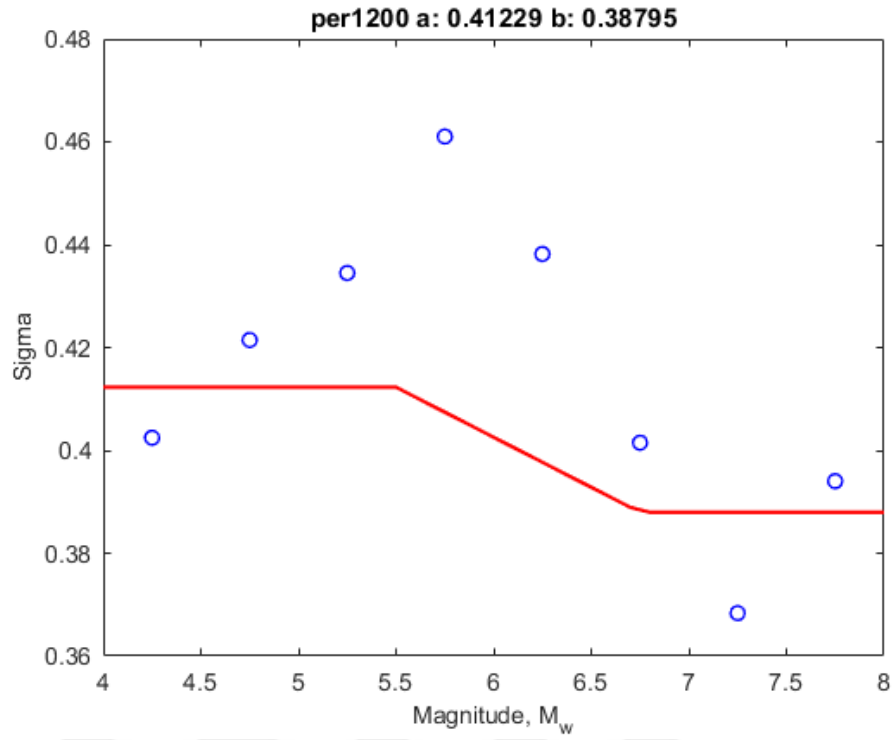


Figure D.21. Single-site within-event standard deviation model for 1.2s.

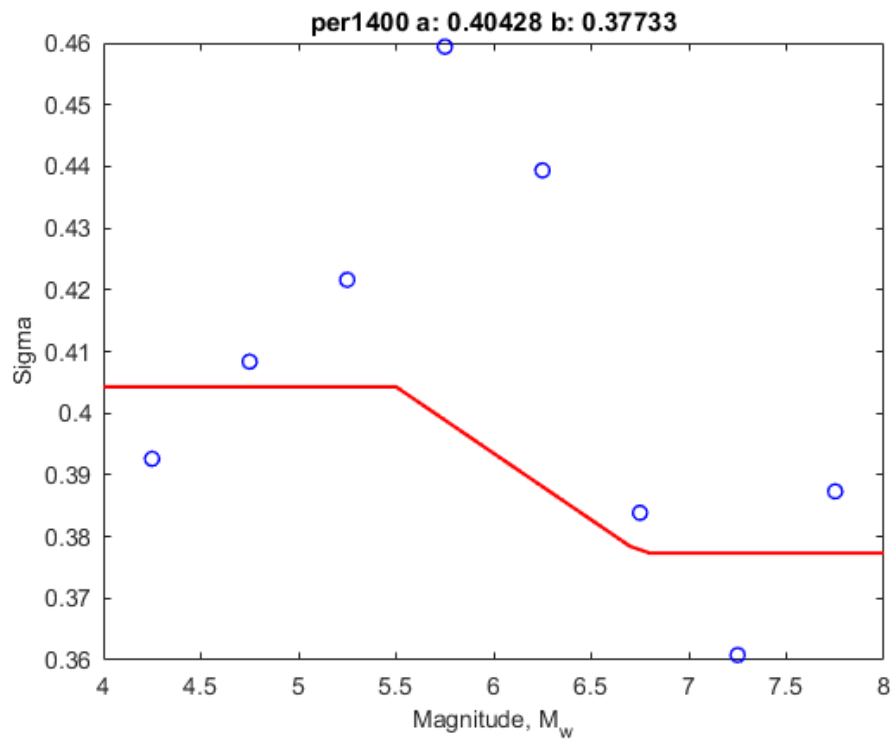


Figure D.22. Single-site within-event standard deviation model for 1.4s.

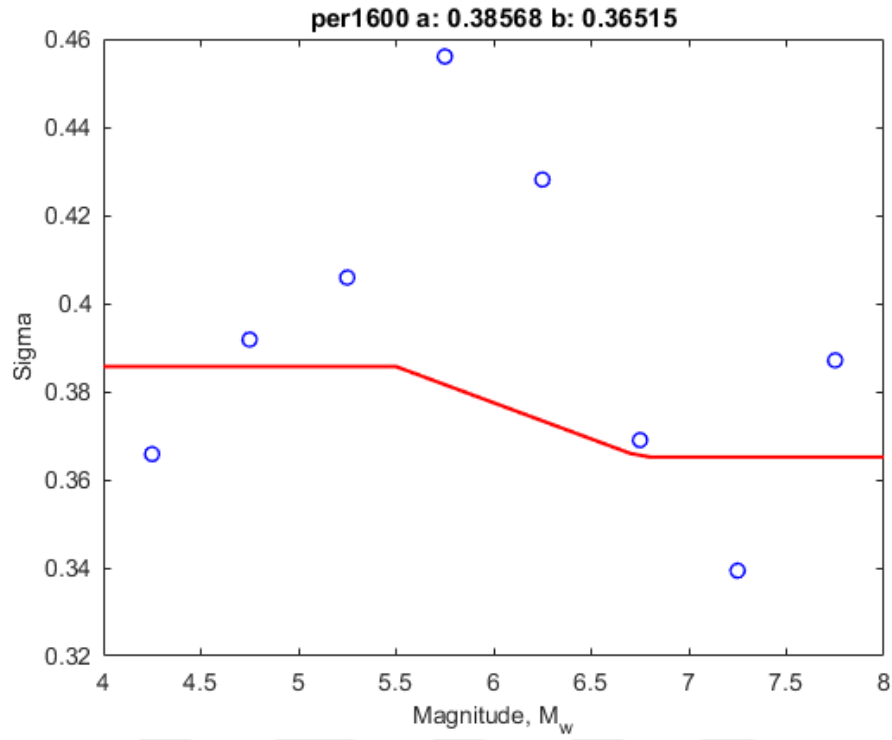


Figure D.23. Single-site within-event standard deviation model for 1.6s.

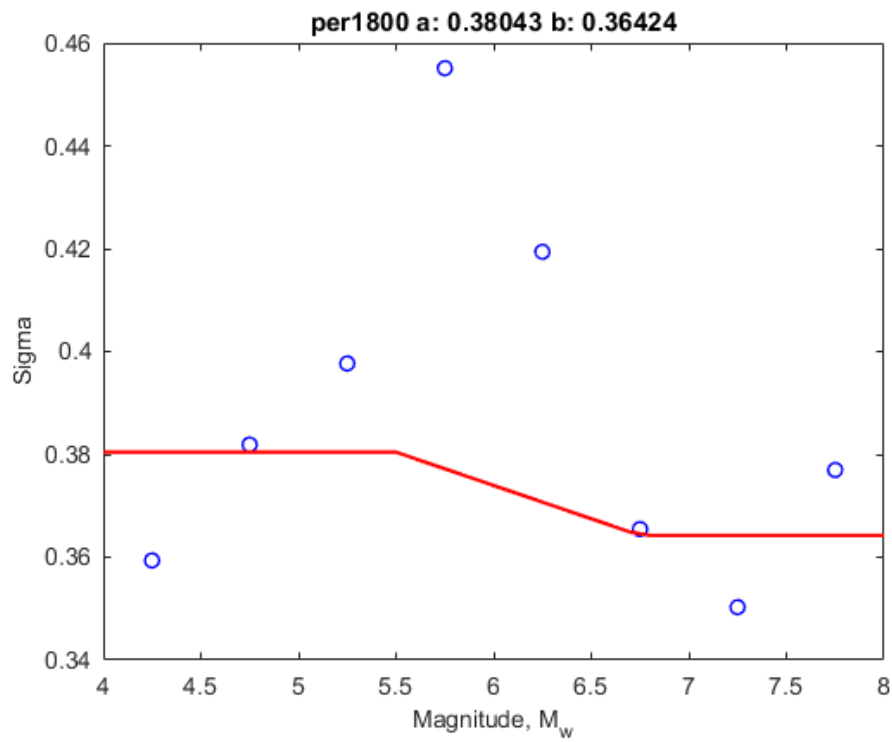


Figure D.24. Single-site within-event standard deviation model for 1.8s.

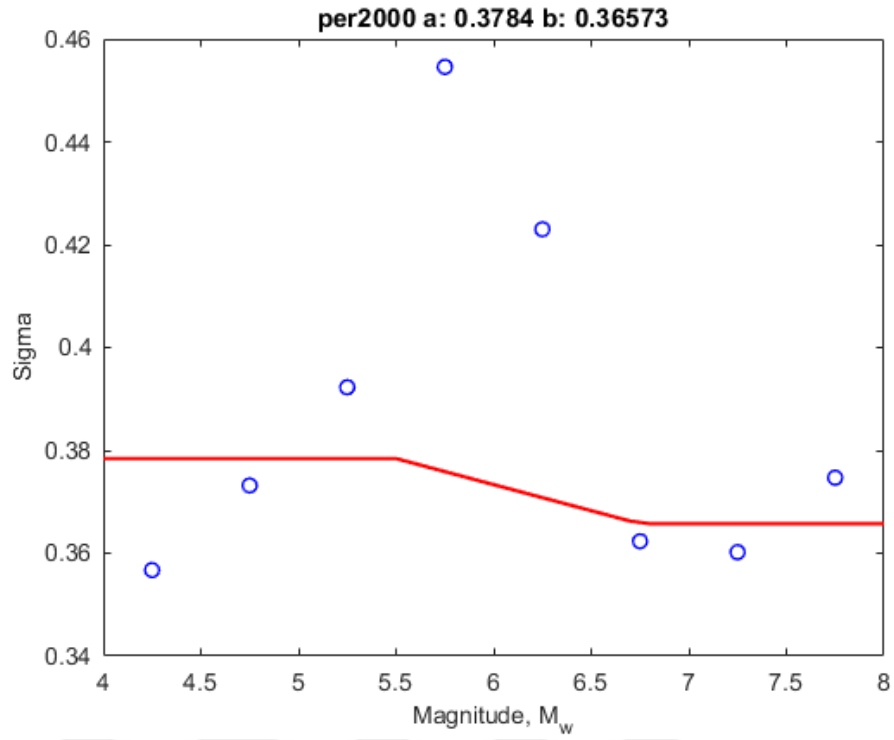


Figure D.25. Single-site within-event standard deviation model for 2s.

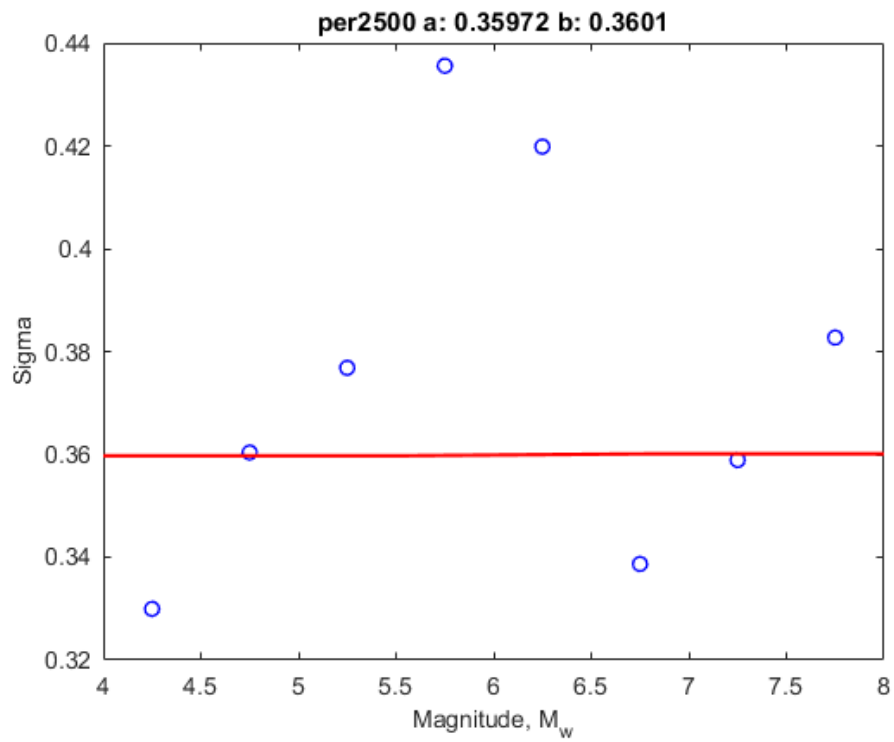


Figure D.26. Single-site within-event standard deviation model for 2.5s.

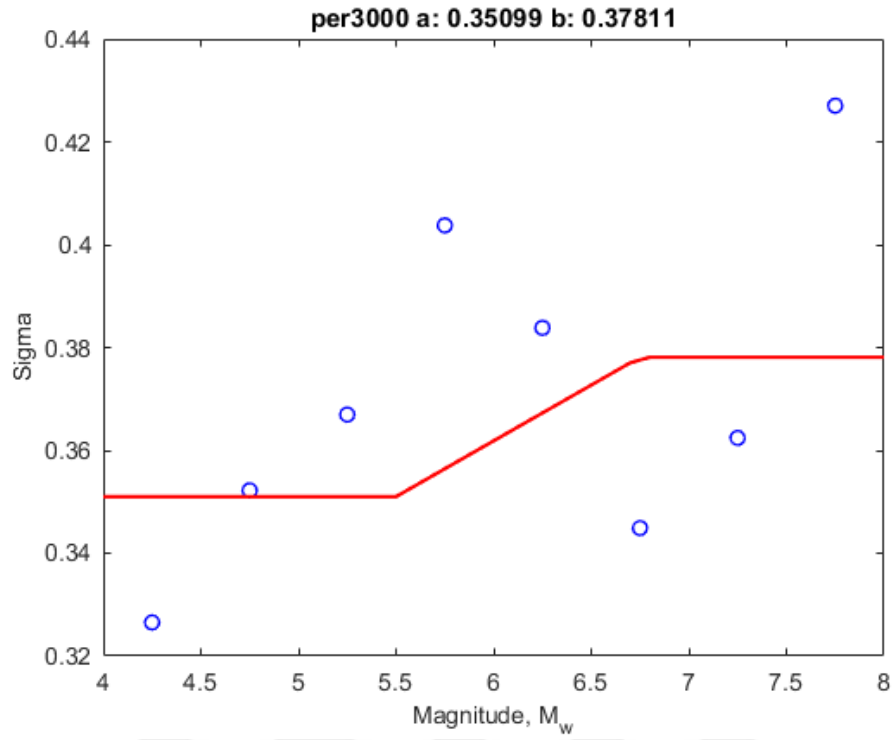


Figure D.27. Single-site within-event standard deviation model for 3s.

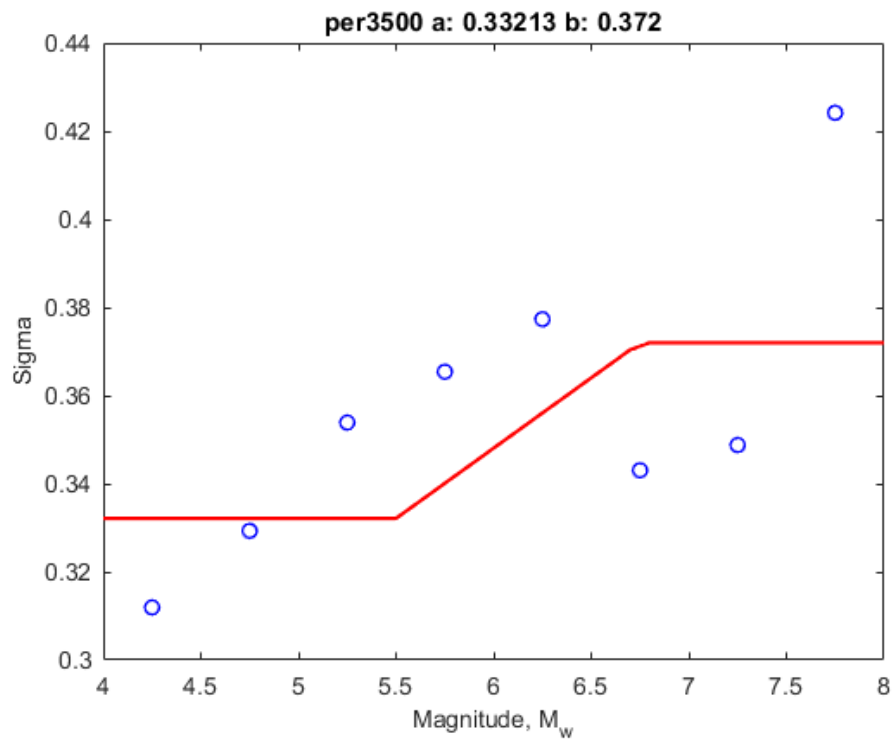


Figure D.28. Single-site within-event standard deviation model for 3.5s.

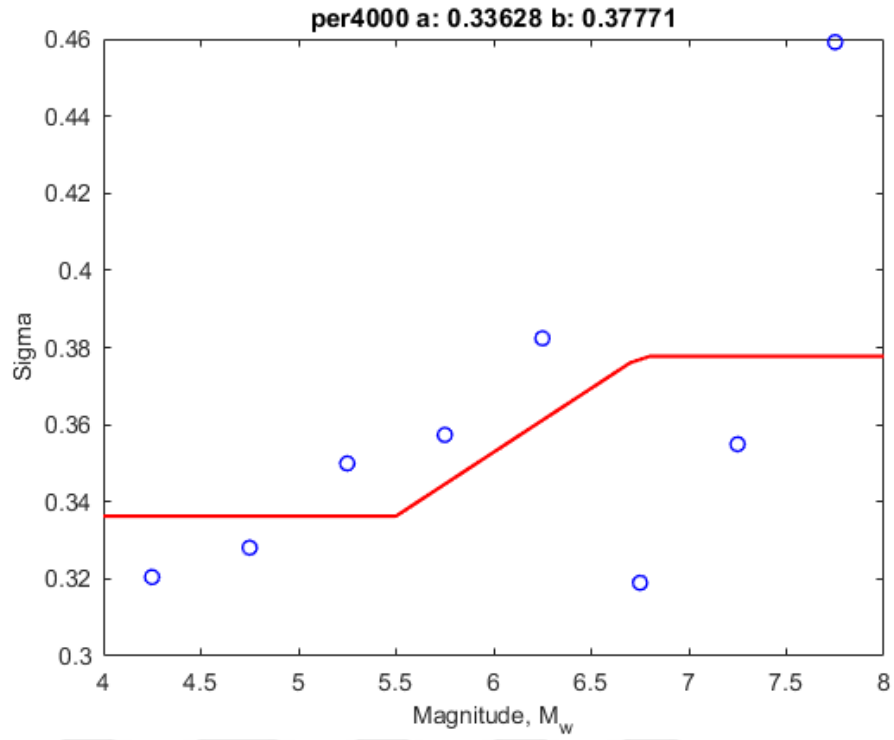


Figure D.29. Single-site within-event standard deviation model for 4s.

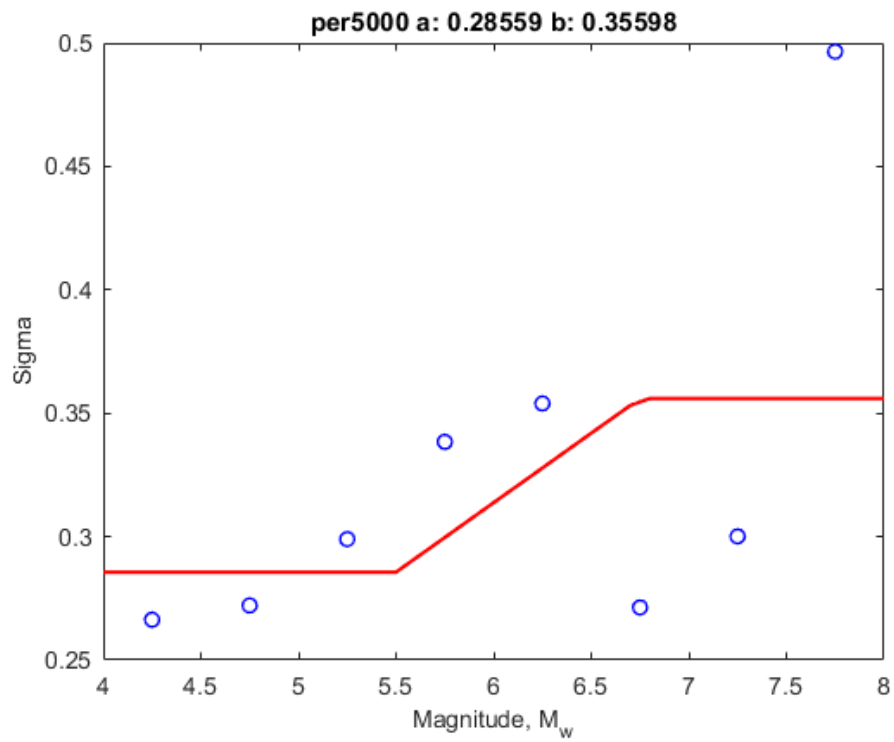


Figure D.30. Single-site within-event standard deviation model for 5s.