Title

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EMPIRICAL SITE RESPONSE OF MEXICO CITY THROUGH REGIONALIZATION OF GLOBAL SUBDUCTION GMMS

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Abstract: *We assemble a dataset which enhances existing Central America and Mexico data for the NGA-Subduction (NGA-Sub) project, including now additional earthquake ground motions and site parameters from Mexico. This data has been used to provide regional customization of NGA-Sub global Ground Motion Models (GMMs) for application in Mexico, paying particular attention to the site response of Mexico City (CDMX). The expanded database for Mexico incorporates smaller magnitude earthquakes (**M** < 6) and three significant events (**M** 7.2-8.3) that occurred in 2017 and 2018. These latter events are particularly important, because they are well recorded over a broad distance range and apply for hazard-critical conditions. Our focus here is on presenting the observed site response in CDMX, which we model based on the time-averaged shear wave velocity in the upper 30 meters (V_{S30}) and the Peak Ground Acceleration at a reference rock site (PGA_r). The empirical model we propose is different from previous work in several ways. First, it is properly centered with respect to GMMs. Second, it is referenced to V_{S30}=760 m/s, which is significantly firmer than the reference site previously used in practice, taken from a location on the UNAM campus with V_{S30} ~ 300 m/s. Third, we identify site amplification as nonlinear, whereas linear response has been assumed in prior models. The extent of this nonlinearity is characterized using an established seismic zonation for CDMX, being more pronounced in softer sites (Zone III) compared to stiffer ones (Zone I). This nonlinear effect is prominent at short periods and disappears at long periods. The advantages of the provided model include a unified framework for both within and outside CDMX (contrasting current practices) and the integration of applicable features from global models with necessary local customization.*

1 Introduction

The NGA-Subduction (NGA-Sub) project was a significant, multi-year international endeavor in engineering seismology, employing a multidisciplinary methodology to establish database resources and develop Ground Motion Models (GMMs), specifically for subduction-zone earthquakes. It resulted in an extensive database and multiple GMMs addressing subduction-zone earthquakes in active tectonic regions, including Cascadia, Alaska, Japan, Taiwan, Mexico, Central America, and South America, among other areas (Bozorgnia et al., 2022). This database provides uniformly-processed ground motion data from various tectonic settings and regions, encompassing time series and intensity measure values. The resulting databases and associated documentation are publicly accessible online, providing a resource for researchers and practitioners. The project has produced several NGA-Sub GMMs, including global models by Kuehn et al. (2020), by Parker et al. (2022), among others. This article primarily discusses the site response observed in Mexico City (CDMX), derived from residual analysis using mixed-effects regression methods. Additional information on ground motion networks in Mexico, processing of ground motions, the development of source, path, and site metadata, adaptation of global GMMs for Mexico, and site response outside the Valley of Mexico, are detailed in Contreras et al. (2023).

2 Ground motion dataset

The NGA-Sub database, structured as a relational database, encompasses comprehensive information on earthquake sources, source-to-site paths, site conditions, and ground motion characteristics. This database compiles data from global subduction events up until 2016. It categorizes the information into seven distinct global regions, including Central America and Mexico (CAM). The relational database has been documented as a paper in Mazzoni et al. (2022), and the details are accessible in a series of tables available online. Two critical aspects of the dataset, the source/path and site features, have been the focus of extensive research efforts. These features are thoroughly described in Contreras et al. (2022), for source/path characteristics, and Ahdi et al., (2022), for site features.

Figure 1(a) shows the location of the earthquakes in the CAM region that were originally included in the NGA-Sub database, classified by event-type (interface, intraslab, shallow crustal, or outer-rise). We have expanded and improved the database for this region using events with dates extending through 2018. There are two reasons that events now considered in the extended database were not used in the version of the NGA-Sub original database. The first is that the events occurred too late to be considered, which excluded from consideration two large intraslab events in Mexico (**M**7.18 and **M**8.27) that occurred in September 2017 and one interface earthquake (**M**7.2), also in Mexico, that occurred in February 2018. The second reason for events having not been included is that they fall below the magnitude threshold of 6 considered in CAM, which was applied to control workload. For the **M**<6 earthquakes not included in the original NGA-Sub database, a subset of 59 events has been selected to develop source and path metadata. These 59 events were selected because they were recorded at five or more stations, and as such, these data have the potential for greater contributions to the path and site response characterization. Figure 1(b) shows the locations of both classified (colored circles) and unclassified (white circles) events in CAM after addition of the 59 events. The extended database includes 65 interface events, 53 intraslab events, 20 shallow crustal events, and three outer-rise events. The total number of recordings from subduction earthquakes is 1297, including 738 recordings from interface events and 559 from intraslab events.

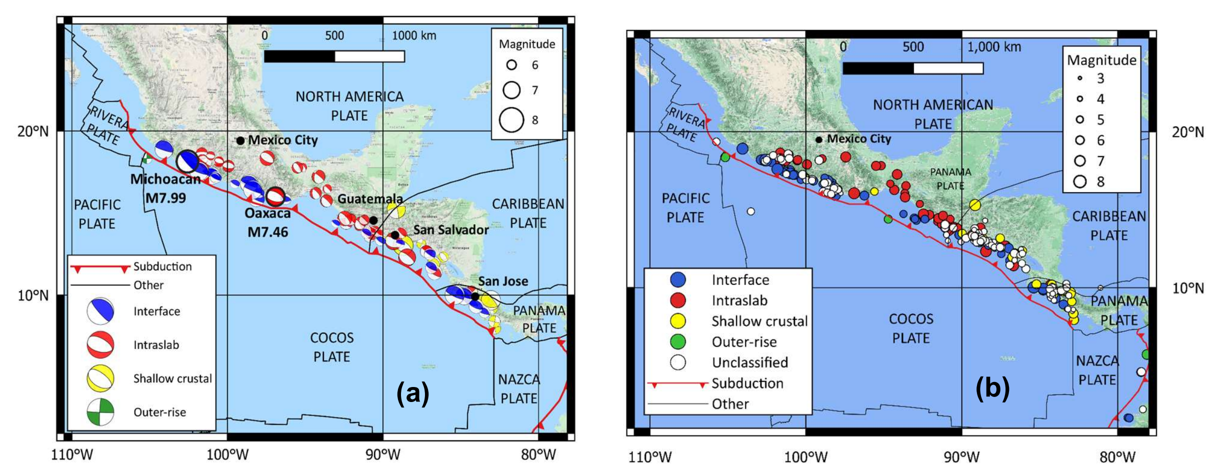

Figure 1. Locations of earthquakes in CAM by event-type: (a) events included in the original NGA-Sub database, and (b) all events of the extended NGA-Sub database.

Two large intraslab events occurred in Mexico in September 2017: the September 8, 2017, **M**8.27 offshore Chiapas earthquake and the September 19, 2017, **M**7.18 Puebla earthquake. Each event produced substantial numbers of recordings which are now included in the updated database. Additionally, ground motion recordings from the February 16, 2018, **M**7.2 Oaxaca earthquake (an interface event) are also included in these updates. In total, these three earthquakes contributed 585 additional recordings to the data set. Figure 2(a) shows a map of Mexico with the epicenters and trimmed rupture areas of the three events, along with the ground motion stations where they were recorded. The stations are from the IG, UV, and VM networks operated by the SSN (Servicio Sismológico Nacional); the RAII-UNAM network operated by the Institute of Engineering at UNAM (Universidad Nacional Autónoma de México); and the RACM network operated by CIRES (Centro de Instrumentación y Registro Sísmico). Figure 2(a) also shows the relocated forearc-backarc boundary utilized to classify the earthquakes and stations in the forearc or backarc regions. Each of these three large events is in the forearc. Mexico City is located in the backarc region as shown in Figure 2(a). Of the 121 subduction events considered in the combined database, 98% are in the forearc and the remainder are backarc (based on hypocenter location). Of the 612 recording stations, 51% are in the forearc, 46% are in the backarc, and the remainder are outside of the volcanic-arc zone.

The cumulative data set for Mexico includes the NGA-Sub data that was considered in model development (**M** > 6 and pre-2016 events), data processed in NGA-Sub for which event metadata has been added in this study (**M** < 6 and pre-2016), and data from the three large events described previously. For this cumulative data set, Figure 2(b) shows the distribution of recordings in magnitude-distance space, with different symbols for the three data subsets. The data covers a magnitude range of about 5-8.3 and a distance range of about 20-2000 km. Subduction data is dominant in the data set with 932 recordings from interface events and 950 intraslab recordings.

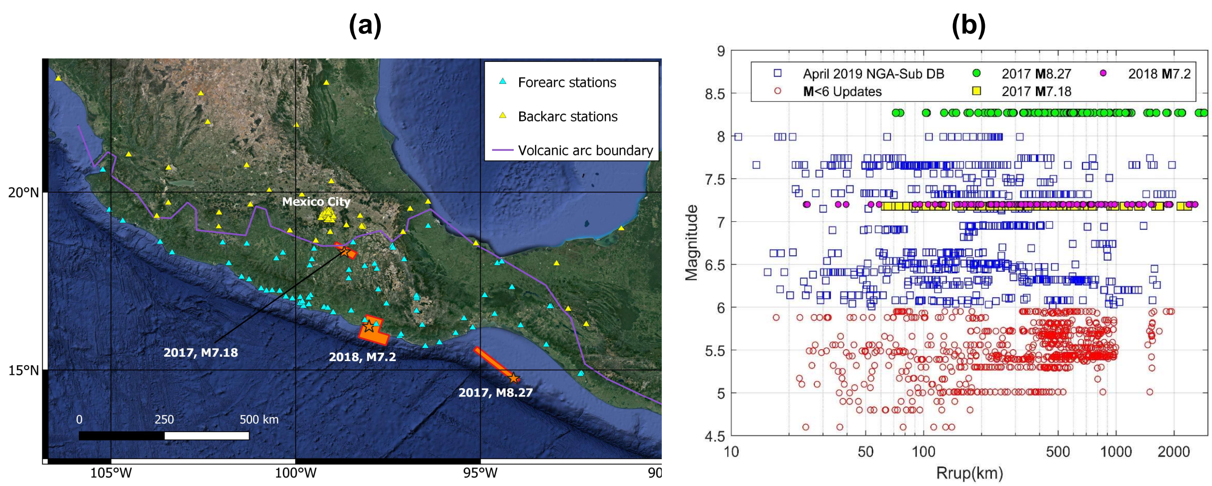

*Figure 2. (a) Map of central Mexico showing adopted volcanic front, ground motion stations considered in this region of Mexico, rupture area, and hypocenters of the three large events in 2017-2018. (b) Magnitude-distance distribution of the NGA-Sub database in CAM following updates of events with **M**<6 and the addition of the three large-magnitude events in 2017- 2018.*

Records were selected for use in ground motion analyses in a manner consistent with that of Parker et al. (2022), except for the use of backarc data in this study. There are 369 usable interface records in the screened database at rupture distances of 14-1270 km from events with **M** 5.3-8.0. For intraslab events, there are 460 records following screening from events with **M** 5.3-8.3 and rupture distances of 47-1430 km.

3 Regional customization of global GMMs for Mexico

Using the screened data that resulted from the selection criteria, residuals analyses are performed to examine various attributes of the Mexico ground motions, including:

1. <u>Constant term</u>: assessment of the degree to which the data are systematically higher or lower than those for a global NGA-Sub model.

2. <u>Source parameter scaling</u>: Check of whether the Mexico data are consistent with magnitude- and source depth-scaling relations in an NGA-Sub model.

3. Distance attenuation: Investigate Mexico-specific regional attributes of anelastic attenuation, both in the forearc and backarc, and for interface and slab events.

4. Site response: The scaling of site response with V_{S30} is a regionalized feature in NGA-Sub models. At the time the models were developed, regional V_{S30} scaling terms different from those of the global model were not considered to be justified by the data by Parker and Stewart (2022), although the data were limited. Despite the limited data, a regionalized model was provided by Kuehn et al. (2020). Regionalization of site response is evaluated with the larger data set, and site response in Mexico City is examined as a special case.

Consider an earthquake event i that produces ground motion j. Ground motion intensity measures (e.g., PGA, PGV, PSA for a range of oscillator periods T) can be computed for each ground motion, which are denoted Y_{ij} in arithmetic units. We compute the total residual, R^v, as the difference between the ground motion intensity measure (Y_{ij}) and a model prediction:

$$R_{ij}^{v} = ln(Y_{ij}) - [\mu_{ln,ij}^{r}(\mathbf{M}_i, F_S, (R_{rup})_{ij}) + F_{V,j}] \quad (1)$$

where $\mu_{ln,ij}^{r}$ is the mean ground motion prediction for reference rock site conditions in natural log units from a GMM. We use the Parker et al., 2022 (Pea22) and Kuehn et al., 2020 (Kea20) GMMs with the arguments of moment magnitude (**M**), event-type parameter (F_S), and rupture distance (R_{rup}). F_V is a site amplification model conditioned on V_{S30}:

$$F_V = F_{lin} + F_{nl} \quad (2)$$

where F_{lin} and F_{nl} are linear and nonlinear site-amplification models. For both GMMs, these site amplification models are initially taken from those incorporated into the GMMs; for Pea22, we use the global model of Parker and Stewart (2022); for Kea20, we use the regional V_{S30}-scaling coefficients provided with the GMM. The use of superscript v on the residual in Eq. (1) is to indicate that a V_{S30}-based site amplification model is considered in their derivation.

To quantify systematic event and site misfits from the ergodic model (referred to as event terms and site terms, respectively), we partition total residuals from Eq. (1) using mixed effects:

$$R_{ij}^{v} = c_0 + \eta_{E,i} + \delta W_{ij}^{v} \quad (3)$$

where c_0 is an overall model bias, η_E is the event term, and δW_{ij}^{v} is the within-event residual. The within-event residual contains information on misfit of path and site parameters, and for many applications it is useful to separate these by further partitioning the within-event residual as,

$$\delta W_{ij}^{v} = c_1 + \eta_{S,j}^{v} + \varepsilon_{ij} \quad (4)$$

where η_S^v is the site term and ε_{ij} is the remaining residual. If it is found that non-zero constant terms or adjusted path coefficients are needed to fit the data, these modifications are made and the GMM updated accordingly. This requires re-computation of residuals, event-terms, and site-terms, to confirm that misfits are removed. In this way, the residuals analyses are iterative with the steps to regionalize the model. Site response can be examined by computing site terms relative to the reference condition in the adjusted GMM:

$$\eta_{S,j}^{r} = c_1 + \eta_{S,j}^{v} + (F_V)_{ij} \quad (5)$$

Superscript r indicates the term is relative to the reference-rock velocity condition of 760 m/sec. Reference rock site terms η_S^r are not expected to average to zero because they represent the difference between data for site and model predictions for a reference-rock condition. In aggregate, these residuals estimate site response per the non-reference site approach (Field and Jacob, 1995). Plots of η_S^r with V_{S30} illustrate V_{S30}-scaling, which can be checked against models such as Parker and Stewart (2022). For sites in CDMX, η_S^r can be examined within zones or as a function of V_{S30} or site period to evaluate the effectiveness of different site parameters for predicting site response.

4 Site response in the Valley of Mexico

The site response topic is of particular interest in Mexico City, which has typically been evaluated in past work using reference site approaches, in which ground motions on various site conditions are normalized by ground motions on reference sites, usually consisting of bedrock. A well-known drawback of reference site approaches is that the site amplification that is derived depends on the attributes of the reference site or sites, which generally do not align with the reference conditions in ground motion models. This can create biased ground motion estimates in forward applications if the misfits of reference conditions are not accounted for (e.g., Seyhan and Stewart, 2012). In this section we revisit the well-studied problem of Valley of Mexico (VM) site response using a non-reference site approach (e.g., Field and Jacob, 1995), which to our knowledge has not been applied previously for this important locale. The benefit of this alternative approach is that it can produce site factors that are consistent with regional GMMs, thus avoiding the need for distinct ground motion estimation procedures in Mexico City and the remainder of Mexico, while also removing potential biases implicit to current methods. Such approaches have been successfully applied elsewhere to derive regional (e.g., Parker and Stewart, 2022) and local (Wang et al., 2022) site response models in subduction zone regions.

Geotechnical conditions in Mexico City have commonly been defined in terms of a hill zone, transition zone, and lake zone (Romo et al., 1988). The lake zone includes the Texcoco Lake (while this was once encompassing the entire VM, as used here it refers to a smaller lake in the post-Aztec era), Xochimilco Lake, and Chalco Lake. General characteristics of these zones are as follows (Romo et al., 1988):

- Hill Zones: In the western part of Mexico City, this zone consists of firm soils including silty sands with gravels and cemented tuffs. To the south, lava flows up to 20 m in thickness overlie these formations.
- Transition Zones: Located between the hill and lake zones, the transition zone has variable sequences of firm soils, sands, silty sands, and soft clays.
- Lake Zones: The Texcoco Lake has a surface layer of desiccated alluvial deposits overlying thick soft lacustrine clay interbedded with thin seams of sands, silty sands, volcanic glass, and fossils, which is locally known as the Upper Clay formation. Underlying this formation are hard deposits of silty, weakly cemented sands, a deeper clay stratum known as the Lower Clay formation, and compact lacustrine cemented silty sands and gravels. The Xochimilco-Chalco Lake consists of a clay deposit (somewhat stiffer than the Upper Clay formation in Texcoco) with interbedded seams of silty sands, silts, and sands. This clayey deposit is underlain by a basalt layer (lava flow).

Seismic design in Mexico City uses response spectra that are derived by applying a procedure that takes into account the different ground conditions described above. This is accomplished by assigning zones to the different parts of the city, which are depicted in Figure 3(a) (NTCS, 2004). Figure 3(b) shows the influence of this zonation in the hazard level (250 years of return period). The main site attribute used to distinguish the zones in Figure 3(a) is site period (T_S):

- Zone I (hill): < 0.5 sec.
- Zone II (transition): = 0.5-1.0 sec.
- Zones IIIa-IIId (lakebed): = 1.0-1.5, 1.5-2.5, 2.5-3.5, > 3.5 sec.

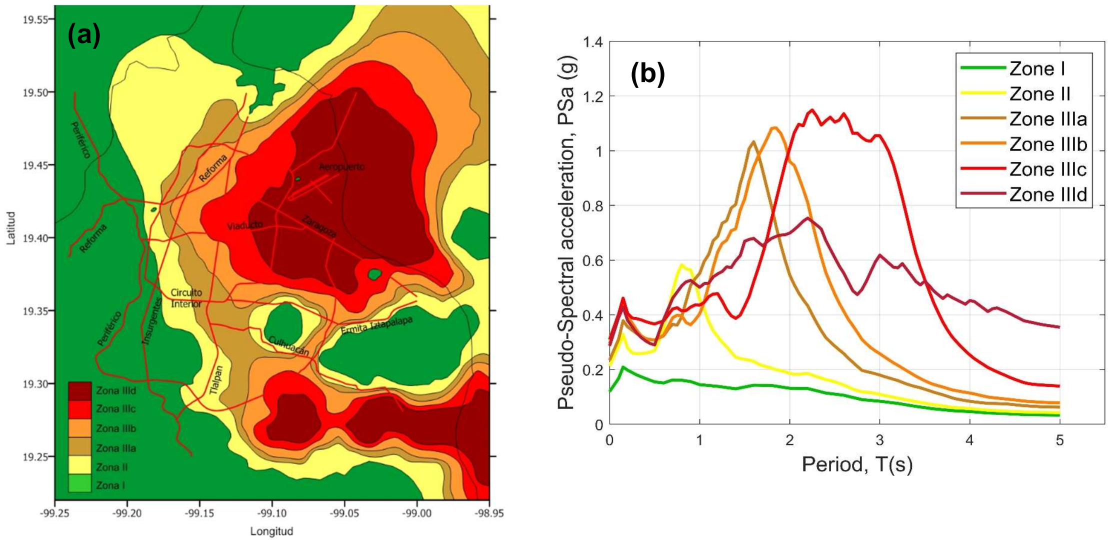

Figure 3. (a) Zone map for CDMX in which the lakebed zone is divided into four subzones that are used to predict site period based on location (NTCS, 2004). (b) Influence of zones (site period) on uniform seismic hazard spectra at selected sites.

4.1 Data compilation and assignment of site parameters

We have compiled available information on velocity profiles and site periods in the VM. The data are from technical reports, research papers, and student dissertations. Velocity data comes from invasive (downhole, crosshole, suspension logging, seismic cone penetration) and noninvasive methods (Multi-channel Analysis of Surface Waves – MASW, Microtremor Array Measurements – MAM, Modified microtremor seismic method using SPatial AutoCorrelation – MSPAC, seismic interferometry – SI, seismic refraction). Site period data are derived from microtremor-based measurements of Horizontal-to-Vertical Spectral Ratios (mHVSR), the lowest peaks of which reveal the fundamental mode site period. Figure 4(a) shows the location of the sites with a V_S profile and site period from results of mHVSR testing. Additionally, locations of sites with HVSR site periods from Lermo and Chávez-García (1994) are indicated, which are used for site period assignments when required. We apply protocols for characterizing V_{S30} for ground motion sites as described by Ahdi et al. (2022). The database contains 97 ground motion sites in the VM. Of these, 17 are Code 0 sites per Ahdi et al., 2022 (their Table 5), meaning that V_{S30} was computed from a V_S profile, which is taken as the median (μ_{lnV}) and the natural log standard deviation (σ_{lnV}) is taken as 0.1. Separation distances up to 300 m were considered in assigning a V_S profile to a ground motion site. For the 80 sites without a V_S profile, we assigned μ_{lnV} based on the zone the site is located in. Figure 4(b) shows box and whisker plots of V_{S30} in the VM, where the red lines indicate the median values (μ_{lnV}) by zone. Further details of the data compilation and assignment of site parameters are given in Contreras et al. (2023).

4.2 Nonlinear Corrections

Our general approach is to evaluate site response effects across the VM using site terms derived relative to the reference site condition of V_{S30} = 760 m/s, which are denoted η_S^r. Those site terms are derived from within event rock residuals (δW_{ij}^r) from different earthquakes i that were recorded at site j. In this section we investigate whether systematic differences are present between δW_{ij}^r values for different events recorded at site j due to site response nonlinearity. If such dependencies exist, they would need to be corrected for before computing the site terms. Within-event rock residuals (δW_{ij}^r) are calculated from the within-event component of total residuals derived from Eq. (3) as follows:

$$\delta W_{ij}^r = \delta W_{ij}^v + (F_{lin})_j + (F_{nl})_{ij} \quad (6)$$

where F_{lin} and F_{nl} are the two components of the ergodic site response model (Eq. 2); note that while both components depend on the site, the nonlinear component also depends on the event because different events produced different shaking intensities and hence have different levels of nonlinearity. The addition of the ergodic model transforms the residuals calculated using a GMM with a site response model (δW_{ij}^{v}) to residuals relative to the reference site condition. It also removes the effects of the ergodic nonlinear model on the residuals, which is desirable because we seek to evaluate nonlinearity that is specific to the VM.

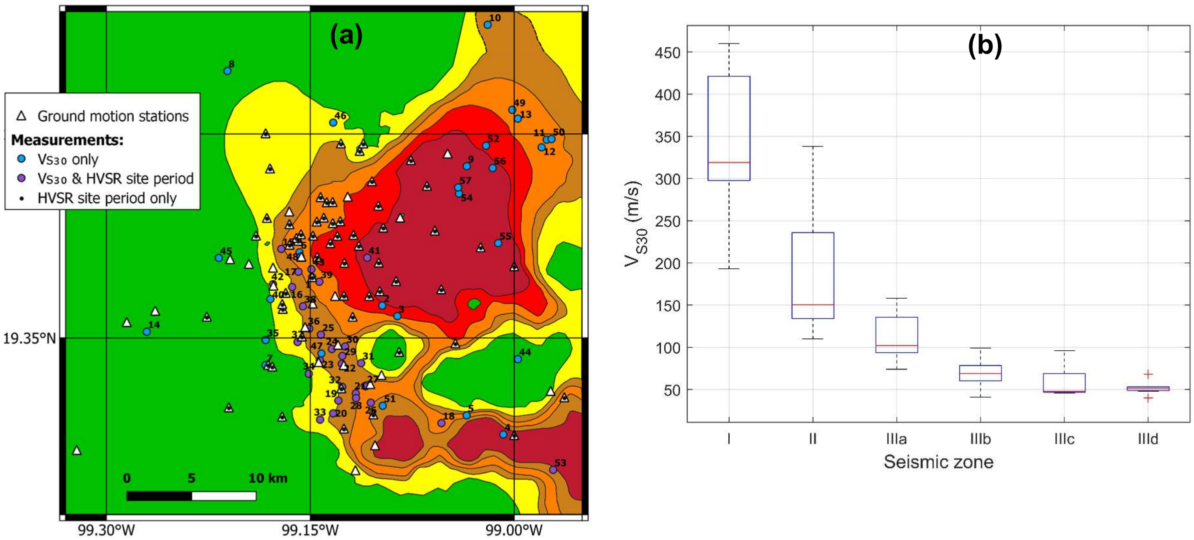

Figure 4. (a) Locations of sites with measured V_S profiles overlain on NTCS (2004) base map. (b) Box and whisker plots of V_{S30} for characterized sites in the VM.

Figure 5 shows example results for two intensity measures [PGA and PSA(2.0 s)] and sites within Zones I and IIIa. The plots show δW^{r} values from the three events described in Section 2 (EQ1: Chiapas, EQ2: Puebla, EQ3: Oaxaca) as a function of the median peak acceleration for reference site conditions (V_{S30} = 760 m/s), denoted PGA_r. Two of these events (Chiapas and Oaxaca) produced weak shaking (PGA_r≈0.0015-0.0025g) and one (Puebla) produced relatively strong shaking (PGA_r≈0.06-0.09g).

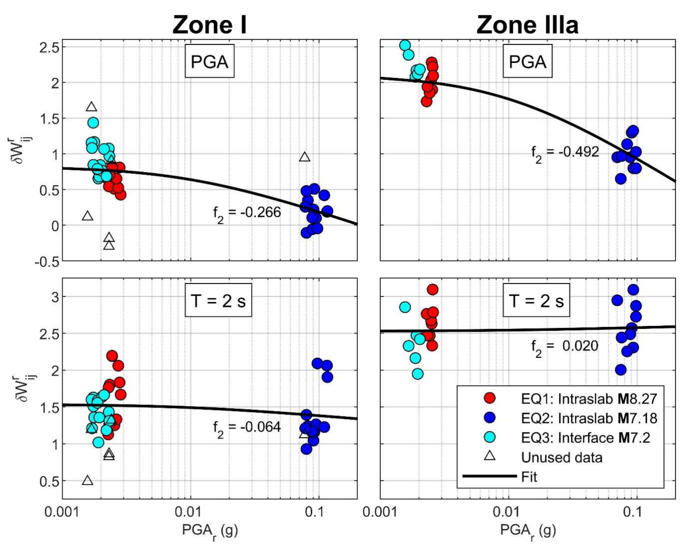

Figure 5. Reference rock within-event residuals for sites in VM Zones I and IIIa for the intensity measures of PGA and PSA(2.0 sec).

The results suggest appreciably lower levels of PGA site response for the Puebla event than for the weaker shaking events, with the level of reduction being greater for the softer site condition (Zone IIIa) than for the firmer condition (Zone I). For PSA(2.0 s), the site responses for the three events are largely similar. These features are consistent with expectation when site response is nonlinear, which is known to reduce short-period site response, has little effect for long-period site response, and is of increasing importance as site conditions soften. These site response features, while consistent with many prior observations world-wide (e.g., Parker and Stewart, 2022), have not been documented previously in the VM. The VM site response has instead been assumed as linear. Accordingly, this is an important finding with significant ramifications for engineering practice in the VM area. To properly model the VM site response, it is necessary to remove nonlinear effects from the δW^r values, which will mainly affect the Puebla earthquake results. We begin by fitting the data trends shown in Figure 5 with Eq. (7),

$$(F_V)_z = f_1 + f_2 ln\left(\frac{PGA_r + f_3}{f_3}\right) \tag{7}$$

where f_1 to f_3 are model coefficients for zone z, and PGA_r is as defined previously. Parameter f_1 represents the linear component of the site response whereas the second term in the sum is F_{nl}. Parameter f_3 represents the level of base shaking where nonlinear effects begin to become appreciable. Given the very soft soil conditions in VM, larger strains could be expected for modest shaking conditions than for relatively firm sites. Fits were performed setting f_3=0.01g and then regressing for f_1 and f_2 using least squared procedures, for the six seismic zones considering the intensity measures of PGA, PGV, and PSA at oscillator periods between 0.01 s and 10 s. The results show strongly negative values of f_2 at short periods for all zones. For softer sites (e.g., Zones III) the values are more negative than for relatively firm sites (Zone I) and the negative values extend to longer periods (e.g., at 1.0 sec, f_2≈0 for Zone I but remains negative for all Zone III groups).

4.3 Estimated linear site responses at recording sites and proposed V_{S30}-scaling model

Typical characteristics of VM site responses are illustrated with example results for seven sites from different zones in the city. The site responses for these seven sites are shown in Figure 6(a). The Zone I site (CUP5) has appreciable amplification, ranging from 0.5 to 1.7 (natural log units), with the maximum amplification being essentially constant for *T* = 1.5-5 sec. The Zone II site (ES57) has higher amplification for PGA and PSA, with a peaked response at 0.8 sec that is much stronger than for CUP5 (~ 2.5), which then decays sharply for *T* > 1 sec. The Zone III sites (IIIa, IB22; IIIb, SCT2; IIIc, XP06; IIId, AE02) also have larger amplification than CUP5 for PGA and PSA. At the longer periods, the site responses peak at amplitudes ranging from 3.2-3.9 (factors of 25 to 50 approximately) at periods of 1.5 sec for IIIa, 1.5-2 sec for IIIb, 2.5 sec for IIIc, and 4-5 sec for IIId. Results in Figure 6(a) for the CUP5 and TACY sites are particularly notable, because they have been widely used as reference sites in prior studies of VM site response (e.g., Reinoso and Ordaz, 1999). The V_{S30} for these sites are 295 m/s and 331 m/s (estimated using Zone I average), respectively, and their site responses are appreciable. Reference sites used in other regions have generally corresponded to much stiffer geologic conditions (e.g., 750-1000 m/s). The implications of taking CU and TACY as reference sites are highlighted in the *Conclusions*. Figure 6(b) shows site response for all VM sites as a function of V_{S30} for the intensity measures of PGA, PGV, PSA(0.3 s), and PSA(3.0 s). At short periods (e.g., PGA), the site response increases as V_{S30} decreases from about 400 to 150 m/s. For softer sites, the site response does not scale with V_{S30}. This general pattern is retained up to a period of 2.0 s, but for longer periods the saturation at low V_{S30} gradually disappears, instead continuing to increase as V_{S30} decreases to its minimum value of 50 m/s. To capture the regional response, the following model is proposed:

$$F_{lin}^{VM} = \begin{cases} s_{1vm} ln\left(\frac{V_{S30}}{V_{1vm}}\right) + s_{2vm} ln\left(\frac{V_{1vm}}{V_{ref}}\right) + f_{VM} & V_{S30} \leq V_{1vm} \\ s_{2vm} ln\left(\frac{V_{S30}}{V_{ref}}\right) + f_{VM} & V_{1vm} < V_{S30} < V_{ref} \end{cases} \tag{8}$$

where the VM superscript indicates it is a Valley of Mexico model, the vm subscript indicates that the coefficients are VM-specific (otherwise the same variable names are used in the Parker and Stewart global model), V_{ref} = 760 m/s, V_{1vm} is a break velocity (model parameter), s_{1vm} is the V_{S30}-scaling for V_{S30} < V_{1vm}, and s_{2vm} is the V_{S30}-scaling for V_{S30} > V_{1vm}. This model is similar to that used by Parker and Stewart (2022), with the following changes: (1) site response is only modelled for V_{S30} < V_{ref} (higher velocities are not applicable in VM); and (2) an amplification shift parameter f_{VM} is introduced that allows for higher site response across all V_{S30}, which is needed across the full period range. Figure 6(b) also shows the fit of the model in Eq. (8) to the data, with model coefficients indicated in the figure. The selected function is seen to fit the data well.

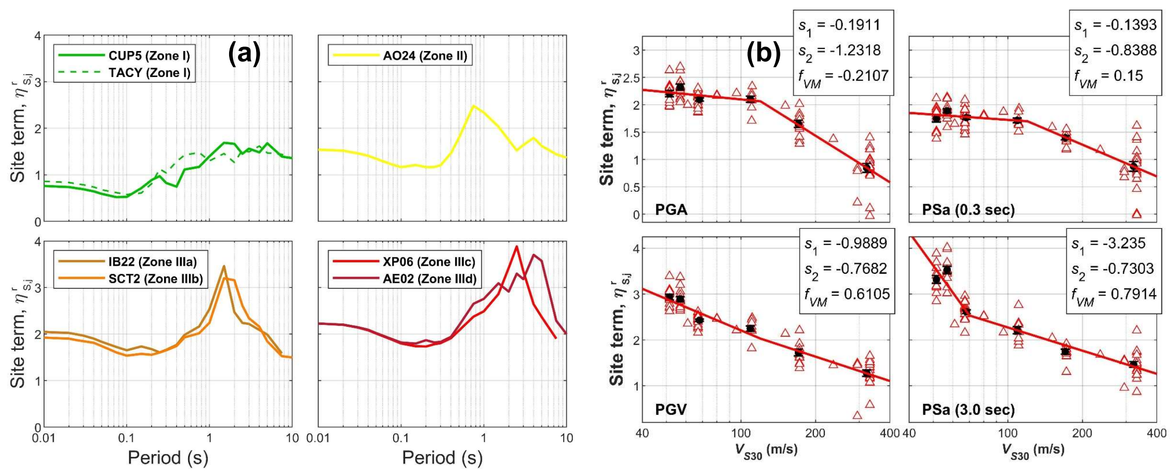

Figure 6. (a) Period-dependent linear site response as derived from non-reference site approach for seven sites in Mexico City. (b) Fit of VM model to site amplification data for peak acceleration, peak velocity, PSA(0.3 s), and PSA(3.0 s).

5 Conclusions

The analysis of ground motion data from Mexico has yielded several key insights. A thorough examination of site response in Mexico City indicates that the CU site has a significant level of site response over a wide range of periods, which is not an ideal condition for a reference site. The findings on site response are broadly consistent with previous studies regarding the relative amplification levels between lakebed zones and the periods where these amplifications are most pronounced. However, two new significant observations emerged: (1) amplification levels are higher in this study due to the use of a reference rock site with velocity V_{ref}=760 m/s, and (2) analysis of data from multiple events reveals that short period site amplifications exhibit nonlinearity. Adopting a non-reference site approach for amplification derivation is particularly significant from a ground motion modeling perspective, as it eliminates the necessity of developing single-station reference GMMs for the CU site. This approach substantially enhances the level of rigor with which the reference site GMM can be defined.

The site response in the Valley of Mexico is characterized by a nonlinear model that is conditioned on the shear wave velocity in the upper 30 meters (V_{S30}). The linear component of this model effectively captures the primary trends in site response variations across the lakebed. While the data do exhibit some resonance effects that this model does not capture, these effects are small compared to what the V_{S30}-based model accounts for. To maintain simplicity in application, these moderate resonance effects are not included in the model. The nonlinear component of the model, despite being less precisely defined, clearly demonstrates the presence of nonlinearity. To develop a more robust nonlinear model, calibrated simulations that incorporate nonlinear soil behavior would be necessary.

6 Acknowledgments

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