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Seismic Ground Motion Prediction for Delta Region of California Including Regional Path Effects and Local Site Response

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ABSTRACT

Levees founded on peaty organic soils in the Sacramento-San Joaquin Delta region of California are vital infrastructure that supply much of the state with fresh drinking water and protects Delta islands from inundation. Therefore, the damage or breach of a levee as a result of an earthquake has the potential for catastrophic impacts. Peaty-organic soils affect the seismic demand and ground deformation potential associated with risk assessment, but existing ground motion models (GMMs) are not calibrated for such soft soils. In this ongoing study, we develop empirical data on small-strain site amplification in the Delta through expansion of the NGA-West2 ground motion database and investigate and adjust an NGA-West2 GMM for regional path effects. A regional site response model is developed using a dataset developed from 45 instrumented sites located within the Delta, as well as 55 sites outside of the Delta. The combination of accounting for regional path effects and local site response holds the potential to significantly improve GMM predictions and significantly reduce epistemic uncertainty.

Introduction

The Sacramento-San Joaquin Delta is located in California's Central Valley, about 50 km east of the San Francisco Bay area. Roughly 700,000 acres of land within the Delta are protected by more than 1700 km of levees [1]. These levees also serve as a conduit for approximately two-thirds of the state's drinking water supply. The damage or breach of one or more levees as a result of an earthquake would prove to be catastrophic [2]. In 2009, the Delta Risk Management Strategy (DRMS) conducted a probabilistic seismic hazard analysis (PSHA) for the Delta, and concluded that seismic events pose a significant hazard to Delta levees [3].

Before the lands were reclaimed, the area was a great tidal freshwater marsh containing abundant organic peat deposits [4]. The thickness of these organic deposits vary across the Delta, reaching up to 15 m in some areas [5]. The peaty organic soils underlying the Delta levees affect risk in two ways: (1) seismic demand is affected as a result of site amplification of ground motions and (2) ground deformation potential associated with permanent shear and/or volumetric deformations in peat. This work is concerned with the first

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of these issues (site response).

Ground motion models (GMMs), which utilize seismic source, travel path, and site terms to characterize the attributes of ground motions, are often used by engineers to assess seismic demands. The GMMs used in California are from the NGA-West2 project [6]. One of the GMMs developed in that project, referred to here as BSSA14 [7], provides regional anelastic attenuation effects, including a statewide model for California. Differences have been observed when investigating regional effects at a more local scale, for example in California by [8] and [9]. The peaty soils in the Delta are suspected to produce site effects that are not well represented by site terms in current GMMs, given that their site conditions are much softer than those considered during NGA-West2 model development.

This study (1) presents a database of earthquake ground motions in the Delta and surrounding areas, (2) develops a regional path model, and (3) develops a regional linear site response model for local site effects in the Delta. Such models are vitally important for seismic hazard and risk analysis for levees and other vital infrastructure for the Delta region of California. The results of this work may also be useful for other regions with soft peaty soils in the US and elsewhere.

Ground Motion Database

A database of ground motion recordings for the California study region was compiled. This database consists of recordings from the NGA-West2 database [6], which is a global database for active tectonic regions, and data added as part of this study and related efforts [10]. Prior research efforts have identified difficulties that may be encountered in the analysis of site terms using smaller magnitude data [11] and therefore we only consider events with moment magnitudes **M**>4. Using this magnitude criterion we pulled data from 222 NGA-West2 events (10,378 ground motions recorded at 1,636 stations). Additionally, we identified 93 earthquakes since 2011 which significantly expand the California ground motion database especially in the northern half of the state. The newly compiled data and the California NGA-West2 data have been converted from a flatfile into a relational database. Fig. 1 shows the locations of 315 events sorted by magnitude along with the locations of 2,733 distinct seismic recording instruments which have produced over 27,484 three-component ground motion records.

Source parameters were compiled for each of the 93 new events. Finite fault models for the 2014 South Napa (**M**6.02) and 2019 Ridgecrest Earthquake sequence foreshock (**M**6.5) and mainshock (**M**7.1) were used to account for finite fault effects in rupture distance calculations as described in [12]. The majority of remaining new events have **M**<5.2, for which finite fault effects are not considered to be significant for the derivation of rupture distances. Therefore, site-to-source distances were computed using the CCLD5 program as described by [13]. Focal mechanisms were assigned using the conventions based on rake angle presented in [14].

Newly added data were screened to remove duplicate and apparent unreliable recordings (e.g., instrument malfunctions) and magnitude-distance cutoffs suggested by [7] are enforced for all ground motions resulting in about 26,260 usable ground motions within the study region. Each newly added three-component record has been processed in accordance with standard protocols developed during Pacific Earthquake Engineering Research center (PEER)-NGA projects [15], which provides a lowest usable frequency as 1.25 times the low-pass corner frequency used during signal processing. Horizontal components are combined to median-component (RotD50) intensity measures as defined by [16] using the R routines outlined in [17].

Site parameters such as time-averaged shear wave velocity of the upper 30 m (V_{S30}) and basin depths ($z_{1.0}$ and $z_{2.5}$) were updated for NGA-West2 sites and assigned for the 1,097 newly added sites. Sites with V_S measurements obtained from a V_S profile database [18] were used to assign V_{S30} following protocols given in [19]. For sites without V_S measurements, we assigned V_{S30} by combining the geologic- and topographic-based proxy relationship of [20] (2/3 weight) and the terrain-based proxy model of [21] (1/3 weight). Sites located in the Delta without measured V_S profiles were assigned V_{S30} from a regional model based on peat thickness. All basin depth parameters were assigned using updated and expanded versions of California basin models including, but not limited to, [22], [23], and [24].

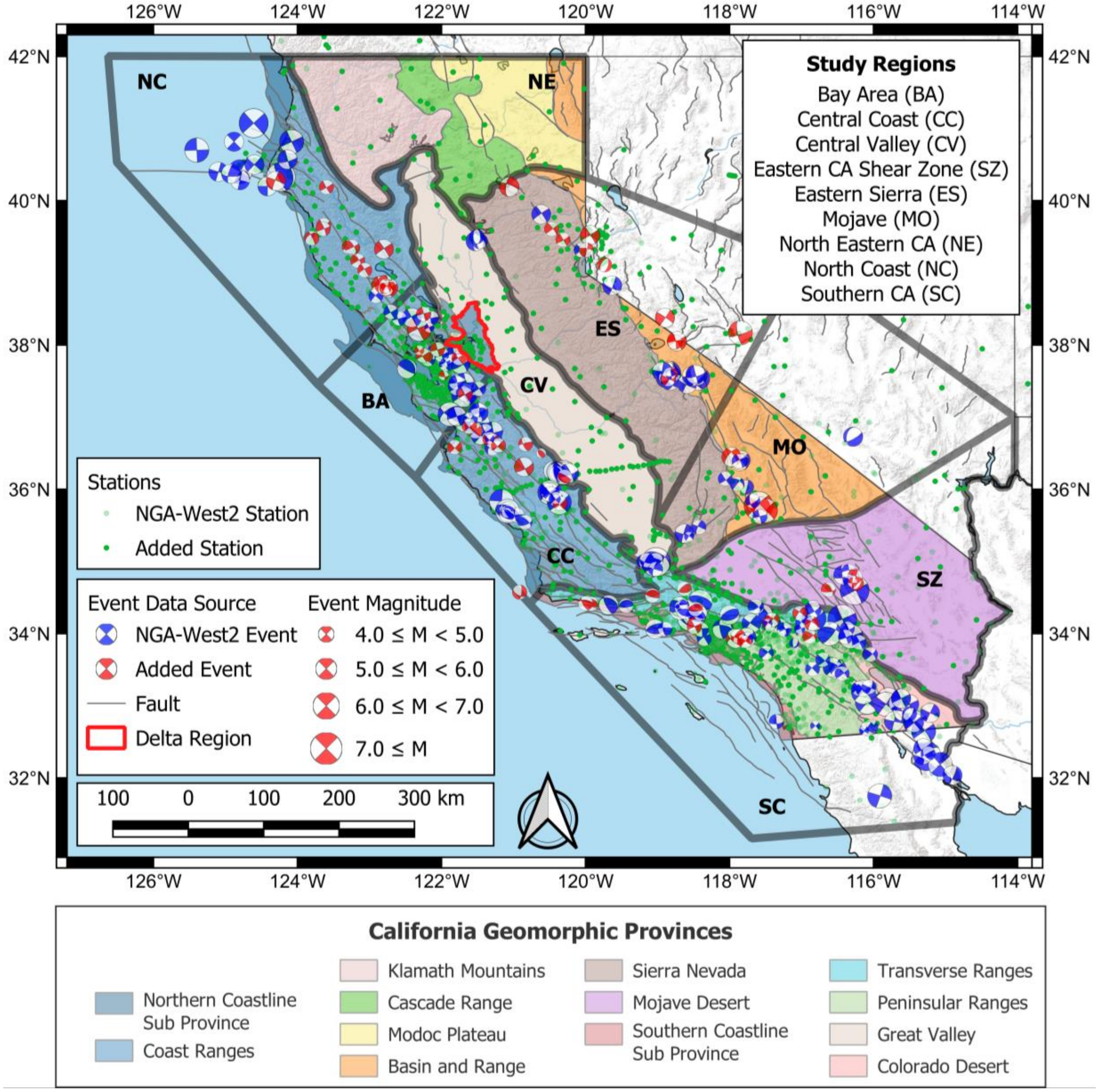

Figure 1. Locations of earthquakes in California, Northern Mexico, and Nevada from NGA-West2 and since 2011 for which ground motion data has been compiled, as well as seismic recording stations that recorded the events, and boundaries of the nine subregions defined in this study

Regional Path Effects

Recent research efforts have found that rates of anelastic attenuation vary across the state relative to the statewide average [11, 25]. Prior work on the spatial variations of anelastic attenuation in California have used NGA-West2 or earlier databases; therefore we elected to perform our own analysis using the expanded database for California described in the previous section. Inspired by the method developed by [25] to incorporate nonergodic path effects into GMMs, we subdivided the state into nine broad regions (shown in Figure 1) based on geomorphic province and preliminary observations of event terms and spatially varying path effects.

BSSA14 contains a Δc_3 term to account for regionally varying rates of attenuation. Using mixed effects residuals analysis, we have investigated the relation between within-event residuals (δW_{ij}) and distance to assess path effects. By investigating subsets of data partitioned based on whether or not a particular path traverses a particular region we can infer whether or not the rate of attenuation for a particular region is different than what the GMM predicts (i.e., path bias). Fig. 2a and 2b present plots of δW_{ij} versus R_{JB} for two example regions. One of these shows no appreciable bias relative to that provided in BSSA14 (southern California), while the other (north coast) shows significantly faster distance attenuation as indicated by the downward trending residuals with distance. Using the proportional contribution (w_R) of attenuation from each region traversed for a particular source-to-site path, we compute the path-specific Δc_3 as described in Eq. 1.

$$\Delta c_3 = \sum_{R=1}^{9} \Delta c_{3,R} \times w_R \tag{1}$$

where $\Delta c_{3,R}$ represents the Δc_3 value for region R (i.e., BA, CC, CV, etc.) and $\Sigma w_R = 1$. Our path model captures regional path effects that are otherwise not included in the default BSSA14 path model, thus improving the accuracy of ground motion prediction and reducing epistemic uncertainty.

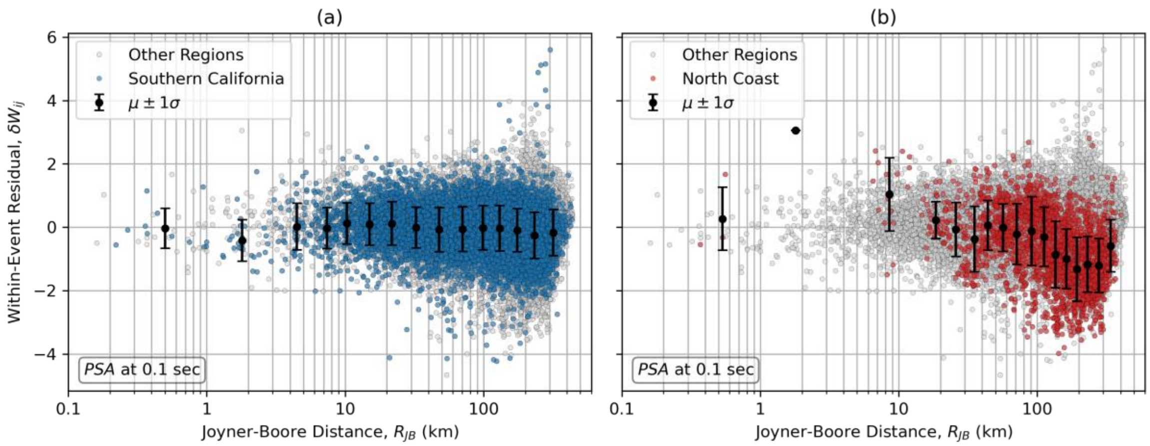

Figure 2. Plots of within-event residuals (δW_{ij}) for 5%-damped pseudospectral acceleration at 0.1 sec versus Joyner-Boore distance (R_{JB}) for data with no apparent path effects (southern California; a) and significant path effects (north coast; b). Data shown for paths with >80% of total path length within region of event origination.

Local Site Response

The site response model utilized in BSSA14, hereafter SS14 [19], was developed using the NGA-West2 database and lacks proper constraint for soft soil sites in the Delta. Given the increase of data available in the Delta in our ground motion database, we are investigating linear site response empirically (data corresponds to weak motions which do not introduce nonlinearity effects). Using mixed-effects regression we obtain reliable estimates of site terms for 33 of the 45 sites within in the Delta. The results show weaker-than SS14 amplification at short periods and stronger-than-SS14 amplification at long periods. We are investigating the correlation with site parameters beyond V_{S30}, including peat thickness, and site period to develop a local site response model applicable to the soft soil conditions found in the Delta.

Conclusions

Using an expanded (relative to NGA-West2) ground motion database for California, we have identified regional path effects across the state and developed models to capture these effects. We are also developing local site response model(s) for the Delta, which will be valid for small-strain (linear) conditions. Additional work (in the form of simulations) are being performed in order to investigate nonlinear effects so as to develop a complete local site response model applicable for Delta sites.

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