Title

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Estimating ground motions from past earthquakes for levees founded on soft soils

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ABSTRACT

Levees are earth structures sited along river channels and coastlines for flood control purposes. We are engaged in a long-term project to evaluate seismic fragility of levees founded on soft peaty organic soils using case history data from Hokkaido, Japan. As part of this effort, it is necessary to characterize seismic demands in the form of peak ground acceleration or velocity using data recorded at regional strong motion recording stations. Such stations are typically situated on stiffer soils than levees, thereby exhibiting different site effects. This paper presents a procedure for spatially interpolating strong motion recordings while accounting for differences in site conditions. Ground motion models (GMMs) for subduction earthquakes are first used to compute within-event residuals at the recording stations. These residuals are then spatially interpolated at levee locations, and added to the sum of the event term and median GMM prediction (which includes a nonlinear site term) to estimate ground motions at the softer sites. The procedure is applied to the data recorded during the 2003 **M**8.2 Tokachi-oki earthquake from PARI, JMA and NIED arrays, but not a local array deployed by Obihiro River Management Office at the Hokkaido levees. This enables validation of the procedure, which amounts to validation of the nonlinear site term for the peaty soil conditions present at the levees. The results show an underprediction bias from existing site terms when applied to the site conditions at the Hokkaido levees.

1 INTRODUCTION

Levees are earthen embankments constructed to protect communities and infrastructure from floods. Their proximity to river channels and coastlines often place them on loose, soft soils with shallow groundwater conditions. Such soil materials are susceptible to settlement and deformation from liquefaction, cyclic softening, and/or post-cyclic volume change in the levee body and the foundation (Youd et al. 2001, Sasaki et al. 2012). This paper addresses issues in ground motion characterization for such spatially distributed systems, not for the case of future earthquakes (needed for seismic risk characterization) but for past earthquakes.

The interest in past earthquakes is related to an ongoing research project in which we are seeking to evaluate the seismic fragility of levees on peaty organic soils. An essential step in this process is evaluation of ground motion demands along levees in the form of intensity measures such as peak ground acceleration or velocity (PGA or PGV).

Obviously, recordings at the site of interest is the most reliable way to quantify seismic demands. However, recording stations are rarely located on levees and are too sparse to provide intensity measures at regular intervals along the levees. Estimating the ground motions along the levees is a non-trivial task as levee systems typically span tens of kilometers, over which the subsurface properties and the shaking intensities may vary significantly. Additionally, site conditions at the recording stations are typically stiffer than the levees. Site response will be systematically different, which prevents the direct interpolation of intensity measures at recording stations.

Kwak et al. (2016) encountered a similar situation while estimating shaking intensity along levees to develop seismic fragility functions, and proposed a methodology to account for variable site conditions. Spatial interpolation is performed on the within-event residuals computed from a suitable Ground Motion Model (GMM) rather than the recorded intensity measure. This process is most effective if the GMM captures the average path and site effects in the target region, and is capable of accounting for the differences in site response between the levee sites and the recording stations. The residual is the difference between the observed and the predicted values, and represents the deviation from the model's prediction due to processes not fully captured by the model (e.g., directivity, complex site effects). For a given earthquake *i*, the within-event residual is given by:

$$R_{i,j} = \ln\left(IM_{i,j}\right) - \left(\mu_{i,j} + \eta_i\right) \qquad [1]$$

where $IM_{i,j}$ is the observed intensity measure at station *j*, $\mu_{i,j}$, is the median intensity measure predicted by the GMM for the magnitude, distance, and site conditions at station *j*, and η_i is the event term for the earthquake.

The within-event residual at any location (ideally within the area encompassed by the measurements) can be estimated with spatial interpolation. The shaking intensity at the site of interest (i.e., along the levee) is given by:

$$\ln(IM_{i,k}) = (\mu_{i,k} + \eta_i) + R_{i,k} \qquad [2]$$

where $R_{i,k}$ is the residual at site k, $\mu_{i,k}$ is the median intensity measure predicted by the GMM for the conditions at location k, and η_i is the event term previously determined from the station recordings.

We applied the Kwak et al. (2016) approach with three combination of GMMs and non-linear site amplification functions to derive the PGA residuals for the 2003 **M**8.2 Tokachi-oki earthquake for stations from the PARI, JMA and NIED arrays. The estimated PGA are compared to the recorded values for an independent subset of stations along the levees for validation and identification of areas for fine-tuning.

2 STUDY REGION

Extensive levee systems protect the urban and agricultural land adjacent to the Kushiro and Tokachi Rivers in Hokkaido, Japan. The levees have experienced several large magnitude earthquakes occurring in the subduction zone directly offshore. Figure 1 shows the levee systems and the surface projection of the finite fault solution for the 2003 **M**8.2 Tokachi-oki earthquake, which strongly shook and damaged substantial lengths of levees along the Tokachi River. Levees along the Kushiro River experienced lower shaking and sustained minor damage.

The environment in Hokkaido is favorable for the formation of peat, which is a soft and highly compressible material composed of partially decomposed organic material. Prior geotechnical investigations by the Kushiro Hokkaido River Disaster Prevention Research Center (2004) and Kushiro Development and Construction Office (1994) found peat deposits ranging from 1 - 6 m thick underlying the levees in the downstream regions of both rivers.

2.1 Recording Stations

Japan has several ground motion networks managed by various government and local agencies. We collected recordings from stations maintained by the Japan Meteorological Agency (JMA), Port and Airport Research Institute (PARI), the National Research Institute for Earth Science and Disaster Prevention (NIED), and the Obihiro River Management Office. The recordings are filtered in a consistent manner with assistance from T. Kishida following standard protocols (Ancheta et al. 2013). PGA obtained from the processed records is used as the primary ground motion intensity measure. Table 1 summarizes the data available from each agency. Stations near the levees are shown in Figure 1.

Table 1. Strong motion networks and available stations

Network	Number of stations
Japan Meteorological Agency	55
Port and Airport Research Institute	9
National Research Institute for Earth Science and Disaster Prevention	553
Obihiro River Management Office	7

The NIED network has the highest density with stations spaced at approximately 20 km intervals within Japan, and contributes the bulk of the available records. The Obihiro River Management Office are concerned with rapid assessment of levee performance after earthquakes, and their stations are distinct from the others as they are directly located on the levees with very soft site conditions. Each station consists of a pair of sensors, located on the landside toe and the crest of the levee respectively, and are oriented to be parallel and perpendicular to the levee in the horizontal plane. Of the 7 existing stations, 6 of them recorded the 2003 event. They are set aside in the initial development of the residual map and are used to validate the interpolation methodology, which effectively amounts to validation of the empirical site term used with the GMPE.

2.2 Site Conditions

Site conditions are commonly represented by the time-averaged shear wave velocity in the upper 30 m (V_{S30}). The level of site characterization varies between the four networks. The NIED and PARI stations have shear-wave velocity profiles from downhole logging. Measured profiles are unavailable for the JMA stations, and V_{S30} is estimated from the geomorphology, elevation, slope and distance to hill/mountains at the station location based on Wakamatsu and Matsuoka (2013).

The Obihiro stations lack measured shear-wave velocity profiles and geotechnical investigations. Geophysical measurements are not routinely performed along levees, with the exception of reconnaissance studies and post-seismic repair efforts.

We measured the dispersive properties of the surficial materials at five of the Obihiro stations using the Spectral Analysis of Surface Waves (SASW) technique. Sixteen additional measurements were performed along the levees in both systems. Figure 1 also shows the Obihiro stations and SASW measurements along the Tokachi River.

The inversion of the dispersion curves to obtain the shear-wave velocity profiles was constrained by the stratigraphy from neighboring borings. The depths of the resulting profiles depend on the site conditions present, and are shallower for softer sites. The majority of the tested sites have profiles extending to less than 30 m. For such sites, we compute the time-average velocity to the profile depth (V_{sz}), and then compute V_{S30} using the Midorikawa and Nogi (2015) model as follows:

$$\log(\overline{V_{S30}}) = c_0 + c_1 \log(V_{SZ}) + c_2 \log(V_s(z_p)) \qquad [3]$$

where z is the profile depth and $V_S(z_p)$ is the V_S at the bottom of the profile.

Figure 2 shows the distribution of V_{S30} at the recording stations and for tests performed along the levees. Site conditions at the levees are consistently softer than the recording stations, with most having V_{S30} between 100 - 150 m/s. In contrast, the majority of the stations have V_{S30} > 200 m/s. The systematic difference presents issues for estimating intensity measures along the levees from station recordings, since such estimates are based on extrapolations beyond the range of the event-specific data guided by the site term in the GMM.

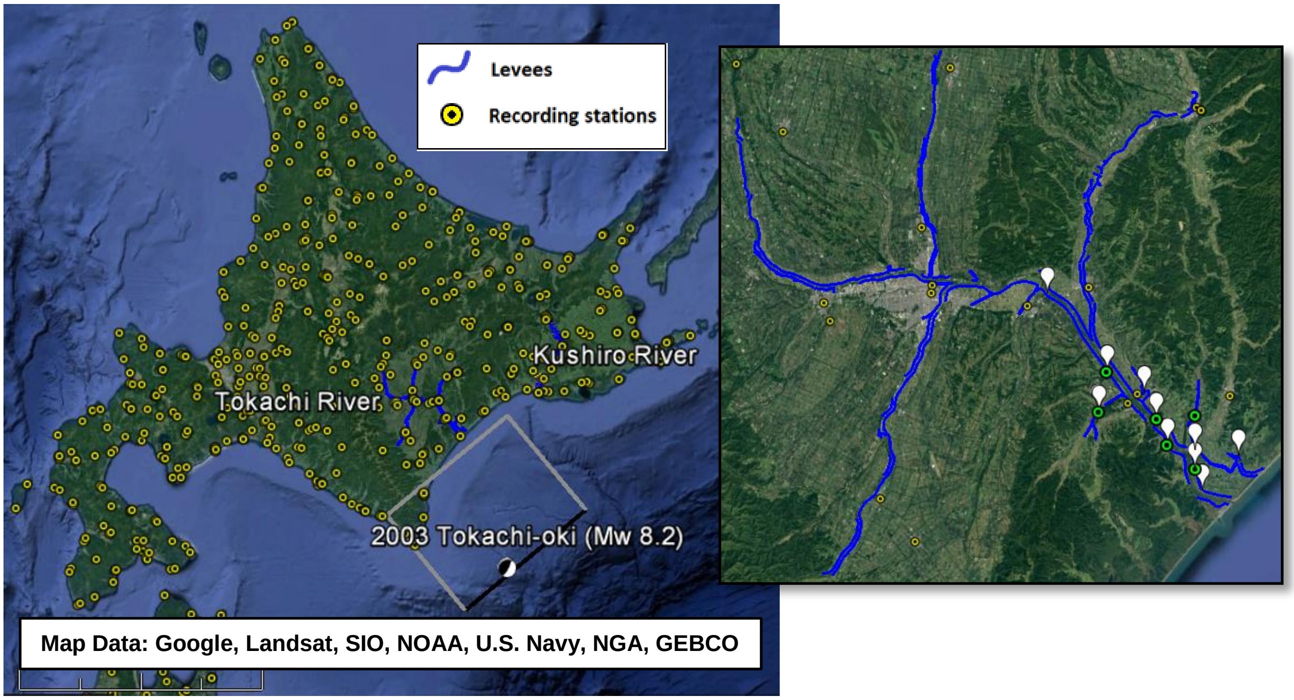

Figure 1. Surface projection of the finite fault plane (black line at top) and the mechanism for the 2003 **M**8.2 Tokachi-oki earthquake are shown together with active stations. The insert is a close-up of the levees along the Tokachi River, only a small fraction of the stations is near the levees, and is sparse relative to the dimensions of the overall levee system. The Obihiro stations (green circles) and SASW test locations (white balloons) are mainly in the downstream region with very soft site conditions.

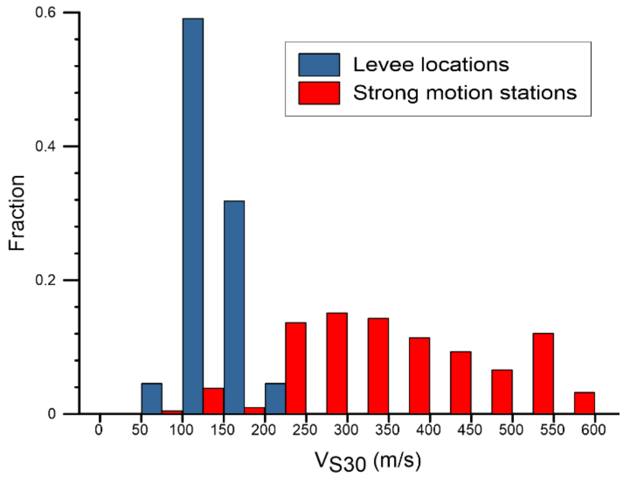

Figure 2. Distribution of V_{S30} along the levees and the stations. The site conditions at the recording stations are consistently stiffer than at the levees.

3 GROUND MOTION ESTIMATION

The available strong motion recordings are divided into two sets, the first consisting of NIED, JMA and PARI stations with stiffer site conditions representative of typical strong motion stations. The second set contains only the Obihiro stations, which are on uncharacteristically soft sites due to their placement on the levees. We will use the first set to produce the residual map and estimate the ground motions at the softer Obihiro stations, and compare the estimated to the measured PGA.

3.1 Ground Motion Models

The GMMs by Zhao et al. (2006) (Zea06) and Abrahamson et al. (2016) (Aea16) are selected. Both are developed for subduction earthquakes using datasets containing large number of Japanese recordings, and are applicable to the 2003 Tokachi-oki earthquake. The Zea06 model has a linear site term. As the effects of nonlinearity is important for softer soils, PGA for rock conditions is first estimated with the Zea06 model, then modified using a suitable amplification model to reflect the site effects expected for the conditions at the stations. The model by Kishida et al. (2009) (Kea09) and the semi-empirical model by Seyhan and Stewart (SS14) are selected.

Kishida et al. (2009) performed simulations of one dimensional equivalent-linear ground response analysis for soil profiles with thick deposits of highly organic soils. The simulated soil type and condition is closest to that present at the stations. The model uses M_w and PGA at NEHRP site class D (V_{S30} between 180 - 360 m/s) as the predictive variables, which requires an intermediate step using Seyhan and Stewart's model to estimate the PGA for site class D from the PGA for hard rock from Zea06.

Abrahamson et al. (2016) have implemented a nonlinear site term and PGA is estimated directly using the model. The within-event residuals at the recording stations are determined based on Equation [1] and spatially interpolated.

3.2 Spatial Interpolation

Sites in close proximity tend to experience similar ground motions as they have comparable site conditions and travel paths, with the correlation decreasing for larger separation distances. The average dissimilarity of a spatially distributed random variable can be expressed with a semi-variogram. A simplifying assumption is that the variable is stationary (i.e., constant mean with no regional or directional trends), such that the variance between two points depends on the separation distance only. As local site conditions and position from the rupture surface affects PGA, the semi-variogram of the within-event residuals is developed instead. In addition, directly interpolating PGA will introduce systematic bias, as the levee sites are consistently softer and have different site response than the observed recordings at the strong motion stations. The within-event residuals is the difference between the observed and predicted median value from a suitable GMM after accounting for the event term. As the GMM accounts for the effects of source, site and path, the within-event residuals have a mean of zero and is independent of the location, satisfying the stationarity assumption.

Simple Kriging is a linear interpolation method for estimating the unknown values of a spatially distributed random variable based on values sampled at other locations. The mean squared error of the predicted and the observed values is minimized using weights derived from the semi-variogram model. The predicted value is heavily influenced by the closest measurements, and therefore the fitted semi-variogram model prioritize capturing the behavior at short separation distances rather than producing the best-fit overall (Jayaram and Baker 2009).

Figure 3 shows the empirical and the fitted semi-variograms for PGA residuals from the 2003 earthquake. All available recordings are used in 3(a)-(c). Several studies observed the backarc (the region behind the volcanic arc and away from the Pacific Ocean) to have less rapid distance attenuation, particularly at high frequencies (Sasaki. 2009, Ghofrani and Atkinson 2011). As all the sites and stations of interest lie in the forearc region, an alternate set of semi-variograms, shown in 3(d)–(e), are derived using only forearc stations. The second set of models have reduced nugget (variance at zero separation) and decreased range (distance beyond which correlation is effectively zero), suggesting that when only forearc stations are considered, the PGA between closely located sites are more correlated, but the correlation drop off more rapidly with increasing separation. As the levees and all the Obihiro stations are in the forearc, the semi-variogram models shown in 3(d)-(e) is used in subsequent Kriging analysis to interpolate the residuals.

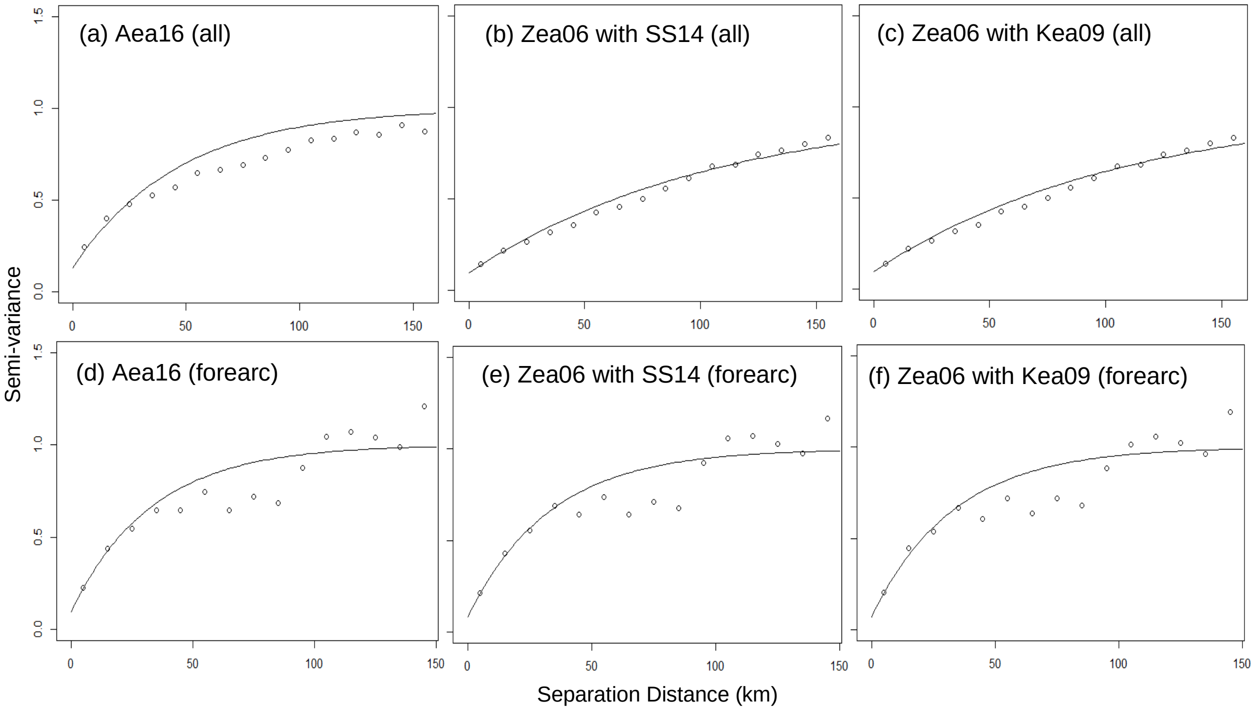

Figure 3. Empirical and fitted semi-variograms for the PGA residuals from the 2003 earthquake based on (a)(d) Abrahamson et al., Zhao et al. with (b)(e) Seyhan and Stewart, and (c)(f) with Kishida et al. Variance is small for closely spaced locations with similar ground motions, increasing with separation distance. (a)-(c) use all available recordings, while (d)-(f) use only forearc stations, where the sites of interest are. The nugget and the range of the forearc only models are reduced, suggesting higher correlation at short distances that decays quickly with separation.

Figure 4 shows the estimated V_{S30} based on Wakamatsu and Matsuoka (2013), taken from the Japan Seismic Hazard Information Station (J-SHIS) online database, and within-event residuals kriged with the forearc only semi-variograms. Positive residuals, shown in red, indicate areas where the recorded motions exceed the model predictions. They mainly occur in the forearc and areas with lower V_{S30} (red and yellow zones). Negative residuals, where the models are over-predicting the ground motions, tend to occur in the backarc and mountainous regions with stiffer site conditions (blue and green zones). The residuals maps in 4(c) and 4(d) is largely similar as Kishida et al. applies only to sites with organics and V_{S30} below NEHRP site class D (180-360 m/s). V_{S30} at stations are generally in exceedance of that. All the residual maps display similar trends of the recorded PGA being systematically lower than the predicted PGA in the backarc. Considering Aea16 differentiated between forearc and backarc in model development, but still has a similar pattern as Zea06, which does not distinguish between the two, may suggest that the difference in attenuation is not fully captured. Alternatively, the site effect may be more dominant than the path effect on the PGA.

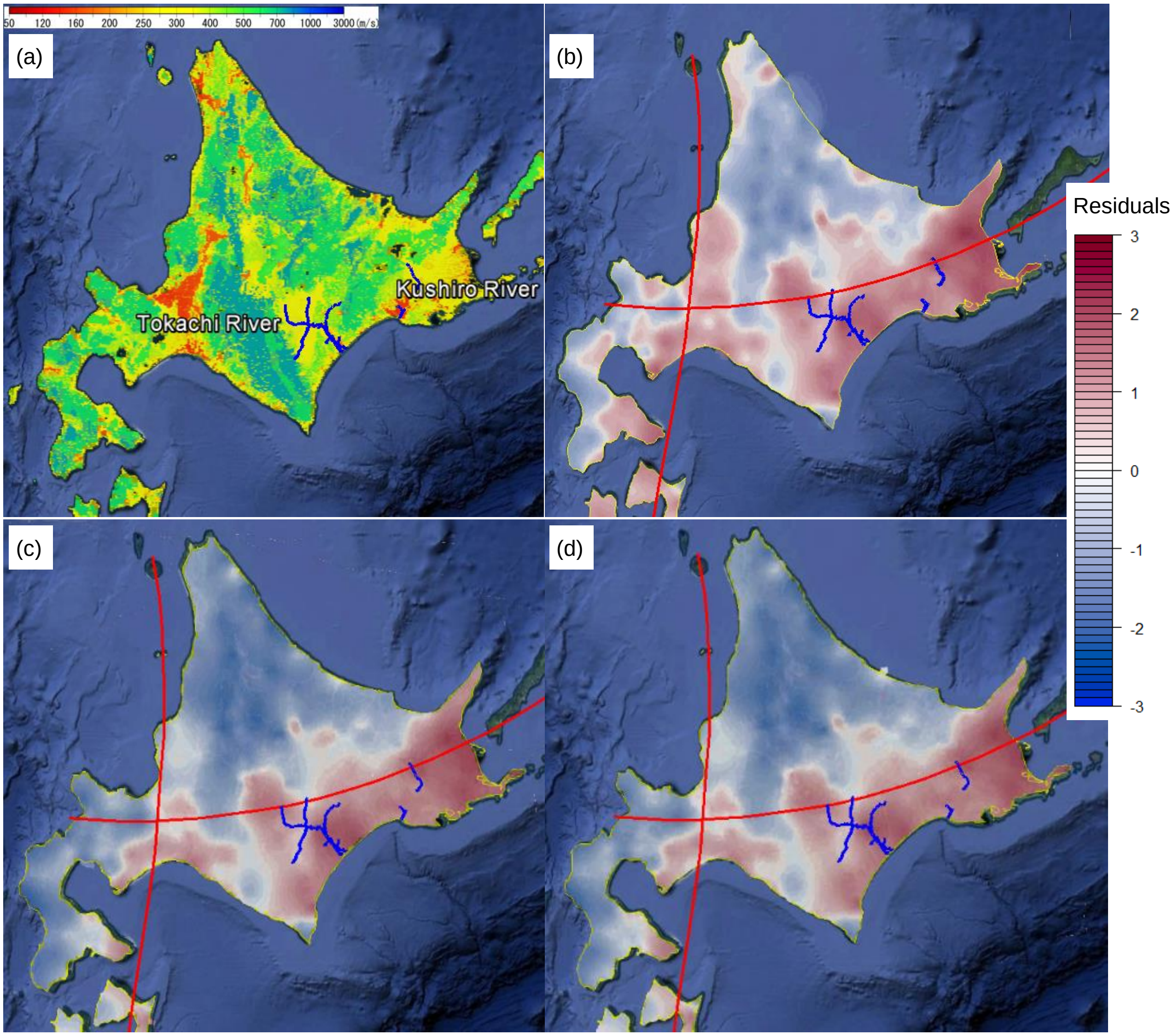

Figure 4. Maps of the study region showing (a) V_{S30} estimated from terrain and geomorphology by J-SHIS and interpolated within-event PGA residuals calculated using models by (b) Abrahamson et al. (2016), and Zhao et al. (2006) with site amplification model from (c) Seyhan and Stewart (2014) and (d) Kishida et al (2009). The levees, outlined in blue, are mostly located on floodplain deposits with lower V_{S30}. The volcanic arc, outlined in red, separates the forearc from the backarc. Strong regional trends for the residuals are apparent, with most of the forearc having positive residuals, and the backarc having negative residuals. Stiffer deposits with higher V_{S30} are generally associated with negative residuals.

3.3 Predicted PGA at Obihiro stations

The Obihiro stations are listed in Table 2, in order of increasing V_{S30}, with the PGA recorded during the 2003 Tokachi-oki earthquake. All the stations are located directly on the levees with soft ground conditions. The comparison of the observed with the measured PGA is a valuable gauge of the method's performance at the levees, where the eventual goal is to have a continuous estimate of ground motions.

Table 2. Obihiro station properties

No.	Station	Lon.	Lat.	V_{S30} (m/s)	PGA (g)
1	Horooka	143.55	42.78	107.3	0.344
2	Toitokki	143.60	42.73	118.5	0.654
3	Gyushubetsu	143.46	42.79	139.3	0.444
4	Rabirai	143.56	42.76	154.6	0.412
5	Reisakubetsu	143.48	42.84	159.7	0.685
6	Higashiinaho	143.61	42.81	165.0	0.645

Using the recordings from the JMA, PARI and NIED stations, the PGA at each Obihiro station is estimated by interpolating the measured PGA (direct), and the within-event PGA residuals from the GMMs. Figure 5 shows the predicted and measured PGA for each station. The mean and standard deviation of the difference between the predicted and measured PGA are shown in Table 3. Overall, the predicted values are lower than the measured PGA, particularly for strong shaking, and is reflected by all the applied method having negative means. In particular, station 2 and 5 have exceptionally high PGA that none of the methods could capture.

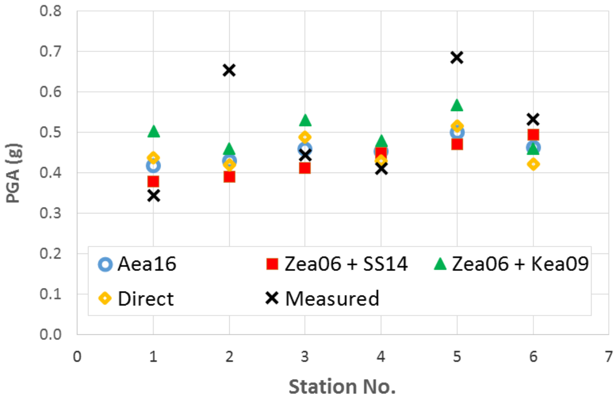

Figure 5. Observed and estimated PGA for the Obihiro stations, ordered by increasing V_{S30} at the station.

Table 3. Difference between predicted and measured PGA

Method	Mean	Standard Deviation
Aea16	-0.058	0.12
Zea06 (SS14)	-0.079	0.12
Zea06 (Kea09)	-0.011	0.14
Direct	-0.060	0.13

The ratio of the estimated to measure PGA is shown in Figure 6, ratios close to unity indicates good agreement between the two. The difference between the PGA predicted with the Zea06 GMM is due to the implementation of the SS14 and Kea09 site amplification models respectively. The Kea09 model was based on simulations with profiles containing peat, and has the lowest mean between the four methods, suggesting that it is a better representation of the behavior of the peat soils. The Aea16 model (blue donuts) and the Zea06 model with the SS14 nonlinear site term (red squares) performs well at low shaking intensities, but underestimates at higher shaking intensities. As both of the site terms used are developed from datasets consisting predominantly of recordings made on inorganic soils with higher V_{S30}, the soft peat soils at the Obihiro stations is near the limits of their applicability and not well constrained.

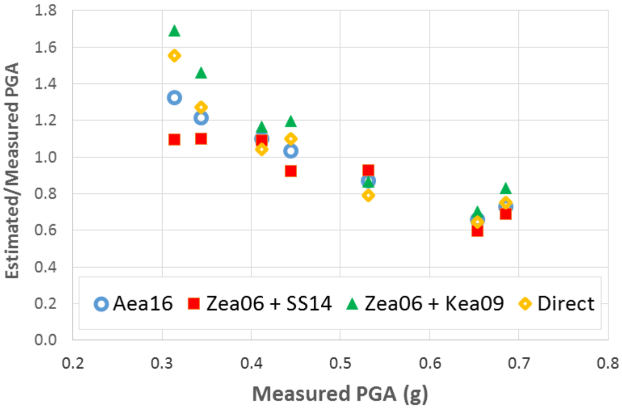

Figure 6. Ratio of estimated to measured PGA. Overestimation of small ground motion and underestimating of high ground motion tend to occur.

4 SUMMARY AND CONCLUSIONS

Levees are vulnerable to damage from seismic events as they are frequently located on soft and loose materials. Estimating the ground shaking intensity along the levees is a necessary step to determine the seismic demands for hazard characterization. The lack of instrumentation on the levees require interpolation from recording stations that have systematically different site conditions. This paper tested a methodology to account for differences in site response by including ground motion models and nonlinear site amplification models, and interpolating the residuals instead of the intensity measures.

The site amplification model has a strong influence on the estimated PGA. Most existing models are developed from datasets with minimal sites on peat, and cannot fully capture the behavior of the soft peat soils, as shown by deviation of the estimated from the observed PGA at the Obihiro stations on the levees. There is on-going work to develop site-specific amplification functions for the study region from additional ground motion recordings coupled with nonlinear ground response simulations. Simulations will be performed for the conditions and profiles along the levees to determine the amplification function and identify predictive parameters. We are also collecting additional recordings for the Obihiro stations from other earthquakes to derive the amplification function empirically from the residuals. The site amplification function suited to the soft peat soils present will improve the estimated ground motion intensity along the levees. The ground motion intensities will be combined with observed levee damage to develop fragility functions for the levee systems.

5 ACKNOWLEDGMENTS

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