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GROUND MOTION ESTIMATION FOR EVALUATION OF LEVEE PERFORMANCE IN PAST EARTHQUAKES

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Abstract: Levees provide vital functions for water delivery and flood protection. However, they present unique challenges for seismic design because their great length makes engineering evaluation of stability at closely spaced regular intervals impractical. Accordingly, relatively broad, empirically-driven risk assessment tools have the potential to serve as effective screening tools. We are undertaking a large data collection and synthesis effort to support the development of such tools, with the initial focus being on levee performance from the 2007 M_w6.6 Niigata Chuetsu-oki earthquake in Japan. Naturally, ground shaking is a key variable in this process, so the reliable estimation of ground shaking hazards from seismic networks is an essential element of the case history analysis. We postulate that direct application of Kriging techniques can produce biased ground motion estimates due to variable site conditions. Accordingly, we apply Kriging to residuals of ground motion prediction equations (GMPEs), which remove the average site effect. The resulting maps of residuals can be readily applied with the GMPE to produce ground motion maps that properly reflect spatial variations of geologic conditions. The proposed procedure produces ground motions near levees that are lower in some areas than those produced by direct Kriging.

1. INTRODUCTION

A levee is a natural or artificial embankment that provides flood protection adjacent to rivers or coastal areas. Because levees are generally constructed on soft soils, seismic hazards are generally driven by ground failure involving weak and potentially liquefiable soils in the foundations and in the levees themselves.

Historically, levees were often constructed in a haphazard manner without proper engineering, for example in the San Francisco Bay-Delta region and in Japan prior to the 1995 Kobe earthquake (CDWR 2009; Sugita and Tamura 2008). More recently, levee design standards have been established which consider seismic demands (CDWR 2009; Sugita and Tamura 2008), but the principal problem remains the substantial levee networks already in place that were not properly engineered (CDWR 2009).

Modern standards for engineering evaluation of levees involve subsurface exploration, development of cross sections, analysis of seismic demands within the levee and foundation using finite element analysis, and evaluation of liquefaction and landslide potential based on the outcome of those analyses (CDWR 2011; Sugita and Tamura 2008). There are two potential problems with this approach when applied to a broad levee network. First, such analyses are very labor intensive and costly. As such, screening tools to identify the most critical conditions requiring detailed analyses have the potential to be a useful component in the risk assessment toolbox. Second, researchers tend to focus on case histories that exhibited poor performance rather than good performance, thereby biasing empirical observations and making traditional methods inherently conservative. Hence, calibration against field observations of entire levee systems, including both good and poor performance, is important. For both of these reasons, we have undertaken a large, multi-agency project to compile and analyze case history data of levee performance and to leverage the lessons learned into improved risk assessment and relatively detailed analysis tools. Agencies contributing to this effort include the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan, the California Department of Water Resources (CDWR), the U.S. Army Corps of Engineers (USACE), the University of California (Berkeley (UCB) and Los Angeles (UCLA) campuses), and the University of Tokushima in Japan.

In this article, we describe procedures for the evaluation of ground motions across a levee network where observations of field performance and (non co-located) ground motions recordings are available. This is an essential component of the broader project, because seismic demands have significant spatial variations and are a major driver of levee damage. The process is illustrated using data from the 2007 Niigata-ken Chuetsu-oki earthquake in Japan. This event was selected because the level of ground shaking was strong (maximum recorded PGA ≈ 0.9g), the levee performance was well documented by staff of the MLIT and the Niigata Prefectural Office agencies (NPO) in Japan (who walked the full length of the levees in the effected regions), and significant geotechnical data has been compiled for the region as part of engineering studies to support repair work.

2. GROUND MOTION RECORDINGS

Ground motion recordings were gathered from three data providers: Japan Society of Civil Engineers (JSCE), National Research Institute for Earth Science and Disaster Prevention (NIED), and Japan Meteorological Agency (JMA). JSCE provides earthquake strong motion data at a web site (JSCE 2011) where recordings of the 2007 Niigata Chuetsu-oki Earthquake are available along with boring logs. East Japan Railway Company, East Nippon Expressway, and Kashiwazaki City Office maintain the networks that provide the ground motion data and boring logs for the JSCE web site. The 15 stations located within 100km source-site distance were selected. NIED maintains two seismic networks known as the Kyoshin Network (K-net) and the Kiban Kyoshin Network (KiK-net) (NIED 2011b; NIED 2011c). The 35 K-net stations and 32 KiK-net stations located within 100km source-site distance were selected. Each station has a three-component digital strong-motion accelerograph as well as geophysical logs of P and S-wave velocities from downhole measurements. Like JSCE, JMA maintains a web site from which data was obtained for this study (JMA 2011). The seismic stations for which data is distributed on the JMA site are operated both by JMA and local governments; 52 stations from this network were included.

The site parameter most often used in GMPEs is the time averaged shear wave velocity in the upper 30 m, V_{s30}. The V_{s30} parameter at recordings sites was developed according to the following protocol:

1. measured and extrapolated V_{s30} from direct downhole measurement,
2. inferred V_{s30} from the correlation of shear wave velocity and SPT blow counts, and
3. inferred V_{s30} from correlations with geomorphology and geology.

The stations on KiK-net have shear wave velocity profile more than 30m depth so that V_{s30} was calculated from the profiles directly. For K-net, shear wave velocity profile depths are generally either 10m or 20m, so time averaged velocities to the profile depth z_p were computed (denoted V_{sz}), and recommended correlations between V_{sz} and V_{s30} were used to estimate V_{s30} (Boore 2004; Boore et al. 2011). We used empirical relationships developed as part of this research between SPT blow counts and shear wave velocity for stations where boring logs are available (e.g., stations provided by JSCE). For most of the JMA stations, geological and geomorphological proxies were used to estimate V_{s30} since no geotechnical or geophysical data is available.

Table 1 Number of stations regarding source-to-site distance (R_{rup}), V_{s30}, and PGA.

R_{rup}	< 20km	20~50km	> 50km
	29	65	40
V_{s30}	< 180m/s	180~360m/s	> 360m/s
	10	64	60
PGA	< 0.1g	0.1~0.5g	> 0.5g
	46	80	8

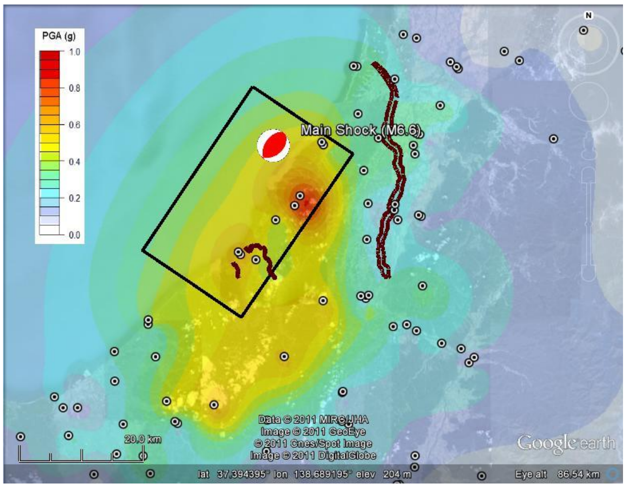

Figure 1 PGA contour map using direct Kriging method. The epicenter (beach-ball), fault plane (black rectangular), recording stations (white donut), and levees along rivers (brown lines) are plotted on the map.

Source-site distances (R_{rup} and R_{jb}) were calculated using fault plane information (Miyake et al. 2010) and site coordinates. Table 1 lists distance, V_{s30}, and PGA parameters for recording stations. The PGA parameter used here is averaged between the two horizontal components using the RotD50 parameter (Boore 2010). Figure 1 shows location of seismic stations and a regional PGA contour map developed through direct Kriging analysis (Oliver and Webster 1990) on the data. Our objective in this paper is to improve upon this map through more rational consideration of site conditions, as explained in the following section.

3. GROUND MOTION INTERPOLATION

3.1 Description of the Problem

To understand the problem addressed in this manuscript, consider the portion of the strongly shaken region from the 2007 earthquake shown in Figure 2. A site shown in the figure (triangle) has an estimated PGA of 0.838g based on the Kriging technique used to develop Figure 1. As shown in Figure 2, the PGA at the site is strongly influenced by the closest recording, which is on stiff soil, and has PGA = 0.867g. The site at this location has soft foundation soils with V_{s30} = 214 m/s, whereas the recording station with stiff soil has V_{s30} = 500 m/s. Based on empirical and semi-empirical site factors (e.g., Choi and Stewart 2005;

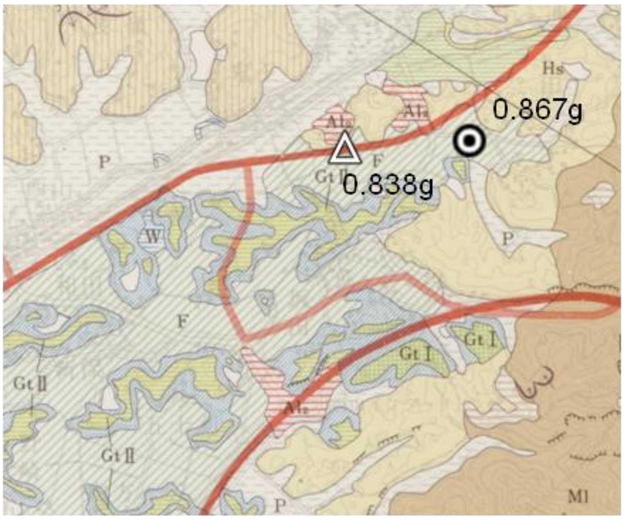

Figure 2 Geology map (NLSD 2011) in highly shaken region (PGA > 0.8g) along with a seismic station provided by JMA (Station code 65059) marked as white donut and a borehole provided by NIED-Borehole Data Checker (NIED 2011a) marked as white triangle. The V_{s30} for the seismic station is 500 m/s and 214 m/s for the borehole. Both sites are placed on alluvial fan (marked as F), but the seismic station is on stiff soil near hill (Hs) and mountain (Ml) and the borehole is on soft soil near valley plain (P) based on the geology.

Walling et al. 2008; Boore and Atkinson 2008), the ratio of soil/rock PGA for these velocities and the strength of the stiff soil motion ranges from around 0.55 to 0.60, suggesting that a better estimate of the motion on the relatively soft soil is about 0.6×0.87=0.52g. Hence, the stiff soil recording is providing a biased estimate of the ground motions on the soft soil conditions.

The condition illustrated in Figure 2 is not anomalous. The levees are preferentially located on soft materials along rivers, whereas ground motion stations tend to either be in urbanized regions (typically having soil conditions, but firmer ground than along rivers) or mountainous area (typically rock, stations are cited there deliberately to avoid large site effects). Hence, we postulate that direct Kriging will tend to produced systematically biased ground motion estimates that are too large in strongly shaken regions and too small in more weakly shaken regions (due to nonlinearity in site response).

3.2 Proposed Approach

The proposed methodology for estimating spatially distributed ground motion from recordings in a regional network is as follows:

1. For earthquake *i*, compute intra-event residuals between intensity measures from recording *j* and the median from a selected ground motion prediction equation (GMPE) computed for the magnitude, distance, and site conditions present at site *j* for event *i*. This residual is computed as follows:

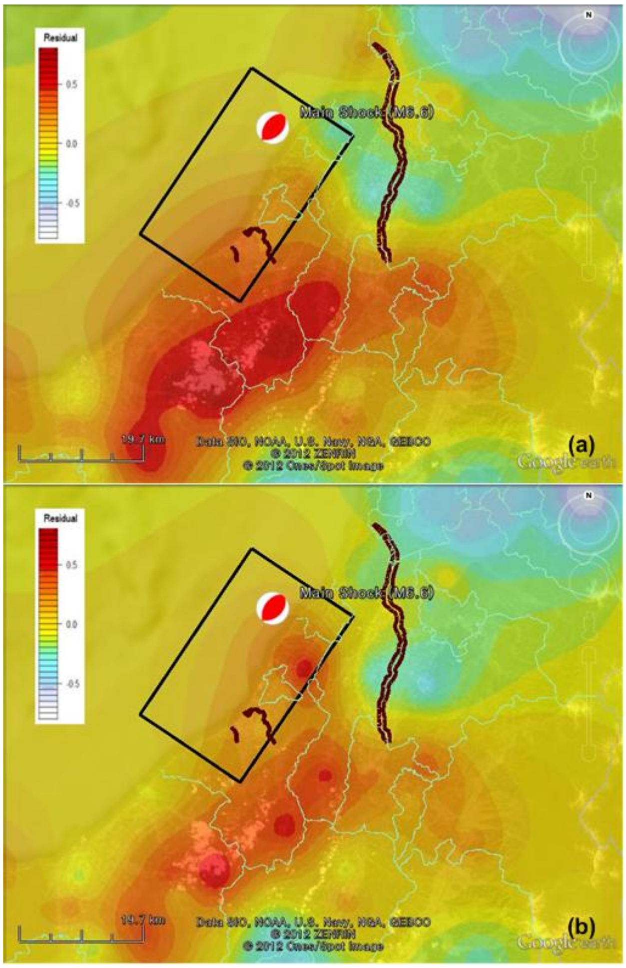

Figure 3 Contour map for intra-event residual of (a) Boore and Atkinson (2008), and (b) Zhao et al. (2006).

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

   where *IM* denotes the intensity measure from the recording, μ denotes the GMPE median, and η denotes the event term (effectively the mean residual of the GMPE for event *i* for well-recorded events, Abrahamson and Youngs 1992).

2. Map the spatial variation of residuals R_i using the simple Kriging method.
3. Estimate V_{s30} for the foundation conditions beneath levees or other sites of interest using measurements where available, and otherwise using correlation between SPT blow counts and shear wave velocity or other proxies (geology, geomorphology).
4. Calculate ground motion for sites of interest as sum of mapped residual from (2), GMPE median using the site condition from (3), and event term as follows:

$$\ln\left(IM_{i,k}^{K}\right) = R_{i,k}^{K} + \ln\left(\mu_{i,k}\right) + \eta_i \qquad (2)$$

   where $R^K_{i,k}$ represents the mapped residual from (2), and index *k* refers to sites for which ground motions are to be estimated.

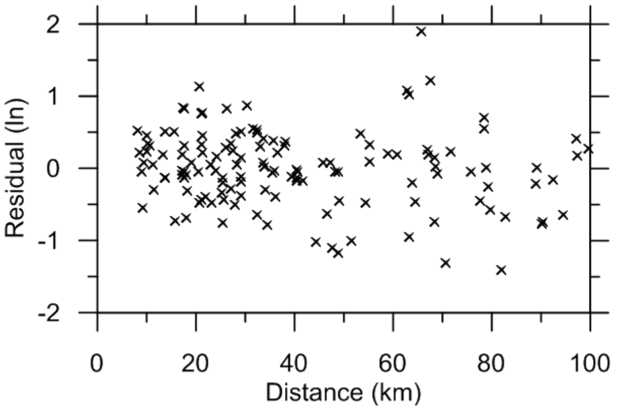

Figure 4 Intra-event residual (in natural log unit) versus source-to-site distance. Residuals are randomly scattered with respect to distance.

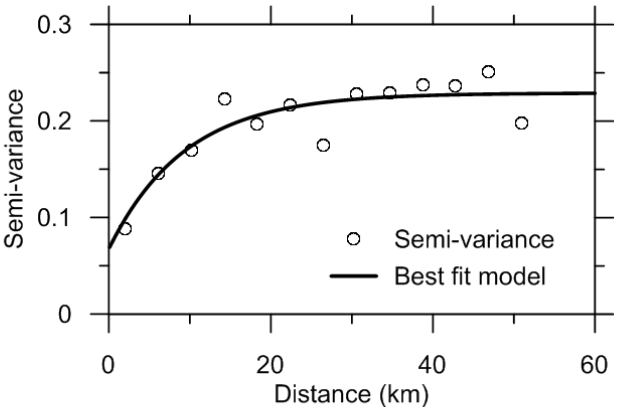

Figure 5 Semi-variance of residual and best fit model using exponential weighted least square method. The partial sill, nugget, and range are 0.161, 0.068, and 9.44, respectively.

3.3 Related Previous Work

Some prior studies have utilized approaches similar to that proposed here for the development of ground motion maps from accelerograph recordings. Yamazaki et al. (2000a) show spatially interpolated IM and macroseismic intensities (i.e. PGA, PGV and JMA seismic intensity) for the 1995 Kobe earthquake in Japan using the following procedure:

1. Convert surface ground motion to reference base ground motion by subtracting a linear site amplification factor defined from geology and geomorphology (from Yamazaki et al. 2000b) for every 1×1 km grid.
2. Distribute base motions spatially using *Kriging method with a distance trend component*, which means that the Kriging tracks both distance attenuation and intra-event residuals (the distance attenuation is selected *a priori* based on a GMPE).
3. Add site amplification factors to the distributed base motion to obtain spatially distributed ground motions at the surface.

Shabestari et al. (2004) evaluated ground motion for 2000 Tottori-ken Seibu earthquake and 2001 Geiyo earthquake in Japan using a similar procedure to Yamazaki et al. (2000a), and Sawada et al. (2008) did as well for the 2004 and 2007 Niigata earthquakes but used V_{s30} for the site parameter, which was calculated from either SPT blow counts or geology and geomorphology for every 250×250 m grid, with the distance attenuation taken from the GMPE by Si and Midorikawa (1999). The principal differences between these previous approaches and that proposed here are (1) the use of simple Kriging of residuals (this study) vs direct Kriging of ground motions with trend component (previous work), which should produce similar results for a common data set and distance attenuation model; and (2) the use of relatively robust (i.e., well constrained by data) nonlinear site amplification factors in the present work.

Jayaram and Baker (2009) examined the spatial correlation of residuals computed as in Eq. (1) using semi-variogram theory. They found a strong correlation of residuals at close separation distances [for PGA, < 40.7km for sites with similar geology (referred to as “clustered sites”) and < 8.5km for sites with relatively variability geology (non-clustered)], but rapid decay of correlation with distance. The rate of decay of the correlation is slowest for long period spectral ordinates, indicating stronger correlation of residuals.

3.4 Kriging and Semi-Variogram

Using the procedure described in Section 3.2, we compute residuals for the 134 recordings of the 2007 earthquake data relative to the Next Generation Attenuation (NGA) GMPE by Boore and Atkinson (2008) (BA). A second GMPE by Zhao et al. (2006) (ZEA) is also considered. For the intensity measure of PGA, the event terms are 0.06 for BA and 0.24 for ZEA in natural log units. This indicates under-prediction on average of the GMPE relative to the data. Figure 3 shows the residual contour maps for the study area using the (a) BA and (b) ZEA GMPEs.

Figure 3 shows that the region south of the rupture plane has high intra-event residuals (stronger shaking) relative to other sites with the same source-to-site distance and site condition. The region northeast of the fault plane has low residuals, which may be a rupture directivity effect. Note that the Shinano river passes through the low residual region, whereas levees along the Sabaishi and U rivers are in regions having positive residuals. We note parenthetically that damage reports indicate the most severe damage along the Sabaishi river (NPO 2007), where the ground motions were unusually large.

The contour maps in Figure 3 are based on simple Kriging method (i.e., no distance trend) because intra-event residuals were found to be randomly distributed with respect to source-site distances as shown in Figure 4, which indicates unbiased distance attenuation in the GMPE relative to the data. The Kriging method is a linear interpolation method between known data points to get values at unknown data points. The basic equation is

$$\hat{Y}\left(s_0\right)=\sum_{i=1}^{n} w_i Y\left(s_i\right) \tag{3}$$

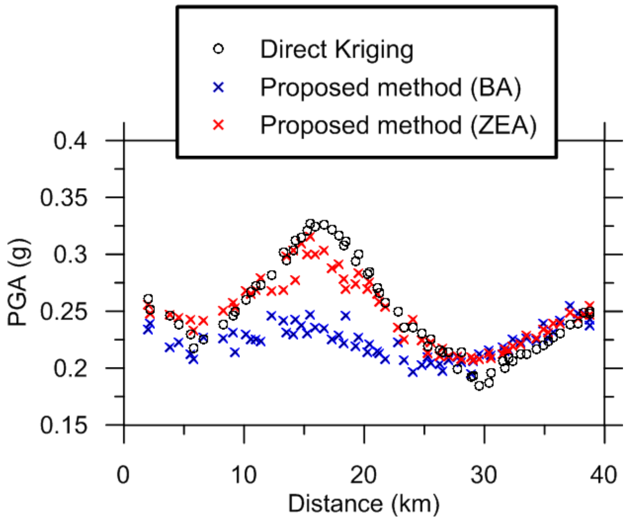

Figure 6 PGAs interpolated from seismic stations using direct Kriging and PGAs estimated by proposed method using residuals from BA and ZEA GMPEs along the Shinano river levees. The x-axis indicates distance upstream from river mouth.

where $\hat{Y}(s_0)$ is a target unknown point, $Y(s_i)$ is a known data point at i, and w_i is a weight, which depends on distance and a semi-variogram (a semi-variogram is a model that expresses semi-variance vs distance, where semi-variance is half of variance). Known data points closer to the target point have larger weights (lower variance), and vice versa. The sum of weights is unity.

Figure 5 plots semi-variance versus distance. Each data point in Figure 5 represents the semi-variance from data, the semi-variance being computed from the residuals of ground motions in common distance bins. A weighted least square regression method was used to fit a semi-variogram model to the data. The semi-variogram model tends to be poorly constrained at large separation distances, which can affect regression parameters controlling model performance at close distance as well. Accordingly, we set a distance beyond which ground motions are assumed to be uncorrelated. After performing sensitivity studies related to this maximum distance, we select 53km. We use an exponential form for the semi-variogram model using data within 53km as follows:

$$\gamma(h) = c_0 + c_1\left(1 - \exp\left(-\frac{h}{\alpha}\right)\right) \tag{4}$$

where h is the distance between points, and constants c_0, c_1, and α are found by regression as 0.161, 0.068, and 9.44, respectively. Parameter α is referred to as the range in km. The exponential model for semi-variance increases continuously with distance but the slope is small beyond the range. The range from Jayaram and Baker (2009) for PGA residuals as mentioned above is either 40.7km for clustered sites or 8.5km for non-clustered sites. The sites used for semi-variogram analysis in this study have variable geology, so our range of 9.44km should be compared to the non-clustered result of 8.5km from Jayaram and Baker (2009), which is similar.

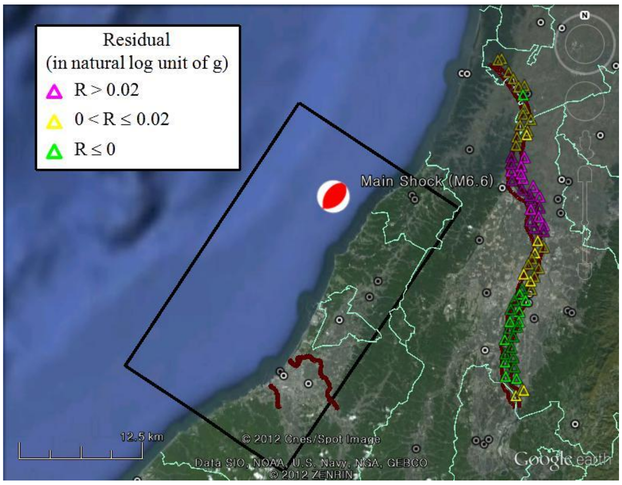

Figure 7 Aerial map showing residuals between PGA estimates from direct Kriging of the ground motions and estimates from residual analysis using BA GMPE. Triangles along river indicate locations of borings along levees (provided by Shinanogawa River Office, MLIT) which provide V_{s30}. Borings at the boundary between mountain and deltaic area have high positive residuals (purple triangle).

3.5 Effect of Proposed Procedure on Mapped Ground Motions and Sensitivity to GMPE

Figure 6 shows PGAs along the Shinano river levees produced by the proposed procedure using the BA and ZEA GMPEs as the basis for residuals calculations as well as PGAs by direct Kriging of ground motion data. We note that BA GMPE has a nonlinear site term but ZEA GMPE does not.

In Section 3.1, we explained how biased ground motions would be expected from direct Kriging of ground motion recordings for locations on relatively soft site conditions, such as levees. As shown in Figure 6, the PGAs from direct Kriging methods are higher than PGA estimates from residual analysis using BA GMPE, especially in the distance range of 10km to 25km. Figure 7 shows the difference along levees as an aerial map. The largest positive differentials (direct Kriging relative to proposed procedure using BA GMPE) occur on levees near rock sites. This bias is associated with a strong influence of a rock recording that is very close to the levee on the predicted levee motion, which is on soil. The applied procedure reduces the levee motion due to nonlinear site response. On the other hand, the direct Kriging method produces estimates that are only slightly higher thanthe ZEA GMPE because nonlinear site effects are not considered in ZEA. In other areas, where geologic conditions at seismic stations are relatively similar to those beneath levees, the PGA estimates from direct Kriging, GMPE with nonlinear site term (BA), and GMPE without nonlinear site term (ZEA) are similar.

4. CONCLUSIONS

We present a procedure for ground motion estimation from past earthquakes using array recordings. The procedure considers nonlinear site effects at the recording stations and at the mapped grid points to remove bias that would otherwise be present in the maps. The procedure uses simple Kriging techniques on intra-event residuals calculated using GMPEs with and without a nonlinear site term. The spatial variation of the residuals is evaluated and used to develop ground motion estimates for the map locations in combination with the GMPEs.

The resulting ground motions are shown to differ significantly from those computed from the direct Kriging method when a soft soil site is located near a ground motion recording station with a stiffer site condition. The difference is significant when a nonlinear site term is incorporated into the GMPE, and small when the GMPE does not incorporate a nonlinear site term.. In the particular case considered in this paper the levels of ground shaking were relatively strong, and ground motion predictions were reduced (relative to those from direct Kriging) as a result of applying the proposed procedure. If the procedure were applied in a region further from the fault with weaker shaking, we would expect the procedure to produce stronger ground motion estimates due to amplification of lower intensity ground motion. This ground motion estimation procedure is being used in a broader study directed towards the development of empirical risk assessment tools for levees as well as case histories for use in calibration of relatively detailed analysis procedures.

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