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A spatial correlation model of peak ground acceleration and response spectra based on data of the Istanbul Earthquake Rapid Response and Early Warning System

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ABSTRACT

Ground motion intensity measures such as the peak ground acceleration (PGA) and the pseudo-spectral acceleration (PSA) at two sites due to the same seismic event are correlated. The spatial correlation needs to be considered when modeling ground-motion fields for seismic loss assessments, since it can have a significant influence on the statistical moments and probability distribution of aggregated seismic loss of a building portfolio.

Empirical models of spatial correlation of ground motion intensity measures exist only for a few seismic regions in the world such as Japan, Taiwan and California, since for this purpose a dense observation network of earthquake ground motion is required. The Istanbul Earthquake Rapid Response and Early Warning System (IERREWS) provides one such dense array with station spacing of typically 2 km in the urban area of Istanbul. Based on the records of eight small to moderate (M_w3.5–M_w5.1) events, which occurred since 2003 in the Marmara region, we establish a model of intra-event spatial correlation for PGA and PSA up to the natural period of 1.0 s.

The results indicate that the correlation coefficients of PGA and short-period PSA decay rapidly with increasing interstation distance, resulting in correlation lengths of approximately 3–4 km, while correlation lengths at longer natural periods (above 0.5 s) exceed 6 km. Finally, we implement the correlation model in a Monte Carlo simulation to evaluate economic loss in Istanbul's district Zeytinburnu due to a M_w7.2 scenario earthquake.

1. Introduction

In probabilistic and deterministic earthquake loss assessments, prediction of ground motion intensities is critically important [1]. For a given earthquake scenario, intensity distributions can be modeled by Ground Motion Prediction Equations (GMPE) in the form of ground motion parameters such as the peak ground acceleration (PGA), the peak ground velocity (PGV) and the pseudo-spectral acceleration (PSA). The uncertainty in these predictions is often represented by the between-earthquake (inter-event) variability and the within-earthquake (intra-event) variability [2]. The latter indicates that the extent of ground shaking at different sites shows individual scattering around the event median. When comparing recorded earthquake motion with a prediction model, it is observed that the intra-event residuals are spatially correlated and that the correlation decreases with increasing separation distance between two sites. In the past, this issue has been empirically investigated by using strong motion records from Japan, California, Taiwan and Italy [2–6]. It has been reported that intra-event correlation results in greater variability in the estimates of aggregate earthquake loss due to a single earthquake scenario [1]. Other studies have shown that intra-event spatial correlation can have a significant influence on the probability distribution of aggregate seismic losses [7] and specifically that rare losses are underestimated when spatial correlation is ignored [8].

Istanbul is a mega-city which is exposed to high seismic hazard, located close to the Marmara Fault, a part of the North Anatolian Fault, where a large earthquake of $M_w \geq 7$ occurring in the next 30

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years is expected with a probability of more than 40% [9]. Particularly after the 1999 Izmit and Düzce Earthquakes, major efforts have been made by scientists and engineers to assess the earthquake hazard and vulnerability in Istanbul. A dense array of more than 100 strong motion recorders, making up the Istanbul Earthquake Rapid Response and Early Warning System (IERREWS) has been installed in the urban area for rapid response and early warning purposes.

This dense array with an average station-spacing of 2–3 km provides a suitable basis to develop a regional spatial correlation model, which is currently lacking. Since 2003, eight small-to-moderate events (M_w3.5–M_w5.1) with epicenters in the Marmara region have been recorded by stations of the IERREWS. Based on those records, we develop an intra-event spatial correlation model of PGA and PSA up to the natural period of 1.0 s for the urban area of Istanbul. To analyze the impact of the proposed correlation model on seismic risk assessments, we then implement this model in a Monte Carlo simulation to estimate seismic loss in Istanbul's district Zeytinburnu due to a scenario event occurring south of Istanbul in the Marmara Sea.

This work is structured as follows: First, we briefly summarize how spatial variability of ground motion parameters is characterized and how a spatial correlation model can be established by using recorded ground motion data. Subsequently, we present the IERREWS and the ground motion data which we use to establish the correlation model for the Istanbul area. A summary of the ground-motion data processing is given. The PGA and PSA from the processed acceleration time-histories are then used to evaluate the intra-event spatial correlation based on the ground motion model by Akkar and Bommer [10]. Finally, we implement the correlation model in a Monte Carlo simulation to estimate economic loss in Istanbul's district Zeytinburnu due to a M_w7.2 scenario earthquake.

2. Spatial variability and correlation of ground motion parameters

GMPEs relate the logarithm of a ground motion parameter, such as PGA and PSA, at a site to the earthquake magnitude M, the distance R between earthquake source and site, other source properties and site effects (often modeled by the average shear-wave velocity in the upper 30 m below the surface V_{S30}):

$$\ln(GMP) = f(M, R, \text{source, site}) + \eta + \varepsilon \quad (1)$$

where GMP is the ground motion parameter whose median is predicted by the function f. The uncertainty in the prediction is modeled by the inter-event variability η and the intra-event variability ε, which are assumed to be independent and normally distributed with zero mean and standard deviations σ_η and σ_ε, respectively.

The inter-event component indicates that the radiated energy released during the rupture process can vary even for the same modeled source parameters, resulting in systematically higher or lower intensities across all sites. The intra-event component represents the individual scattering at different sites due to different propagation paths and local site conditions, which remains after removing the inter-event residual. The total residual ε_T at a specific site is the sum of inter-event and intra-event residuals:

$$\varepsilon_T = \varepsilon + \eta \quad (2)$$

with the total standard deviation:

$$\sigma_T = \sqrt{\sigma_\eta^2 + \sigma_\varepsilon^2} \quad (3)$$

Since the inter-event residual η is constant for a single event, an inter-event correlation coefficient ρ_η can be defined as the ratio between inter-event variability and total variability [11]:

$$\rho_\eta = \frac{\sigma_\eta^2}{\sigma_\eta^2 + \sigma_\varepsilon^2} \quad (4)$$

The similarity of ground motions at close sites due to their proximity can be described by a distance-dependent intra-event correlation coefficient $\rho_\varepsilon(\Delta)$. At zero separation distance, the site-to-site correlation must equal 1 while with increasing separation distance, it is expected to decay from 1. The intra-event spatial correlation can be empirically investigated for a specific region if a dense observation of earthquake ground motion is available. The total correlation coefficient is then [11]:

$$\rho_T(\Delta) = \rho_\eta + \frac{\sigma_\varepsilon^2}{\sigma_\eta^2 + \sigma_\varepsilon^2}\rho_\varepsilon(\Delta) \quad (5)$$

Intra-event correlations of ground motion parameters are available for specific seismic regions such as Japan [3,5,12], Taiwan [3,11], California [4] and Europe [6,28].

3. Analysis procedure to evaluate intra-event correlation

To estimate the spatial correlation structure of a ground motion parameter in a specific area, the correlation of intra-event residuals, derived from earthquake recordings in the area, can be investigated. The following procedure can be adopted [13]:

1. Calculate the intra-event residuals ε for a given event using a suitable GMPE.
2. Construct pairs of intra-event residuals (ε_i, ε_j) and calculate their differences

$$\varepsilon_d = \varepsilon_i - \varepsilon_j \quad (6)$$

3. Assess the sample semivariogram:

$$\hat{\gamma}(\Delta) = \frac{1}{2}\sigma_d^2(\Delta) \quad (7)$$

where $\sigma_d^2(\Delta)$ is the variance of ε_d (Δ) that falls within a separation distance bin represented by Δ.

4. Evaluate the intra-event variability σ_ε^2 via regression residuals from step 1 or from the plateau of the semivariogram, assuming that for long separation distances, the following approximation is valid:

$$\frac{1}{2}\sigma_d^2(\Delta) \approx \sigma_\varepsilon^2 \quad (8)$$

5. Evaluate the distance-dependent correlation coefficient:

$$\rho_\varepsilon(\Delta) = 1 - \frac{\sigma_d^2(\Delta)}{2\sigma_\varepsilon^2} \quad (9)$$

The use of the sample semivariogram assumes stationarity and isotropy of the data [12].

4. Strong motion network, data and data processing

Istanbul is a mega-city which is exposed to high seismic hazard, located close to the Marmara Fault. The Marmara Fault is a part of the North Anatolian Fault, where a large earthquake of $M_w \geq 7$ occurring in the next 30 years is expected with a probability of more than 40% [9]. Particularly after the 1999 Izmit and Düzce Earthquakes, major efforts have been made to investigate the earthquake hazard and vulnerability in Istanbul. The IERREWS, a dense array of 100 strong motion recorders, has been established in the urban area for rapid response and early warning purposes. It provides information on ground shaking, damage and loss distributions within five minutes after an earthquake