On the magnitude –and distance dependency of the Ground-motion variability: comparison between Numerical simulations and real data analysis

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SUMMARY:
The ground-motion variability "sigma" is a fundamental component in Probabilistic Seismic Hazard Assessment, since it controls the hazard level at very low probabilities of exceedance. So far, most of the analyses based on Empirical Ground-Motion Prediction Equations have considered "sigma" to be constant. We then investigate the distance -and magnitude dependency of "sigma" by performing ground-motion numerical simulations from a suite of finite-source rupture models of past earthquakes (up to 3 Hz). Green's functions are calculated for a 1D velocity structure using a discrete wavenumber technique (Bouchon et al., 1981). The simulations reveal that the within-event component of the ground-motion increases with distance and decreases with magnitude. This tendency is consistent with the results of Rodriguez-Marek et al. (2011), based on accelerometric data analysis.

Keywords: Ground-motion variability, Source effects

1. INTRODUCTION

Empirical Ground-Motion Prediction Equations (GMPEs) are developed by means of regression techniques from recorded strong motion data, generally based on very simple parameterization with magnitude (M), distance (d) and site category (s). The distribution of ground motion for a given M,d and s is then represented in terms of a median and a standard deviation, referred to as the aleatory variability "sigma", which is a fundamental component in Probabilistic Seismic Hazard Assessment (PSHA). It strongly controls the seismic hazard level, especially for long return periods. It is therefore imperative to accurately constrain sigma to improve seismic hazard analyses.

Ideally, sigma should represent the aleatory ground-motion variability obtained from repeated events on the same fault and recorded at the same station, and then include only the natural variability of the source rupture process on a given fault (Anderson and Brune 1999). Nevertheless present practices in GMPEs assume that the variability in ground motion at a single site-source combination is the same as the variability in ground motion observed in a more global dataset, using records at multiple stations from different earthquakes in various tectonic contexts. This is known as the "ergodic assumption" (Anderson and Brune 1999). This means that the total sigma estimated from GMPEs mixes the source variability and site variability while the former could be treated as predictable (e.g. epistemic) and reduced by acquiring additional data.

Some recent studies have been undertaken to split sigma into various component (e.g. Al-Atik et al., 2010; Chen and Tsai, 2002). The variability can then be expressed as:

$$\sigma = \sqrt{\sigma_A^2 + \sigma_E^2} \tag{1.1}$$

where σ_A refers to the within-event variability (variability of site conditions and path effects for a given event recorded at various stations) and σ_E refers to the between-event variability (essentially due to the natural source randomness). The variability σ can further be refined by extracting the contribution of site-specific effects from the within-event variability. It is then referred to as "single station sigma" (i.e. without the ergodic assumption).

A very recent work done by Rodriguez-Marek et al (2011) brings light on the issue of the variation of single station sigma, by analyzing the Japanese KiK-net database. One of the most significant conclusions is that the single station sigma depends on magnitude and distance. The authors propose a new model for the single station sigma, including distance and magnitude dependency, to be used in PSHA studies.

The outcome of the study of Rodriguez-Marek et al. (2011), based on accelerometric data analysis, serves as a motivation to understand the physical phenomena affecting the ground motion variability, especially in the near field region, where the variability is poorly constrained due to the lack of available records. A possible approach is then to study the ground-motion variability from synthetic data (e.g. Ripperger et al. 2007). The contribution of different source features, such as the complexity of the final slip distribution on the fault plane, the directivity effects or the radiation pattern effects can then be carefully examined.

The present paper addresses the issue of ground motion variability in the near field and aims to capture some physical explanation on the origin of the ground motion variability. Our strategy is to evaluate single station sigma from synthetic data, as a function of distance and magnitude. Different kinematic models are considered to describe the slip history on the fault. The slip functions are next convolved with numerically computed Green's functions for a 1D velocity structure, using a discrete wavenumber technique (Bouchon et al., 1981). The single station sigma values are finally compared to the study of Rodriguez-Marek et al (2011).

2. METHODOLOGY FOR ANALYZING SIGMA

This study focuses on the within-event component of the ground motion variability. The strategy followed is to perform synthetic velocity time series (up to 3 Hz) for a simple station layout on a 1D velocity structure, using a kinematic description of the source. We assume strike slip events on a vertical fault plane. The variability of the Peak Ground Velocity (PGV) is then studied with respect to magnitude and distance.

2.1. Synthetic ground motion computation

2.1.1 Source models

We generated a suite of source models for M_w=6.7 and M_w=5. The techniques deployed and the resulting models are listed below.

We first use a model extracted from a database of finite-source rupture models (http://www.seismo.tehz.ch/static/srcmod). All models of this database have been compiled using kinematic inversion from accelerometric, GPS and/or InSAR data. Our first model is then a kinematic description of the Fukuoka, Japan, 2005 earthquake (M_w=6.7) derived by Asano et al. (2006). Note that in order to properly compute ground-motion up to 3 Hz, a fine grid is required to represent the slip history on the fault plane. Since the inverted slip history is defined on a coarse grid (2 km X 2 km), Asano et al. (2006) model has been refined by means of cubic interpolation. The grid size chosen is then about 200 m X 200 m ensuring at least five points per wavelength. This leads to the first source model for M_w=6.7 and it is called here: *s2005FUKUOKasan.*

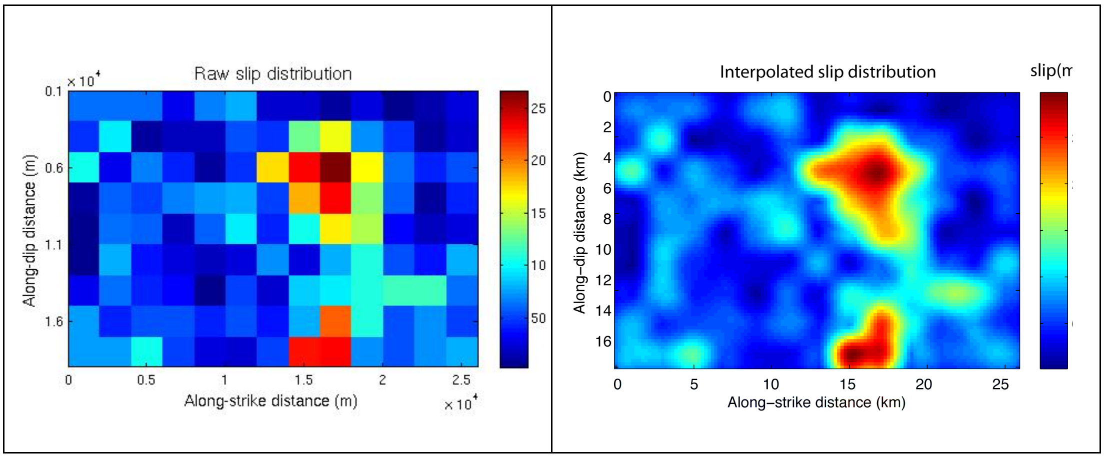

Figure 1. Representation of the static slip on the fault plane for the Fukuoka, Japan, 2005 earthquake after Asano et al. 2006 (left). This static slip image has been refined using cubic interpolation to compute ground motion up to 3 Hz. This leads to our first source model: *s2005FUKUOKasan* (right).

The second and third models (M_w=6.7) are synthetically produced using k^{-2} kinematic source model (Causse et al. 2009) and keeping the same fault plane configuration as Fukuoka. The specificity of our k-2 source model is that the position of the slip spectrum corner wave number, above which the spectral decay is in k^{-2}, can be controlled by a non dimensional parameter C. C can be seen as a measure of the roughness degree of slip. We then generate a smooth slip distribution (C=0.5) and a rough one (C=1) so as to see the effect of the slip roughness on the ground motion variation. The rupture is assumed to be nucleated in the middle of the fault which means the hypo-centre is at 10 km depth from the surface. The rupture velocity is considered as 2.8 km/s and rise time as 1s. Figure 2 shows the interpolated slip distributions of the models. These 2 models are called respectively *k2_C05_FUKUOKA* and *k2_C1_FUKUOKA* (Figure 2).

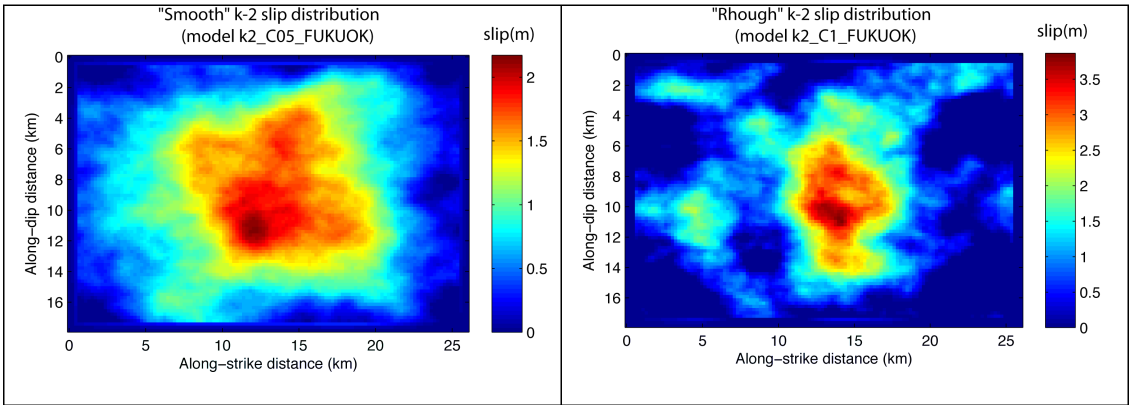

Figure 2. Representation of the static slip on the fault plane for the synthetic k^{-2} source models with various degrees of slip heterogeneity. This leads to our second and third source models: *k2_C05_FUKUOK* and *k2_C1_FUKUOK* (M_w=6.7).

Finally we generate source models for M_w=5. We use not only a k^{-2} source model but also simple source points, so as to compare the effects of extended and punctual sources on the ground-motion variability. Note that we also vary the focal depths to observe the effects of source depth. These models are called *k2_C05_Mw5-xkm* and *Mw5pointxkm* (*x* refers to the hypocenter depth).

We end up with a suite of 8 source models.

2.1.2 Station layout and Green's functions

Following the study of Ripperger et al. (2008), a networks of 50 hypothetical stations at various azimuths and distances have been built, based on the Joyner-Boore distance (r_{jb}) definition which is the closest distance to the surface projection of the fault. The receiver configuration was set up for the r_{jb} distances 1, 3, 10, 30 and 60 km. The receivers have been positioned along the lines parallel to the fault at the specified distances as well as beyond the ends of the fault extending radially outward with azimuths of 0°, 30° and 60° (Figure 3).

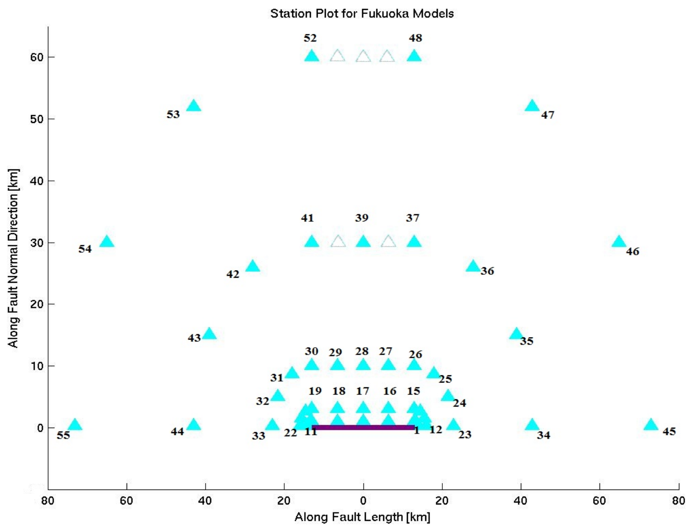

Figure 3. Station network used for the synthetic ground-motion computations. The purple line stands for the fault rupture surface.

The medium of propagation chosen is considered to be a 1D layered velocity structure, based on a simplified version of the Fukuoka 2005 velocity model (Table 2.1). Green's functions are computed using the discrete wavenumber simulation code AXITRA (Coutant, 1989)

Table 2.1. 1D velocity structure used for the synthetic ground motion simulations

Depth (m)	Vp (m/s)	Vs(m/s)	Density (kg/m^3)	Qp	Qs
0	5500	3200	2600	10000	10000
5	6000	3460	2700	10000	10000
18	6700	3870	2800	10000	10000

2.1.3 Ground-velocity computation

Synthetic ground-motions are computed by convolving the Green's functions with the slip history of all the sub-faults. The assumed source velocity function is a smooth ramp (Cotton and Campillo 1995). Synthetics are next low-pass filtered using a second order Butterworth filter with a cutoff frequency of 3 Hz. Finally 3-components velocities time series are obtained at each receiver location for the respective fault models (Figure 4).

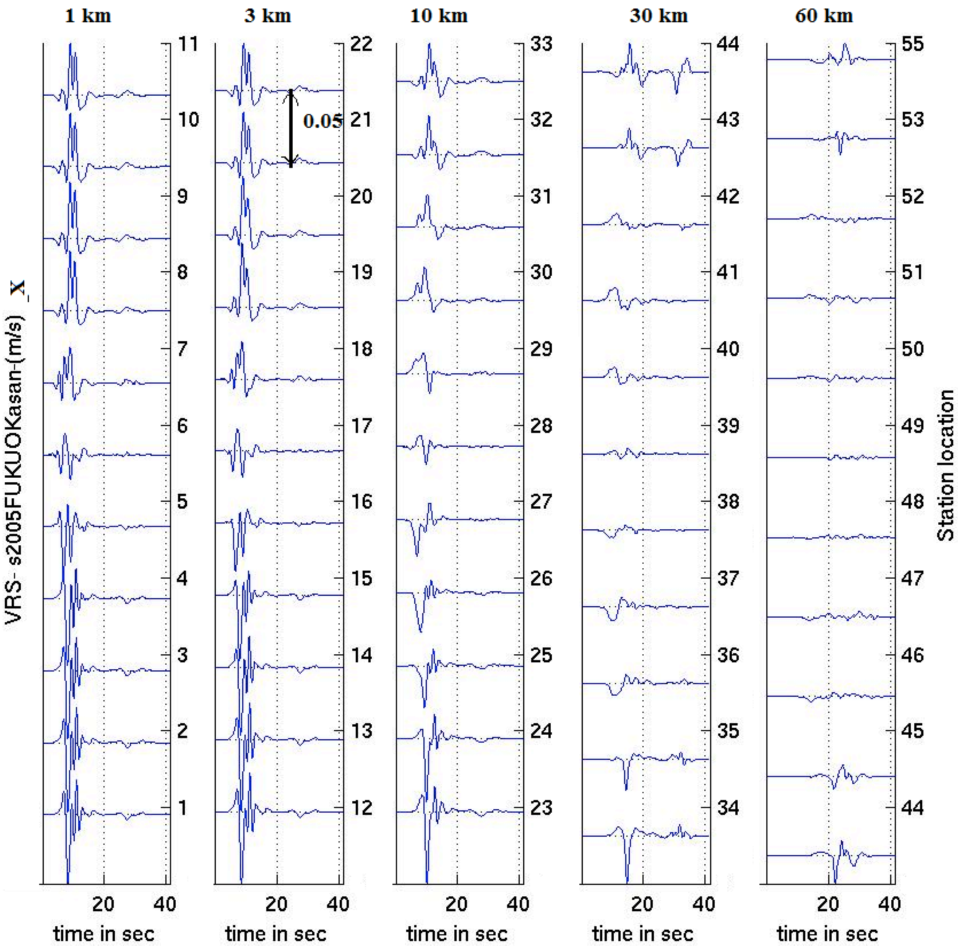

Figure 4. Synthetic velocity time series (fault-vertical component) for kinematic source model s2005FUKUOKasan

2.1.4 PGV calculation

We adopt the GMRotD50 as a measure for PGV (Boore et al. 2006), which is an orientation-independent geometric mean, using period-dependent rotation angles and is determined as the 50th percentile of the value which correspond to the median value of the PGV. The two orthogonal components of the synthetic time series have been rotated from 0° to 90° in 1° steps and the geometric mean for each pair of rotated time series are next stored. Finally the median value of all the 91 values of the geometric means is taken as the PGV value for the model at a particular station.

3. DATA ANALYSIS AND RESULTS

3.1. PVG attenuation with distance

Figure 5 shows mean (and standard deviation error bar) of ground motion in terms of natural log of PGV averaged over the different azimuths and along the r_{jb} distances from the faults. At close distance from the fault, the profile of PGV shows an initial gradual increase in amplitude and then rapidly decreases with increasing distance to the fault. Furthermore, the deeper the hypocentre the farther the maxima of PGV in the near field. This can be simply explained by the contribution of radiation pattern effect and ground motion attenuation with distance (the area located right at the top of the vertical fault corresponds to a node of the S-wave). Finally it can also be noted that PGV values are higher for the simulated Fukuoka events using k^{-2} source models. This is due to the use of a shorter rise time (1 s) compared to the inverted model (~3 s).

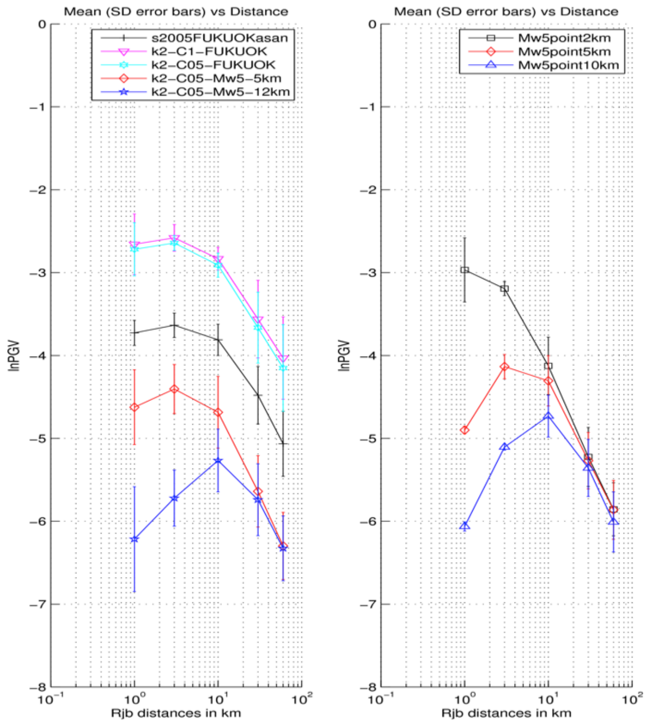

Figure 5. PGV attenuation with distance for the 8 compiled source models.

3.2. PGV variability

Figure 6 shows the standard deviation of the ground motion for the different source models. We remind that we assess here the between-event component of the PGV variability (a single source recorded at several stations).

The first striking observation is that the variability is highly dependent on magnitude and distance. More precisely it seems that: (1) The variability decreases with distance for smaller magnitudes; (2) The variability decreases with magnitude at short distances.

We provide below simple physical explanations.

3.2.1 Variability in the far-field

In far-field conditions (distance larger than the rupture length), the variability has only slight dependence on magnitude. A simple explanation will be that in the far field extended sources behave like point sources, and accordingly, the variability is dominated by the radiation pattern variability. We observe also only slight dependency with focal depth, simply because the sensitivity of the radiation pattern is lower in far-field.

3.2.2 Variability in the near field

The variability is significantly lower for Mw = 6.7, which seems to indicate that smaller event have higher intra event variability at short distances.

Note that point sources have significantly lower variability, indicating that the variability is dominated by the source complexity. The rough k^{-2} model (k2-C1-Fukuoka) results in larger variability than that of the other two models but the difference is small. This is probably because at this distance range of the station network is not dense enough to catch the small scale variability of the slip distribution on the fault plane.

3.2.3 Variability in the Intermediate Distance Range

For extended sources (Mw = 5 and Mw = 6.7) the variability is observed to be smaller between 3 and 10 km. Indeed, in this distance range the impact of the source complexity vanishes and the distance is too small for the variability to be dominated by the radiation pattern effects.

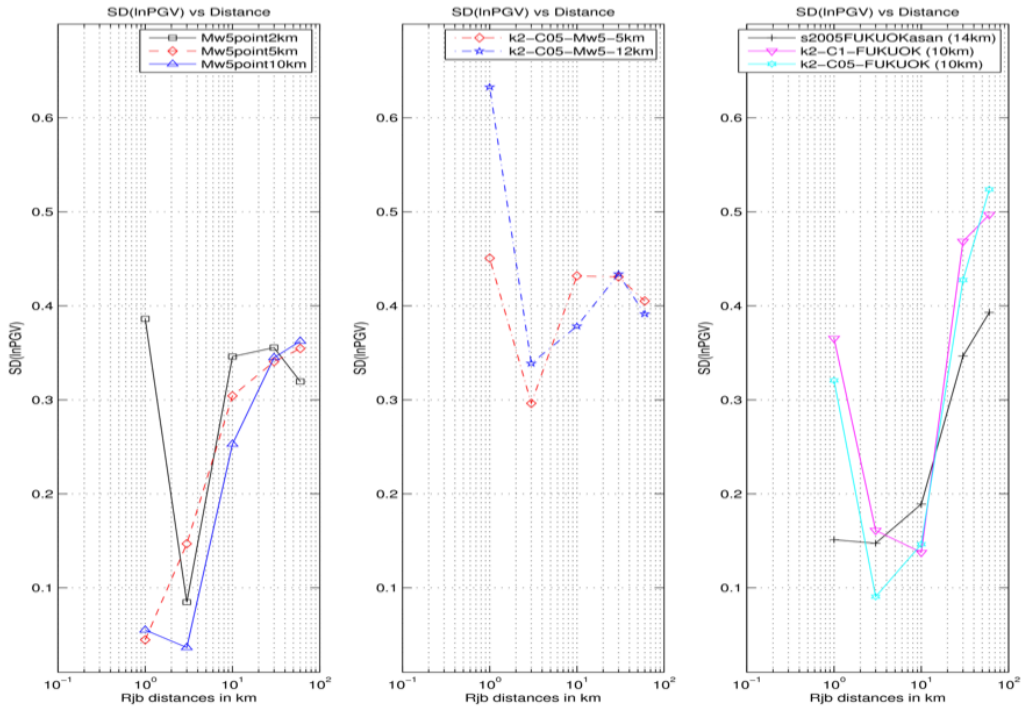

Figure 6. PGV variability vs. distance for the 8 source models generated in this study. Left and middle: Mw=5 and various focal depths. Right: Mw=6.7.

3.3. Comparison with the study of Rodriguez-Marek et al. (2011)

A recent study conducted by Rodriguez-Marek et al. (2011) provides values single station site corrected within-event variability from different acceleration database. Their major observations are that the ground-motion variability decreases with the increase in magnitude and distance, in a large range of frequencies. Eventually, the author came up with a simple model of within-event ground motion variability correlated with magnitude and distance (Figure 7).

An interesting result is that the main tendencies observed by Rodriguez-Marek et al. (2001), from the analysis of real data, can be reproduced with the simple kinematic simulations performed in this study.

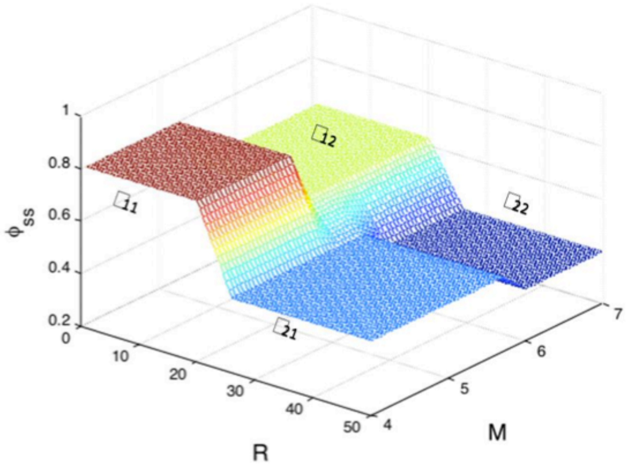

Figure 7. New model proposed for the within-event variability (F. Cotton, personal communication)

4. DISCUSSION AND CONCLUSION

The ground-motion variability sigma is a fundamental component of PSHA studies. However, so far, sigma has been considered to be constant. In this paper, we analyse the magnitude –and distance dependency of sigma, through numerical ground-motion simulations. Our results suggest that the PGV variability (1) decreases with distance for small magnitudes and (2) decreases with magnitude at short distances from the source. This tendency is also observed in a recent independent study from real data analysis.

Nevertheless our study needs to be expanded to confirm these tendencies. First we propose to conduct sensitivity studies to check the influence of the station layout on the variability values. Second our study will be expanded to a larger set of "realistic" kinematic models, all extracted from the database of finite-source rupture models. This will allow the analysis of both the within-event and the between event components of the variability.

REFERENCES

Al Atik L, Abrahamson N, Bommer JJ, et al, The Variability of Ground-Motion Prediction Models and Its Components, SEISMOL RES LETT, 2010, Vol:81, Pages:794-801, ISSN:0895-0695

Anderson, J. G., and J. N. Brune (1999). Probabilistic seismic hazard assessment without the ergodic assumption. Seismological Research Letters 70 (1), 19–28.

Asano, K., T. Iwata, and K. Irikura (2005), Estimation of source rupture process and strong ground motion simulation of the 2002 Denali, Alaska, earthquake, Bull. Seismol. Soc. Am., 95, 1701–1715, doi:10.1785/0120040154.

Causse, M., E. Chaljub, F. Cotton, C. Cornou and P.Y. Bard (2009). New approach for coupling k^{-2} and empirical Green's functions: Application to the blind prediction of broadband ground-motion in the Grenoble basin, *Geophys. J. Int.* **179***,* 1627-1644.

Boore, D. M., Lamprey, J.W. and Abrahamson, N. A., (2006). Orientation-Independent Measures of Ground Motion. Bulletin of the Seismological Society of America, Vol. 96, No. 4A, pp. 1502–1511, August 2006, doi: 10.1785/0120050209.

Bouchon, M., (1981). A simple method to calculate Green's functions for elastic layered media, Bulletin of Seismological Society of America 71 (4) (1981), pp. 959–971.

Chen, Y.-H., and C.-C. P. Tsai (2002). A new method for estimation of the attenuation relationship with variance components. Bulletin of the Seismological Society of America 92 (5), 1,984–1,991.

Cotton, F. And Campillo, M. Inversion of strong ground motion in the frequency domain: application to the 1992 Landers, California, earthquake. J. Geophys. Res., 100:3961-3975, 1995.

Cotton, F. (2011). Personal Communication. Oral presentation on "Toward new single station sigma models" in SSA meeting.

Coutant, O. (1989). Program of Numerical Simulation AXITRA. Research Reports LGIT. Université Joseph Fourier, Grenoble (in French).

Rodriguez-Marek, A., Montalva, G.A., Cotton, F. and F. Bonilla (2011). Analysis of Single-Station Standard Deviation Using the KiK-net data. Bulletin of the Seismological Society of America, doi: 10.1785/012010025.

Ripperger, J., Mai, P. M., Ampuero, J. -P. Variability of Near-Field Ground Motion from Dynamic Earthquake Rupture Simulations. Bulletin of the seismological society of America. Vol 98. No. 3, pp. 1207-1228, June 2008, doi: 10.1785/0120070076