Empirical Evaluation of the Variance Associated with Multiple Ruptures of a Single Fault

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Summary

We estimate the variance in ground motions related to repeated large earthquakes occurring on the same fault segment with similar magnitudes. We find eight earthquake pairs for which suitable strong motion records exist. Two are crustal strike-slip earthquakes from California and six are subduction zone earthquakes from Japan. We consider only large earthquakes and deal with frequencies greater than the earthquake corner frequency, so the variability that is considered here is related to smaller scale differences in the rupture process, particularly on the part of the fault nearest the station. We find that the variance of the 5% damped spectral accelerations of these pairs, termed τ_F^2, averages to about 45% and 80% for the crustal and subduction zone earthquakes, respectively, of τ^2, where τ^2 is the contribution of source variability to the total variability of ground motion estimated by some recent ground motion prediction equations (GMPEs). We suggest that τ_F^2, is lower than τ^2, for the frequencies where τ_F^2, is estimated, because it depends primarily on only local physical properties of a fault that are the same in repeated earthquakes. We therefore suggest that at sites where the hazard is controlled by a single re-rupturing source, one could potentially use a between-event variance that is smaller than τ^2, in seismic hazard calculations. Thus these results may help to resolve the inconsistencies that are now present between the national hazard maps, and some precariously balanced rocks in southern California. The results are described in more detail by Yagoda-Biran et al., 2015.

Technical Report

INTRODUCTION

Recent studies of strong earthquake ground motions have sought to understand the uncertainties in ground motion predictions, e.g. Restrepo-Velez and Bommer (2003), Strasser et al. (2008). Several studies have endeavored to break variability down into component parts. Joyner and Boore (1981) and Abrahamson and Youngs (1992) separated variability associated with earthquake source terms (between-event or inter-event variability, with standard deviation τ) from variability of the ground motions within a single event (within-event or intra-event variability, with standard deviation ϕ). The total standard deviation, σ, is related to these two basic components as $\sigma^2 = \tau^2 + \phi^2$. With better data, it has become possible to also quantify the effects of site condition (e.g. Campbell and Bozorgnia, 2014, Chiou and Youngs, 2014) and estimate the variability of ground motions at a single station (e.g. Atkinson, 2006, Rodriguez-Marek *et al.*, 2011).

Anderson and Brune (1999) discussed "characteristic ground motion earthquakes", associated with a fault that ruptures identically in repeated events. They proposed that the variability from the re-rupture of a single fault could be much smaller than the variability obtained in a typical GMPE model that includes contributions from multiple sites, paths, and sources. An observational test of this idea is to measure the variability in ground motion recordings from repeated rupture of the same fault in "characteristic earthquakes", that rerupture the same fault "segment". Let τ_F be the variability in ground motions from repeated rupture of the same fault segment. An empirical estimate of τ_F would be useful for engineering seismology in development of improved seismic hazard models. In more theoretical studies, it could help calibrate the variability of source models for synthetic ground motion time series (e.g. Ripperger *et al.*, 2008, Ameri *et al.*, 2011, Anderson, 2015).

This report estimates τ_F for earthquakes from repeated rupture of the same fault in similar-sized earthquakes (with $M_w > 6$), for which strong motion records are available from common stations. We found two strike-slip pairs from the US and five subduction thrust pairs from Japan, which in our judgment ruptured in earthquakes that are similar enough, and strong motion stations are close enough together, that the differences in ground motion are relevant to estimating τ_F. We also included a pair of M~ 5 earthquakes from Japan that were recorded on the same instrument, and have bandwidth above the corner frequency. These data comprise all of the event pairs of which we are aware that are large enough to be of engineering interest.

DATA SELECTION

The set of records that are suitable for this study are rather straightforward to identify, since the history of large earthquakes and of important strong motion records is well known. A limitation within the data is that in no case is the earthquake pair identical. Differences in seismic moment alone make comparisons at low frequencies, i.e. below the earthquake corner frequency, irrelevant to the "characteristic ground motion earthquake" model of Anderson and Brune (1999). Thus, this study is compelled to focus on the spectrum above the corner frequency of these earthquakes. In our search for earthquake pairs that were recorded by the same stations, if the rupture areas did not fully overlap for the two events, we exclude stations that would be closer to a part of a fault that ruptured in only one of the events.

Two strike-slip crustal earthquake pairs from the US and six dip-slip subduction zone earthquake pairs from Japan were selected for analysis:

1. *The 1940 and 1979 Imperial Valley earthquakes*. Figure 1 shows a map and surface slip distribution for the 1940 and 1979 earthquakes, and the location of the El Centro station.
2. *The 1966 and 2004 Parkfield earthquakes (Figure 2)*. The 1966 event, M_w 6.19, ruptured a 37 km long segment (Aki, 1968). The 2004 event, M_w 6.0, ruptured the same segment, but in the opposite rupture direction (Bakun *et al.*, 2005, Borcherdt *et al.*, 2006).
3. *The 1952 and 2003 Tokachi-oki (offshore Tokachi) earthquakes.* Both earthquakes occurred along the Kuril-Japan trench, where the Pacific plate is subducting under northeastern Japan.
4. *The 1968 Tokachi-oki (offshore Tokachi) (Mw 8.2) and 1994 Sanriku-oki (offshore Sanriku) (Mw 7.7) earthquakes*. Both events occurred on the subduction boundary between the Pacific and the Eurasia (or the North American) plates.
5. *The 1978 and 2005 Miyagi-oki (offshore Miyagi) earthquakes*. The 1978 event (M_w 7.6) and the 2005 event (M_w 7.2) both ruptured the subduction boundary between the Pacific and the Eurasia (or the North American) plates near the bottom of the inter-plate seismogenic zone (Kanamori *et al.*, 2006).
6. *The 1982 and 2008 (both M_J7.0) Ibaraki-oki (offshore Ibaraki) earthquakes*. Both events occurred on the subduction boundary between the Pacific and the Eurasia (or the North American) plates.
7. *The 1989 M_w 7.0 (Yamanaka and Kikuchi, 2004) and 2011 M_w 7.4 (Suzuki et al., 2012) Iwate-oki (offshore Iwate) earthquakes*. Both events occurred on the subduction boundary between the Pacific and the Eurasia (or the North American) plates.
8. *The 2001 MJ 4.8 and 2008 MJ 4.7(Shimamura et al., 2011)Kamaishi-oki earthquakes.* These two earthquakes are the latest in a sequence of earthquakes that all occur at the same location on the plate boundary off Kamaishi. Shimamura *et al.* (2011) found that the ruptures for both events share the same patterns of propagation, and their source areas largely overlap.

METHOD - VARIABILITY CALCULATIONS

For every pair of earthquakes recorded at one station, the following procedure was followed:

1. The acceleration Fourier amplitude spectra for each pair at each station were examined, to find a range of frequencies that we believe can be compared for the two events. The selected frequency range depends on three factors: estimates of the corner frequencies for each earthquake, and sample rate and noise levels on the accelerograms. Corner frequencies, f_C, were estimated from the maximum rupture dimension of each earthquake. At high frequencies, the main concerns are the effects of instrument response and processing, including filtering, on the spectra.
2. Next, the RotD100 and RotD50 (Boore, 2010) SD were found for a series of periods ranging between 0.01 and 10 s, at 5% damping. The pseudo spectral accelerations (PSA) were calculated by multiplying SD by the square of the angular frequencies (ω^2).
3. The two-point maximum likelihood estimate of the variance, σ^2_{ML}, was calculated for the natural logarithm of the matching components (RotD100, RotD50, east, north, and up) from each pair of earthquakes at a single station, using:

$$\sigma^2{}_{ML} = 1/2\left[\left(\ln(PSA_1) - \ln(PSA_{mean})\right)^2 + \left(\ln(PSA_2) - \ln(PSA_{mean})\right)^2\right] \quad (1)$$

where the subscripts 1 and 2 refer to the two different events recorded at the same station, and PSA_{mean} is the mean value of the two records: $\ln(PSA_{mean})=(\ln(PSA_1)+\ln(PSA_2))/2$. There is no adjustment for the size of the earthquake, as the assumption is that the nearest part of the fault ruptured in its "characteristic" way.

RESULTS – VARIANCE PLOTS

Plots of σ^2_{ML}, for the RotD50 components of 5% damped response spectral values for each pair of earthquakes, as a function of the oscillator period, at the different stations are presented in Yagoda-Biran and Anderson (2015). The results are summarized in Figure 3.

DISCUSSION

In our analysis we estimate σ^2_{ML}, using two observations at each site. The variance of a sample, s^2 and the true variance σ^2, are related through $s^2 = \frac{N-1}{N}\sigma^2$ where N is the sample size. When N=2, the best estimate for the true variance is twice the sample variance. Thus the best estimate of the single fault variance is $\tau_F^2 = 2\sigma_{ML}^2$.

The σ^2_{ML} values obtained from our exercise were compared to between-event variance (τ^2) values modeled by four of the NGA-WEST2 GMPE models (e.g. Abrahamson *et al.*, 2014, Boore *et al.*, 2014, Campbell and Bozorgnia, 2014, Chiou and Youngs, 2014). Figure 3 shows the range of $\tau^2/2$ from the four GMPEs as the shaded gray area. The median value of σ^2_{ML}, for each station is displayed as a horizontal line. Between-event variance, τ^2, is period dependent while the average has smoothed over that dependency. Also, our estimate of σ^2_{ML} is only valid above the corner frequency. Averaged across different periods, the two crustal strike-slip earthquakes and five of the subduction zone earthquakes give σ^2_{ML} values that, for the trusted range of periods, are contained within the lower part of the GMPEs range or are even lower.

There are fewer factors contributing to the variance in σ^2_{ML} than τ^2. Differences that contribute to τ^2 but not to σ^2_{ML} include differences in fault properties (e.g. lithology, wear, recurrence interval, style of rupture), distance (since the distance adjustment may be imperfect), and the main contribution of magnitude related to fault dimension and average stress drop (since the magnitude adjustment in GMPEs may be imperfect). Therefore it is not surprising that σ^2_{ML} would be lower than $\tau^2/2$.

For the two US crustal earthquakes the averaged ratio of σ^2_{ML} (0.022) is 46% of the average of the corresponding GMPE estimates of $\tau^2/2$ (0.048). For 5 of the Japanese earthquakes, leaving out the M4.8 Kamaishi-oki pair, the averaged ratio of σ^2_{ML} (0.044) is 78% of the corresponding average of $\tau^2/2$ (0.057). Our corresponding average estimates of τ_F for the strike-slip and subduction earthquakes are 0.20 and 0.3, respectively.

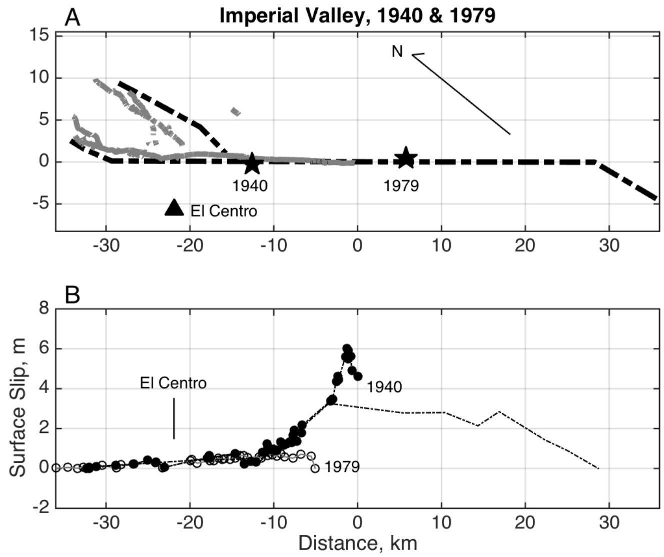

Figure 1. Fault map and slip distribution for the 1940 and 1979 Imperial Valley earthquakes. A) Fault map. Black dashed: generalized 1940 surface rupture, after (Rockwell and Klinger, 2013). Gray: 1979 surface rupture (U.S.G.S and C.G.S., Quaternary Fault and Fold Database 2006). Triangle: El Centro strong motion station. B) Surface displacement. Solid points: 1940; open points: 1979 earthquakes, from (Sharp, 1982). Some 1940 measurements by Rockwell and Klinger (2013) near the international border (Distance=0) exceed the shown values. Thin dashed: smoothed 1940 displacement south of the border (Wesnousky, 2008).

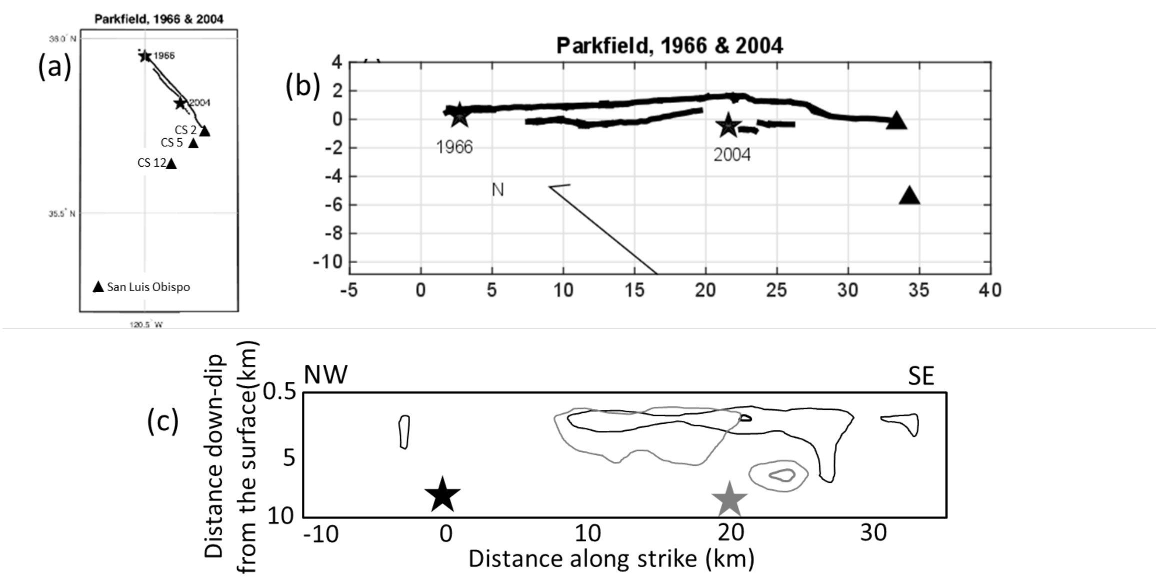

Figure 2 a) epicenter and station locations for the 1966 and 2004 Parkfield events. b) zoom-in map of the epicenter locations, fault trace, and two nearest stations. c) contours of slip, based on inversion of strong motion data (Custodio and Archuleta, 2007). 1966: Black star and contours are, 2004: gray star and contours. After Custodio and Archuleta (2007).

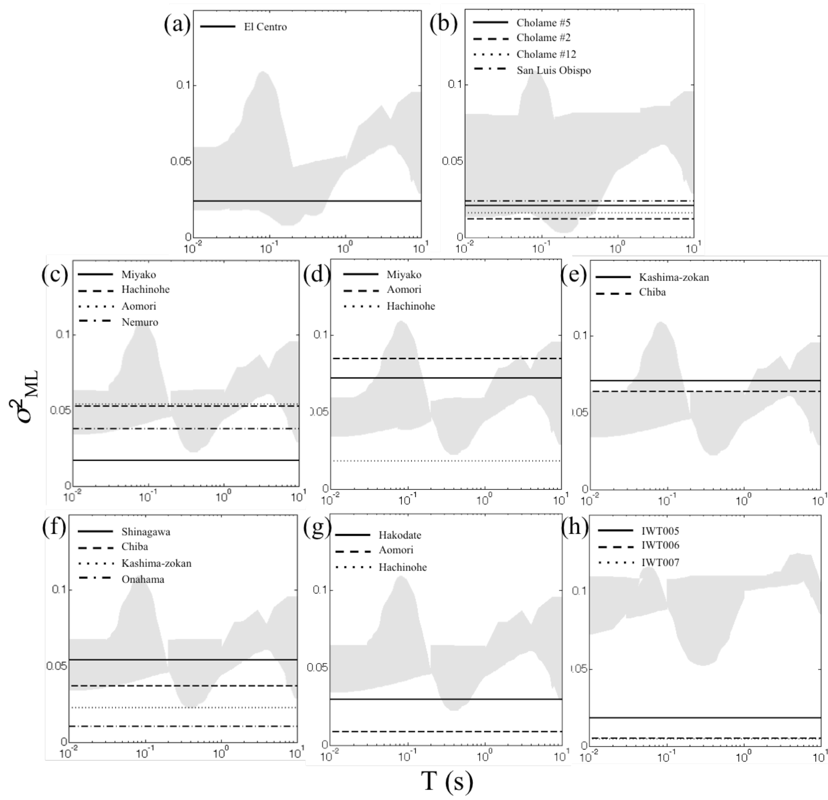

Figure 3. Between-event variance (τ^2) for SA, as calculated by four NGA-WEST2 models, compared with the mean of the maximum likelihood estimate of variance for the trusted range of periods. The GMPEs variance is divided by 2, the factor between the mean of the two-point maximum likelihood estimate of the variance and the true variance. (a) Imperial Valley; (b) Parkfield; (c) Tokachi-oki; (d) Tokachi-oki and Sanriku-haruka-oki; (e) Miyagi-oki; (f) Ibaraki-oki; (g) Iwate-oki; and (h) Kamaishi-oki. The variance from NGA-WEST2 models is used because GMPEs derived from Japanese data do not separate the total variance into its component parts.

REFERENCES

Abrahamson, N., W. Silva, and R. Kamai (2014). Summary of the ASK14 ground-motion relation for active crustal regions, Earthquake Spectra 30 1025-1055.

Abrahamson, N. A., and R. R. Youngs (1992). A stable algorithm for regression analyses using the random effects model, Bull. Seismol. Soc. Am. 82 505–510.

Aki, K. (1968). Seismic displacement near a fault, J. Geophys. Res. 73 5359.

Al Atik, L., N. Abrahamson, J. J. Bommer, F. Scherbaum, F. Cotton, and N. Kuehn (2010). The variability of ground-motion prediction models and its components, Seismol. Res. Lett. 81 794-801.

Ameri, G., A. Emolo, F. Pacor, and F. Gallovic (2011). Ground-motion simulations for the 1980 M 6.9 Irpina earthquake (Southern Italy) and scenario events, Bull. Seismol. Soc. Am. 101 1136-1151.

Anderson, J. G. (2015). The Composite Source Model for broadband simulations of strong ground motions, Seismol. Res. Lett. 86 68-74.

Anderson, J. G., and J. N. Brune (1999). Probabilistic seismic hazard analysis without the ergodic assumption, Seismol. Res. Lett. 70 19-28.

Atkinson, G. M. (2006). Single-station sigma, Bull. Seismol. Soc. Am. 96 446-455.

Bakun, W. H., B. Aagaard, B. Dost, W. L. Ellsworth, J. L. Hardebeck, R. A. Harris, C. Ji, M. J. S. Johnston, J. Langbein, J. J. Lienkaemper, A. J. Michael, J. R. Murray, R. M. Nadeau, P. A. Reasenberg, M. S. Reichle, E. A. Roeloffs, A. Shakal, R. W. Simpson, and F. Waldhauser (2005). Implications for prediction and hazard assesment from the 2004 Parkfield earthquake, Nature 437 969-974.

Boore, D. M. (2010). Orientation-independent, nongeometric-mean measures of seismic intensity from two horizontal components of motion, Bull. Seismol. Soc. Am. 100 1830–1835.

Boore, D. M., J. P. Stewart, E. Seyhan, and G. M. Atkinson (2014). NGA-WEST 2 equations for predicting PGA, PGV, and 5%-damped PSA for shallow crustal earthquakes, Earthquake Spectra 30 1057-1085.

Borcherdt, R. D., M. J. S. Johnston, G. Glassmoyer, and C. Dietel (2006). Recordings of the 2004 Parkfield earthquake on the General Earthquake Observation System array: Implications for earthquake precursors, fault rupture, and coseismic strain changes, Bull. Seismol. Soc. Am. 96 S73-S89.

Campbell, K. W., and Y. Bozorgnia (2014). NGA-WEST 2 ground motion model for the average horizontal components of PGA, PGV and 5% damped linear acceleration response spectra, Earthquake Spectra 30 1087-1115.

Chiou, B., and R. Youngs (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra, Earthquake Spectra 30 1117-1153.

Custodio, S., and R. J. Archuleta (2007). Parkfield earthquakes: Characteristic or complementary?, Journal of Geophysical Research-Solid Earth 112.

Joyner, W. B., and D. M. Boore (1981). Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial-Valley, California, earthquake, Bull. Seismol. Soc. Am. 71 2011-2038.

Kanamori, H., M. Miyazawa, and J. Mori (2006). Investigation of the earthquake sequence off Miyagi prefecture with historical seismograms, Earth Planets Space 58 1533–1541.
Restrepo-Velez, L. F., and J. J. Bommer (2003). An exploration of the nature of the scatter in ground-motion prediction equations and the implications for seismic hazard assessment, J. Earthqu. Eng. 7 171-199.
Ripperger, J., P. M. Mai, and J.-P. Ampuero (2008). Variability of near-field ground motion from dynamic earthquake rupture simulations, Bull. Seismol. Soc. Am. 98 1207-1228.
Robinson, D. P., and L. T. Cheung (2010). Source process of the Mw 8.3, 2003 Tokachi-Oki, Japan earthquake and its aftershocks, Geophys. J. Int. 181 334–342.
Rockwell, T. K., and Y. Klinger (2013). Surface Rupture and Slip Distribution of the 1940 Imperial Valley Earthquake, Imperial Fault, Southern California: Implications for Rupture Segmentation and Dynamics, Bull. Seismol. Soc. Am. 103 629–640.
Rodriguez-Marek, A., G. A. Montalva, F. Cotton, and F. Bonilla (2011). Analysis of Single-Station Standard Deviation Using the KiK-net Data, Bull. Seismol. Soc. Am. 101 1242-1258.
Sharp, R. V. (1982). Comparison of 1979 surface faulting with earlier displacements in the Imperial Valley, in the Imperial Valley, California, earthquake of 15 October 1979, U.S. Geol. Surv. Prof. Pap. 1254 213-221.
Sharp, R. V., J. J. Lienkaemper, M. G. Bonilla, D. B. Burke, B. F. Fox, D. G. Herd, D. M. Miller, D. M. Morton, D. J. Ponti, M. J. Rymer, J. C. Tinsley, J. C. Yount, J. E. Kahle, E. W. Hart, and K. E. Sieh (1982). Surface faulting in the Central Imperial Valley., USGS Professional paper 1254, 119-143.
Shimamura, K., T. Matsuzawa, T. Okada, N. Uchida, T. Kono, and A. Hasegawa (2011). Similarities and differences in the rupture process of the M ~ 4.8 repeating-earthquake sequence off Kamaishi, northeast Japan: comparison between the 2001 and 2008 events, Bull. Seismol. Soc. Am. 101 2355–2368.
Strasser, F. O., J. J. Bommer, and N. A. Abrahamson (2008). Truncation of the distribution of ground-motion residuals, J. Seismol. 12 79-105.
Suzuki, W., S. Aoi, H. Sekiguchi, and T. Kunugi (2012). Rupture process of the Iwate-oki earthquake (M7.4), the aftershock of the 2011 Tohoku-oki earthquake, in Seismological Society of Japan Fall meeting, Hakodate, Japan.
Wesnousky, S. G. (2008). Displacement and Geometrical Characteristics of Earthquake Surface Ruptures: Issues and Implications for Seismic-Hazard Analysis and the Process of Earthquake Rupture, Bull. Seismol. Soc. Am. 98 1609-1632.
Yagoda-Biran, G., J. G. Anderson, H. Miyake and K. Koketsu (2015). Between – Event Variance for Large "Repeating Earthquakes" , submitted to Bulletin of the Seismological Society of America

Intellectual Merit

John Anderson and Jim Brune suggested, in a 1999 paper, the concept of a characteristic ground motion earthquake, in which repeated rupture on the same fault might tend to cause nearly identical ground motions. This project tests that idea with the best available strong motion data. This paper characterizes the differences between ground motions, recorded on the same station from repeated ruptures, with a standard deviation "tau_F". This parameter is best compared with the parameter "tau" that characterizes the uncertainty of ground motion estimates from the source in general, based on single ruptures from multiple faults, including multiple fault geometries and styles of faulting. We estimate that in the frequency range where it can be estimated, tau_F is much smaller than tau for large strike-slip earthquakes in California, and smaller than or equal to tau for repeated subduction zone earthquakes recorded in Japan. To our knowledge, this is the first time anyone has tried to estimate tau_F.

Broader Impacts

The results can be used as a constraint on the input to probabilistic seismic hazard analysis. If these results are accepted and used by the larger hazard community, the result could have a significant impact on the outcome of these seismic hazard analyses. Since in the US alone the output of the US National Seismic Hazard Map influences about $1 trillion in construction every year, improvements of any sort have a large impact.

Bibliography

Yagoda-Biran, G., J. G. Anderson, H. Miyake and K. Koketsu (2015). Between – Event Variance for Large "Repeating Earthquakes" , submitted to Bulletin of the Seismological Society of America.

Yagoda-Biran, G., J. G. Anderson (2015). Investigation of the ground motion variability associated with site response for sites with V_{s30} over 500 m/s, submitted to Bulletin of the Seismological Society of America.