Earthquake Dynamic Triggering and Ground Motion Scaling

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Abstract: While a growing body of evidence indicates that dynamic deformations (seismic waves) trigger earthquakes at all distances, it is not clear what characteristics of the dynamic deformations are most relevant to the mechanisms that cause triggering. In addition, if we are ultimately to account for dynamic triggering in time-dependent hazard assessments, we need to know how the relevant deformations vary, or scale, with distance from and size of the earthquake that generates them. In this study we address these issues by assuming that the probability of triggering aftershocks is proportional to a power of the peak amplitude of dynamic deformations affecting a fault, or a combination of these and rupture duration. We then ask whether these probabilities are consistent with measurements of triggered seismicity, in particular, linear aftershock densities. Preliminary results suggest that the hypothesis that peak acceleration alone controls aftershock triggering can be rejected. The other mechanisms remain viable, but require different values of d, the effective dimension of the fault population.

1. Introduction

Testing the consistency of dynamic deformations with aftershock densities requires developing an analytic model relating the two. The model is constrained by measured scaling parameters and tested using numerical simulations. In this study ‘aftershocks’ are those events that occur within minutes to days after a larger mainshock (triggering earthquake) without a priori limits on their distance. We consider not just the transfer of stresses from triggering to potentially triggered faults but dynamic deformations that we are able to measure using recorded ground motions, which include displacements and their temporal rates of change at the surface. These serve as proxies for displacements, strains, and strain rates at seismogenic depths (Gomberg and Agnew, 1996).

2. Testing Our Hypothesis

We assume that the probability, \( P(r) \), of dynamic deformations triggering a single aftershock at distance \( r \) is proportional to some power, \( \chi \), of the peak deformation amplitude, \( G(r) \), or alternatively of the product of \( G(r)^\chi \) and rupture duration, which scales as \( 10^M/2 \). We measure peak ground motions to constrain a model of \( G(r) \),

\[
G(r) = K \left[ D^n / (\alpha D + r)^m \right]
\]

(1)

\( D \) is the rupture dimension. Constants \( K, m, n, \) and \( \alpha \) are constrained observationally for velocities only in the near-field (\( r < D \)) and accelerations, velocities, and displacements in the far-field (\( r >> D \)). Linear aftershock density, \( \rho(r) \), the total number of aftershocks per unit
distance, is the total number of faults, \( N_f(r) \), times the probability of each failing, or
\[
\rho(r) = \frac{N_f(r)}{\Delta r} P(r)
\]  
Felzer and Brodsky, (2005) show empirically that
\[
\rho(r) = C \Gamma(M - M_{\text{min}}) r^{-\gamma}
\]
with constant distance decay rate, \( \gamma \), to within \( \sim 10 \) s of meters of the mainshock. To measure \( N_f(r) \) we sum all the faults within a volume defined by a surface, \( S \), surrounding the mainshock at distance \( r \) everywhere, and width \( \Delta r \), or
\[
N_f(r) = \int_S F(r') ds | \Delta r
\]
\( F(r') \) describes the number of faults per unit volume and its variation throughout the crust. Numerical models show that \( F(r') \) can be considered locally, as \( A r^{(d-3)} \), in which \( d \) is the effective dimensionality of the fault system. If we consider only planar, rectangular faults, \( S \) is simply defined and the analytic model is derived as
\[
\rho(r) = 4\pi AK^{2/\bar{n}} D^2 [1 + (D/r)^2 + \frac{1}{2}\pi (D/r)^2] r^{d-1} (\bar{D} + r)^{-2n/\bar{m}} = CD^2 10^{-M_{\text{min}}} r^{-\gamma}
\]
The tilde indicates \( m \) or \( m+1 \) if triggering depends on peak ground motions only or on the product of these and duration, respectively. We can now ask if measured ground motion scaling parameters are consistent with this model and measured aftershock densities.

In the far-field, \( r >> D \), this model applies to acceleration, velocity, and displacement (because we can constrain it observationally) and may be simplified to
\[
\rho(r) = 4\pi AK^{2/\bar{n}} r^{-d+1-2n/\bar{m}} = C 10^{-M_{\text{min}}} r^{-\gamma}
\]
This constrains \( d \), noting that
\[
d = 1 + 2\bar{n}/\bar{m} - \gamma
\]
Viable triggering deformations must satisfy the limit that \( d<3 \), and according to previous studies, \( d<<2 \). In the near-field our model applies only to velocities or their product with duration and to be consistent they must have parameters that satisfy the following:
\[
\rho(r) = 2A C^{2n/\bar{m}} K^{2/\bar{n}} D^{2-2n/\bar{m}} r^{-3} = C 10^{-M_{\text{min}}} r^{-\gamma}
\]
This is only satisfied if \( n = \bar{m} \).

We examine three datasets. The first includes aftershock locations and magnitudes, and PGAs, PGVs, and PGDs for 22 Japanese earthquakes with magnitudes of M3.0-6.1. Observations come from the National Research Institute for Earth Science and Disaster Prevention (NIED)’s Hi-net network in Japan, comprised of >700 seismic stations. The second dataset includes the catalog of the California Integrated Seismic Network (CISN) and
PGAs, PGVs, and PGDs for the 2005, Mw5.2 Anza and 2005 Mw4.9 Yucaipa earthquakes in southern California, measured from waveforms recorded by California Geological Survey CSMIP, the US Geological Survey NSMP, University of California San Diego’s (UCSD) Anza networks, and the CISN. We chose these two earthquakes because of the abundance of data and well-characterized aftershock sequences. Because of the depths and source dimensions of these earthquakes, almost all the measurements are in the far-field. We measure the closest distance between the fault and observation point for the California and global data (below) and hypocentral distance for the Japanese data.

Our final dataset of PGVs only was compiled to examine ground motion scaling at both near- and far-field distances, which required data from large earthquakes that rupture near the surface. Measurement of aftershock densities uniformly would be extremely difficult given the heterogeneity of available catalogs and was not done. The PGVs were measured for distances of 0.1 km to 5300 km from earthquakes with magnitudes M4.4 to M7.9. They include already measured values or waveforms from which we measured PGVs; data sources included the Pacific Earthquake Engineering Research Center, the Institutions for Research in Seismology, Japan’s NIED K-Net, and the Seismology Lab at the University of Nevada Reno.

We first constrain the ground motion model parameters. The Japanese data provide the primary constraint on the amplitude scaling of $D^m$, with values of $m \approx 1.0$, 1.5, and 2.0 for PGA, PGV, and PGD, respectively. The global and California datasets are consistent with these, but do not provide as strong a constraint. We find best fitting far-field distance decay rates for PGA, PGV, and PGD of $\sim r^{-n}$ with $n \approx 2.0$, 1.7, 1.5 and $n \approx 2.1$, 1.7, 1.4 for the Japanese and California data, respectively. The far-field global PGV are best fit with $n \approx 1.5$; the higher estimates for the Japanese and California fall within the scatter.

The global data provide the only observational constraint on near-field ground motions, and show that as the triggering faults are approached, the decay rate decreases and PGVs converge to approximately the same value. This is a consequence of fault finiteness; as the triggering fault is approached, smaller areas contribute to the radiation (Brune, 1970, Anderson, 2000). In this particular case, in which $m \approx n$, a convenient scaling of $r$ by $D$ also removes all magnitude dependence (Fig. 1); this is evident from our ground motion model that becomes $G(r) \sim \mathcal{K}/(\alpha+r/D)^n$ when $m \approx n$. 
Figure 1 PGVs for our global dataset versus the distance scaled by rupture dimension D and our ground motion model (red curve); deformations are ~the same for all earthquakes at the same scaled distance, and maximum at < r/D~1, where triggering potential is greatest.

Observations of aftershock densities for the Japanese and California earthquakes suggest distance decay rates of γ~1.1 and 1.3, respectively. These, the PGA, PGV, and PGD parameter estimates and equation (5) imply faulting dimensionality of d~3.9-4.2, 2.0-2.5, and 1.1-1.7, respectively, if we consider peak amplitudes alone. If we also consider the effect of duration, the dimensionalities become d~1.8-2.2, 0.8-1.3, and 0.4-1.0, respectively. The large value of d for PGA (strain rate) alone suggests it does not control dynamic triggering.

We use ground motion observations, G(r), and estimated scaling parameters to predict aftershock densities, to test our model and the consistency of the dynamic deformations with the densities (Fig. 2).
agree within the scatter of the density measurements (triangles). Our analytic model applies to velocities at all distances, so we use it with scaling parameters measured in the far-field to predict aftershock densities in the near-field (red dashed curve); these are consistent with those observed.

The relationships between deformations and densities in the near-field potentially provide strong constraints on viable deformation characteristics, although additional numerical modeling and data acquisition and analyses are required to verify this.

3. Discussion & Conclusion

We test a suite of hypotheses that the probability of dynamic triggering of a fault at distance \( r \) from a triggering rupture is related directly to maximum dynamic deformations of displacements, strains, or strain rates, or to the product of these with the rupture duration. To do this we have developed an analytic model that may be constrained observationally and with numerical experiments. Preliminary results suggest we can reject the hypothesis that aftershocks are triggered by maximum strain rates alone. Additional analyses of near-field data may permit us to rule out other deformation characteristics.

Our model allows us to quantify the probability that a given deformation will trigger an earthquake on a particular fault at distance \( r \), which is important for evaluating the viability of physical models of dynamic weakening and nucleation (Beeler and Lockner, 2003; Brodsky and Prejean, 2005; Johnson and Jia, 2005; Marone and Savage, in preparation). We show an example in Figure 3. Since the deformations approach a constant as the fault is approached, the probabilities very close to the fault are the same. At larger distances, they depend on the rupture dimension such that by \(~1\) rupture dimension they have decreased to 10\% of the maximum probability (corresponding to PGVs of \(~15\) cm/s or \(~50\) \(\mu\)strain), except in cases with exceptionally large (or perhaps long duration) ground motions at remote distances, when the probabilities will be correspondingly elevated (Gomberg and Johnson, 2005). Aftershock densities also describe probabilities, of an aftershock occurring at distance \( r \) anywhere surrounding the triggering fault. However, they fall off at a constant rate with distance, regardless of the rupture dimension. Numerical models show that all these behaviors may be explained if the deformations and triggering from a large rupture are simply the sums of those from smaller ones on the same fault.

Our results do not preclude the possibility that other characteristics of the deformation field may be important, some of which we will measure and test similarly. These include shaking duration, total radiated energy, and perhaps frequency content.
Figure 3. Left) Probabilities calculated as $[G(r)/G(0)]^\chi$ with $m=2, n=1.75, a=.4$ for hypothetical faults with dimensions labeled. Right) The probability of an aftershock occurring at any azimuth within a distance $\Delta r$ varies as $\rho(r); \gamma=1.5$ in this example. The integral of this provides the probability an aftershock occurring at any distance less than $r$.

4. Acknowledgements

This work is supported by the USGS National Earthquake Hazards Reduction Program. We also acknowledge Miaki Ishii and Frank Vernon (both at UCSD) for providing data.

5. References