Rupture parameters of dynamic source models compatible with NGA-West2 GMPEs

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Introduction

Synthetic dynamic rupture database is generated by Monte Carlo random sampling of the generally heterogeneous slip-weakening paramaters on the vertical strike-slip fault. The synthetic seismograms on a set of phanthom stations are compared with the prescribed ground motion prediction equations (GMPEs) based on NGA-West2 database (Boore et al., 2014[a]) in terms of the rotD50 measure of 5% damped acceleration response spectra SA at periods $0.5 - 5\,\mathrm{s}$. Only the events that statistically follow the GMPEs in terms of median and variability are accepted into the database. The resulting database is used to analyze the different stress drop measures

- Static stress drop from dynamic rupture, $\Delta\tau_s = \frac{\int \Delta\tau D \mathrm{d}S}{\int D \mathrm{d}S}$
- Stress drop estimated from the moment rate duration, $\Delta\tau_{e_T} = \frac{7}{16} M_0 \left(\frac{1}{k_1 v_s T}\right)^3$
- Stress drop estimated from the corner frequency of Brune model fitted to the moment rate spectra, $\Delta\tau_{e_f} = \frac{7}{16} M_0 \left(\frac{f_c}{k_2 v_s}\right)^3$
- Stress drop estimated from the circular static crack of rupture area, $\Delta\tau_{e_S} = \frac{7}{16} M_0 \left(\frac{\pi}{S}\right)^{3/2}$

and inspect their relations, in particular in terms of their variabilities.
The presented results are extension to Gallovič and Valentová, 2020[b].

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[a] D. M. Boore et al. "NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes". In: *Earthquake Spectra* 30.3 (2014), pp. 1057–1085.

[b] F. Gallovič and L. Valentová. "Earthquake Stress Drops From Dynamic Rupture Simulations Constrained by Observed Ground Motions". In: *Geophysical Research Letters* 47.4 (2020), e2019GL085880. DOI: 10.1029/2019GL085880.

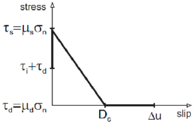
Dynamic rupture modeling

We employ a framework similar to Bayesian dynamic source inversion in Gallovič et al, 2019a[1] and 2019b[2].The dynamic rupture propagation is solved numerically utilizing newly developed FD3D_TSN code by Premus et al., 2020[3] on a 100 m grid.

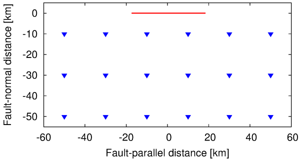
We assume strike-slip vertical fault 36 × 20 km. The dynamic model parameters, treated independently on the grid 1.4 × 1.2 km, are

- prestress τ_i
- linear slip-weakening friction parameters
  - characteristic slip-weakening distance D_c
  - friction coefficient drop $\mu_s - \mu_d$.

Synthetics up to 5 Hz are calculated assuming a 1D velocity model on a regular grid of phantom stations.



Linear slip weakening friction law.



Map view of the fault (red line) and stations (blue inverted triangles).

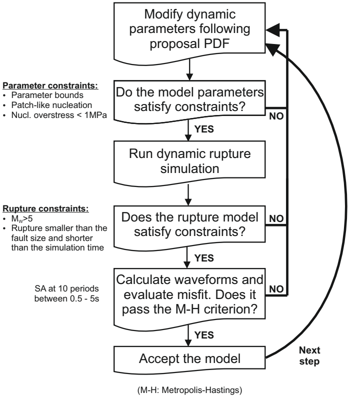
[1] F. Gallovič et al. "Bayesian Dynamic Finite-Fault Inversion: 1. Method and Synthetic Test". In: *Journal of Geophysical Research: Solid Earth* 124.7 (2019a), pp. 6949–6969.

[2] F. Gallovič et al. "Bayesian Dynamic Finite-Fault Inversion: 2. Application to the 2016 Mw 6.2 Amatrice, Italy, Earthquake". In: *Journal of Geophysical Research: Solid Earth* 124.7 (2019b), pp. 6970–6988.

[3] J. Premus et al. "FD3D_TSN: Fast and simple code for dynamic rupture simulations with GPU acceleration". In: *Seismological Research Letters* (2020).

Markov chain Monte Carlo sampling

- Random walk on dynamic model space to propose new model
- The proposed model is tested against the apriori constraints
  - Dynamic parameters within predefined bounds
  - All nuclueating points within 3km radius
  - Mean nucleation overstress less than 1 MPa
- Dynamic simulation performed, discard models with
  - $M_w < 5.5$
  - Rupture area reached the fault size
  - Rupture still evolving after the end of simulation time (20 s)



Posterior PDF

Posterior probability density function (PDF) in Bayesian framework

$$p(m|d) \sim p_{\mathrm{prior}}(m)L(d|m),$$

where $L(m)$ is the so-called likelihood function describing the data fit by the (dynamic) model. $L(m) \sim \exp(-S(m))$ with $S(m)$ misfit between synthetic and observed data calculated as

$$S(m) \sim (d_{\mathrm{obs}} - d_{\mathrm{synth}}(m))^T \mathbf{C}^{-1}(d_{\mathrm{obs}} - d_{\mathrm{synth}}(m)).$$

The mixed model covariance matrix $\mathbf{C}$, for a single event has simplified form $\mathbf{C} = \sigma^2\mathbf{I} + \tau^2\mathbf{1}$, where σ denotes inter-event variability and τ the intra-event (or between-event) variability. Note, that the observed data for our problem consist of the adopted GMPEs.

Acceptance of the proposed model is given by the Metropolis-Hastings criterion, denoting α as the ration between the posterior PDF between the proposed and the previous (original) model, the model is accepted randomly with probability $\min(1, \alpha)$.

To increase the efficiency of the MCMC sampling, we employed parallel tempering algorithm (Sambridge, 2013[a]). However, the sampling of the uncorrelated parameters by the random walk may become inefficient and lead to very similar models, therefore we crosscorrelated the resulting seismograms for the events and discarded models with correlation coefficient > 0.8.

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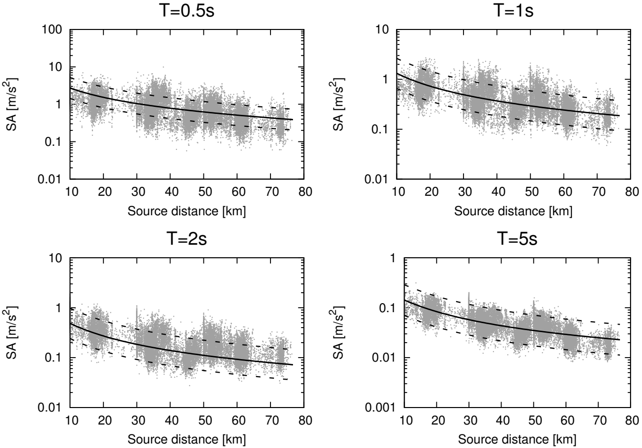
[a] M. Sambridge. "A Parallel Tempering algorithm for probabilistic sampling and multimodal optimization". In: *Geophysical Journal International* 196.1 (2013), pp. 357–374.

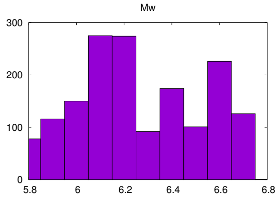
Posterior PDF of the resulting database

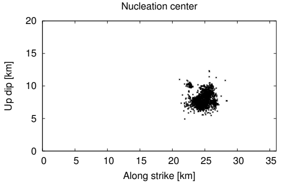


Reponse spectral accelerations for selected periods, for all events and all stations, normalized to $Mw = 6.5$. The prediction by Boore et al., 2014[a], is shown by full line, with total variability shown by dashed lines.

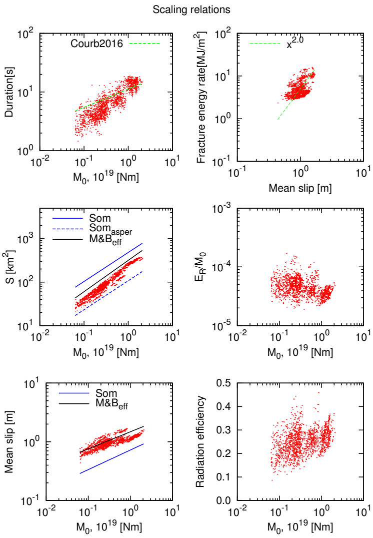
[a] D. M. Boore et al. "NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes". In: *Earthquake Spectra* 30.3 (2014), pp. 1057–1085.

Synthetic event database





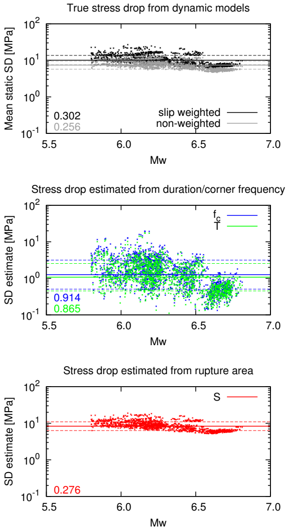
The database comprises events with different magnitudes that follow the basic scaling relations found in real events. Most of the ruptures nucleate from the same area on the fault (to be rectified).



F. Courboulex et al. "StressDrop Variability of Shallow Earthquakes Extracted from a Global Database of Source Time Functions". In: *Seismological Research Letters* 87.4 (2016), pp. 912–918
P. Somerville et al. "Characterizing Crustal Earthquake Slip Models for the Prediction of Strong Ground Motion". In: *Seismological Research Letters* 70.1 (1999), pp. 59–80
P. M. Mai and G. C. Beroza. "Source Scaling Properties from Finite-Fault-Rupture Models". In: *Bulletin of the Seismological Society of America* 90.3 (2000), pp. 604–615

Stress drop analysis

We estimated mean static stress drop directly from dynamic rupture models and compare it with seismologically estimated stress drops using rupture area S, moment rate duration T or corner frequency f_c of the Brune model fitted to moment rate spectrum, together with their variabilities (see numbers in the left bottom corner of each figure). The stress drop variability estimated using the moment rate functions is in agreement with empirical studies, but overestimates the "true" stress drop variability from the dynamic models. We attribute this discrepancy to Brune type approximation that, albeit correctly describing the average source properties, oversimplifies the individual ruptures. In contrast, when considering rupture size S, the obtained stress drop estimates match well the "true" static stress drop both in terms of mean and variability.



Conclusion and future direction

The results obtained from the synthetic event database that was generated using Boore's GMPEs, confirm the previous results regarding the stress drop variability, see also
F. Gallovič and L. Valentová. "Earthquake Stress Drops From Dynamic Rupture Simulations Constrained by Observed Ground Motions". In: *Geophysical Research Letters* 47.4 (2020), e2019GL085880. DOI: 10.1029/2019GL085880.

Future directions:

- Improve sampling algorithm of the dynamic model parameters with prescribed covariance matrix
- Sampling of the events of specific magnitude
- Sampling of the apriori probability without imposing GMPE constraints

References & Acknowledgements

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D. M. Boore et al. "NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes". In: *Earthquake Spectra* 30.3 (2014), pp. 1057–1085.

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