Using geophysical data inversion to constrain earthquake dynamics: a study on dynamically consistent source time functions.

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Abstract

Earthquake kinematic models are often used to retrieve the main parameters of the causative dynamic rupture process. These models are usually obtained through the inversion of seismograms and geodetic data and they can be used as boundary conditions in dynamic modeling to calculate the traction evolution on the fault. Once traction and slip time histories are inferred at each point on the fault plane, it is feasible to estimate the dynamic and breakdown stress drop, the strength excess and the slip weakening distance (Dc). However the measure of these quantities can be biased by the adopted parametrization of kinematic source models. In this work we focus our attention on the importance of adopting source time functions (STFs) compatible with earthquake dynamics to image the kinematic rupture history on a finite fault. First, we compute synthetic waveforms, through a forward modeling, to evaluate the effects of STFs on the ground motion and on the radiated energy. Therefore, adopting different STFs, we perform kinematic inversion of strong motion and GPS data, using a new non linear two-stages search algorithm (*Piatanesi et a*l., 2007) . We have quantitatively verified that the chioce of STFs affects ground motion time histories within the frequency band commonly used in kinematic inversion and that the inferred peak slip velocity and rise time strongly change among the inverted models. These differences has a dramatic impact when kinematic models are used to infer dynamic traction evolution. The shape of the slip weakening curve, the ratio between Dc and the final slip and the dynamic stress drop distribution are remarkably affected by the assumed STFs. We recommend the adoption in kinematic inversions of source time functions that are compatible with earthquake dynamics.

1. Purposes

In order to investigate the importance of the adoption of source time functions, we consider different slip velocity time histories (Fig.1): a boxcar, a modified cosine function and the regularized Yoffe function (*Tinti et al.*, 2005a).

In this study we follow this strategy:
1) through forward modeling we study the influence of the different STFs on the computed ground motions and radiated energy;
2) by means of geophysical data inversion, we evaluate the importance of STFs to retrieve kinematic source models on a finite fault;
3) then, we use the inverted rupture histories as boundary conditions in 'dynamic' rupture modeling to assess the dependence of relevant dynamic parameters on the STF used in the kinematic input model.

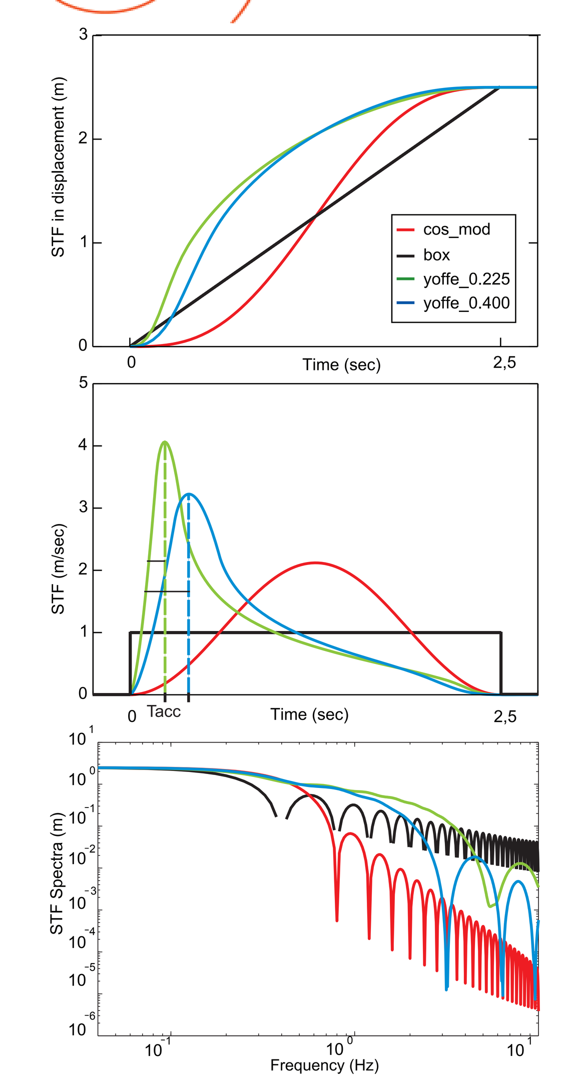

Figure 1. Slip, Slip Velocity functions and theirs discrete Fourier spectra (upper, middle and bottom panels, respectively) used in this study. See legend for the different adopted STFs. For the same final slip STFs yield very different values of peak slip velocity.

2. Kinematic Forward Modeling - Radiated Energy

The forward modeling is performed with a discrete wavenumber technique (*Spudich and Xu*, 2003), taking into account the fault geometry and the station distribution of the 2000 Western Tottori earthquake, Mw=6.8, (Fig.2). The target rupture model (Fig.3) has the following characteristics: the slip has two main patches reaching a maximum value of 1m; the maximum rise time is 2.5 s; the rupture front propagates at nearly 2.5 km/s except in the upper part of the fault, where it reaches 3.5 km/s. We use a crustal model obtained by overlapping the velocity model of the Tottori region (DPRI, 2000) with the KiK-Net borehole information (*Pulido and Kubo*, 2004).We compute synthetic ground velocities in the frequency band 0-1 Hz commonly used in kinematic inversions and we study the effect of STFs on the radiated energy. The latter is computed integrating the energy flux, due only to the S-waves, over the focal sphere at distances (100 km) longer than the fault dimensions, accounting for the slip velocity histories on the fault plane (*Boatwright et al.*, 2005).

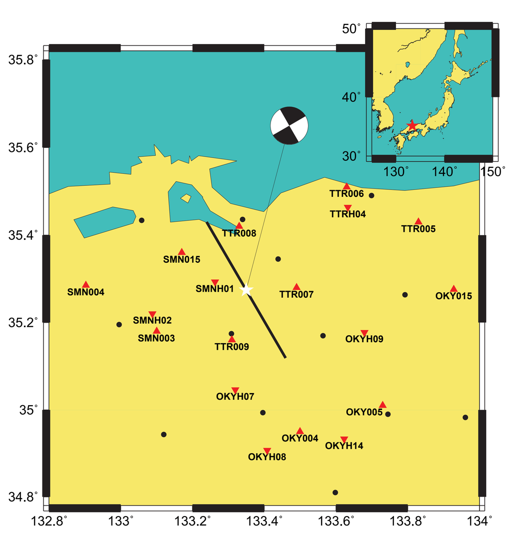

Figure 2. Location and focal mechanism of the Tottori earthquake. Red triangles and inverted triangles denote K-Net (surface sensor) and KiK-Net (borehole) strong motion. Black circles show GPS sites.

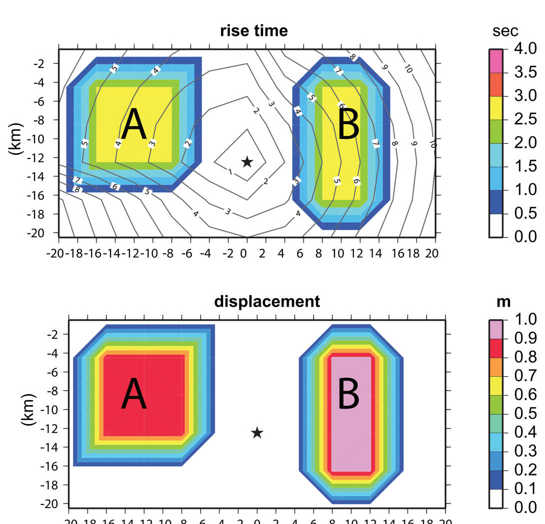

Figure 3. Target rupture model used in forward modeling

2.1 Results

The assumption of STF may have an important role to retrieve earthquake rupture history on a finite fault:

1. The computed ground motions depend on the choice of STF especially at stations located near the source (Fig.4, left panels);

2. The spectra highlights that the regularized Yoffe functions have a greater high frequency content and therefore they are able to better constrain the details of the rupture in near field region (Fig.4, right panels).;

3. The rms velocity spectra, i.e. the integrand of the radiated energy (Boatwright et al. 2005), highlights the frequency contribution of the different STFs (Figure 5a). The cumulative functions of radiated energy (Figure 5b) show appreciable differences for frequencies higher than about 0.5 Hz

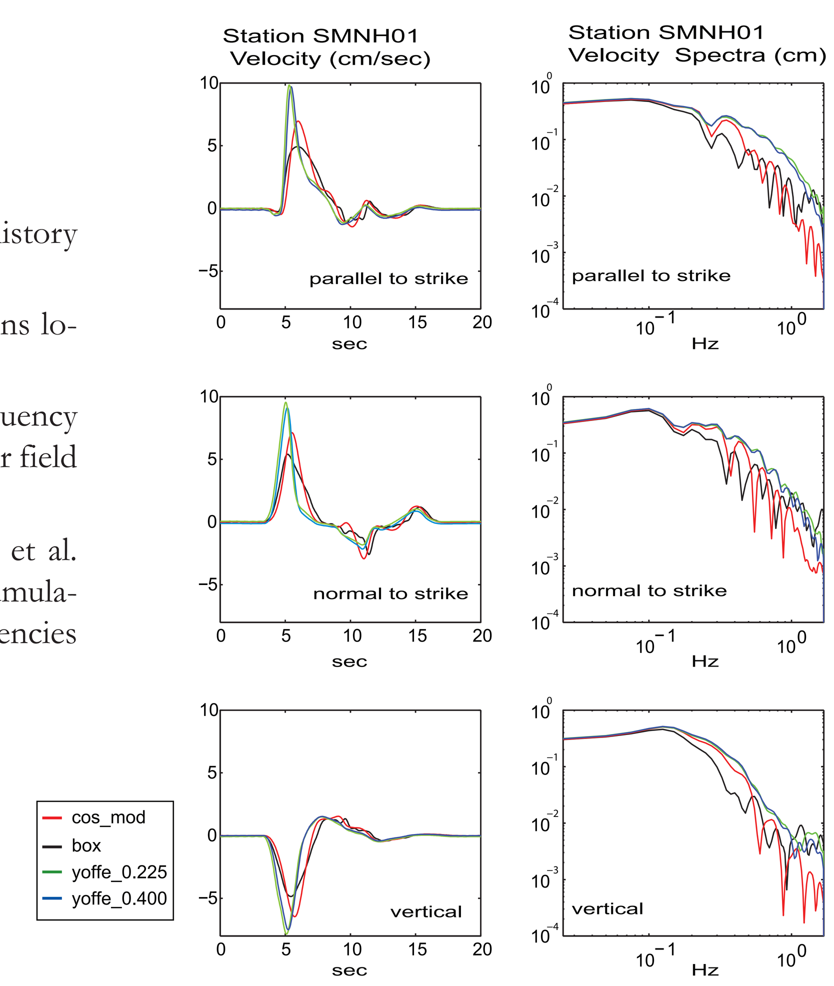

Figure 4. Comparison between seismograms and spectra calculated with different STFs (see legend), for one station at near epicentral distance (SMNH01; d=8 km).

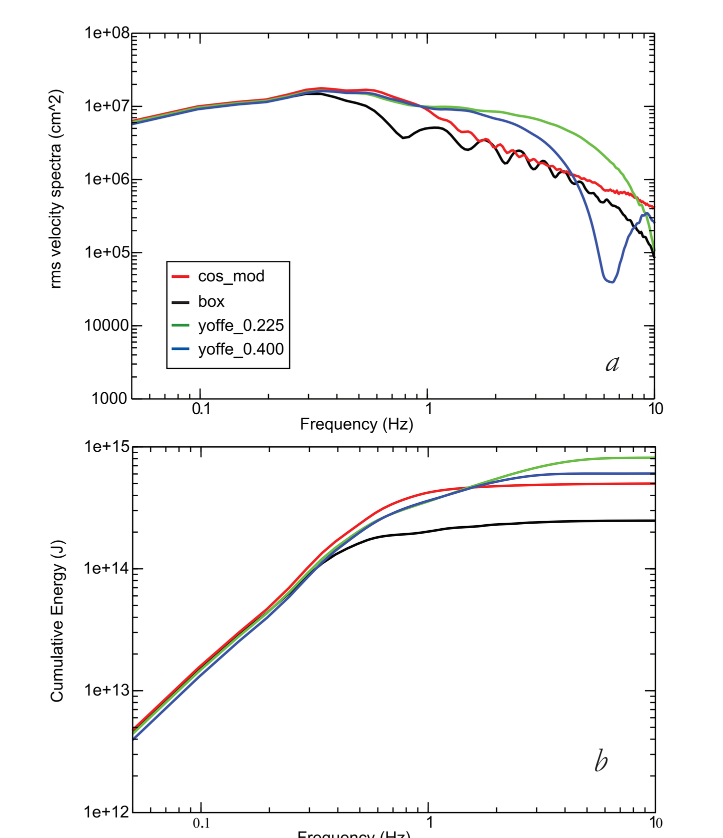

Figure 5. (a) rms velocity spectra; (b) cumulative radiated energy.

3. Kinematic Inversion: 2000 Western Tottori Earthquake

We perform four different kinematic inversions adopting different STFs (Fig.1). We use a new two-stage non linear technique (*Piatanesi et al.*, 2007) to jointly invert 18 strong motion and 14 GPS data recorded during the 2000 Western Tottori Earthquake, Mw=6.8. We simultaneously invert for rupture time, rise time, peak slip velocity and rake. For each inversion we show the weighted average models.

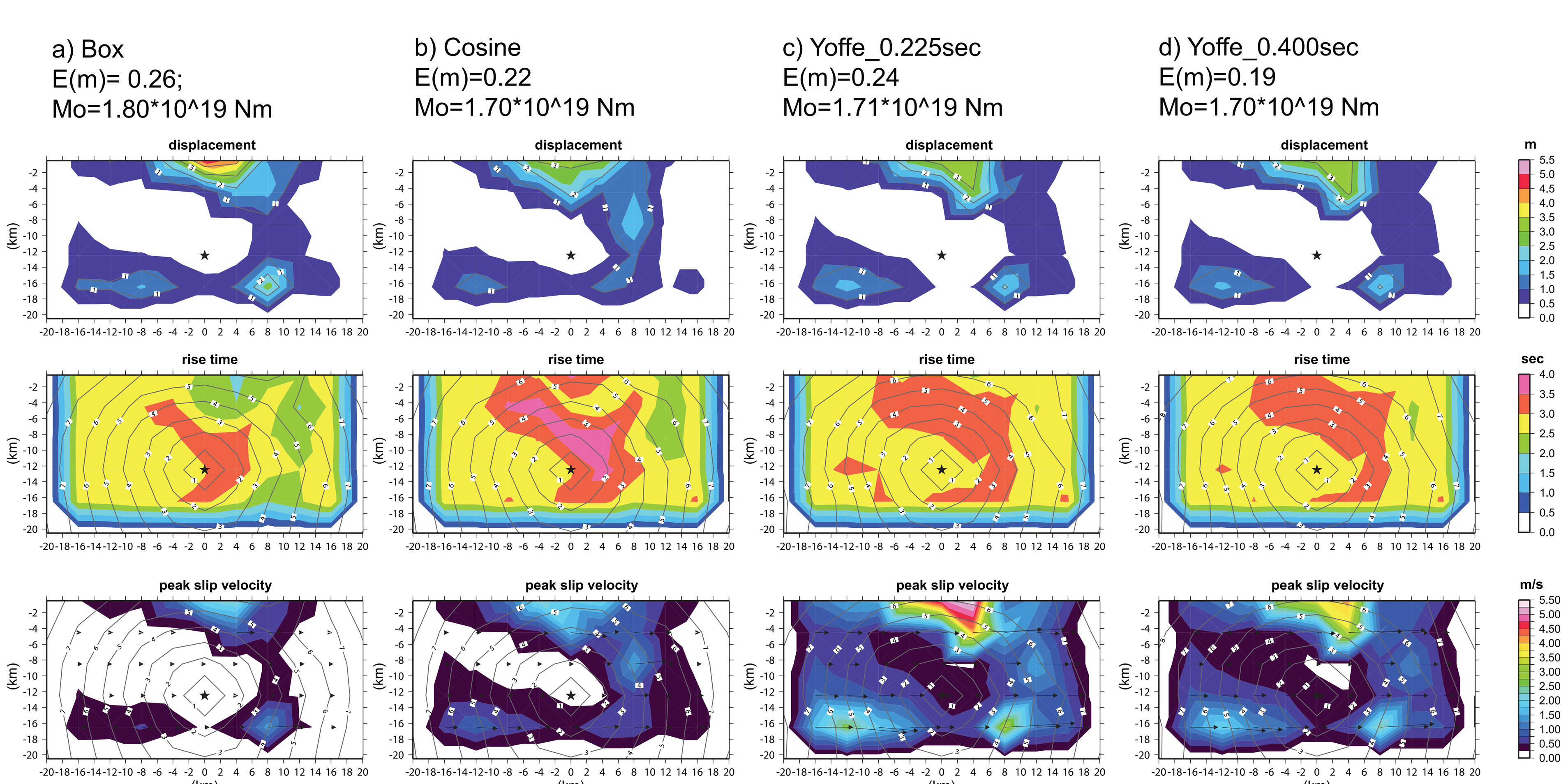

Figure 5. Retrieved rupture histories (average model from ensemble inference), for the Tottori earthquake, obtained from the four inversion performed with: a). a boxcar; b). a modified cosine; c). a Yoffe function with Tacc=0.225 sec; d). a Yoffe function with Tacc=0.400 sec. For each STFs: top panels displays displacement on the fault; middle panels show the rise time; bottom panels shows the peak slip velocity. Rupture time is shown by contour lines. Arrows represent the slip vector. For each test are specified the minimum cost function value and the recovered seismic moment.

3.1 Results

1. Kinematic Parameters.

For all four retrieved models, slips mainly occur at shallower part with at most 3.0-3.5 m left lateral slip, except for the boxcar that yields a slightly higher value. All models show a similar shape of displacement distribution (Fig.5, upper panels) and a resulting moment of about 1.7*10^19Nm, in agreement with previous results(*Semmane et al.*, 2005, *Festa and Zollo*, 2006). In spite of the similarity of slip distribution, the different STFs yield very different peak slip velocity and rise time distributions (Fig.5, middle and bottom panels). STF with the steepest initial slope (Yoffe_0.225sec) yields greater values of peak slip velocity.

2. Data-Fit.

Synthetic waveforms and displacement vectors agree satisfactory the observations (Fig.6). The coseismic deformation pattern (Fig.6b) clearly shows left lateral strike slip motion in agreement with the retrieved rake distribution (Fig.5, bottom panel).

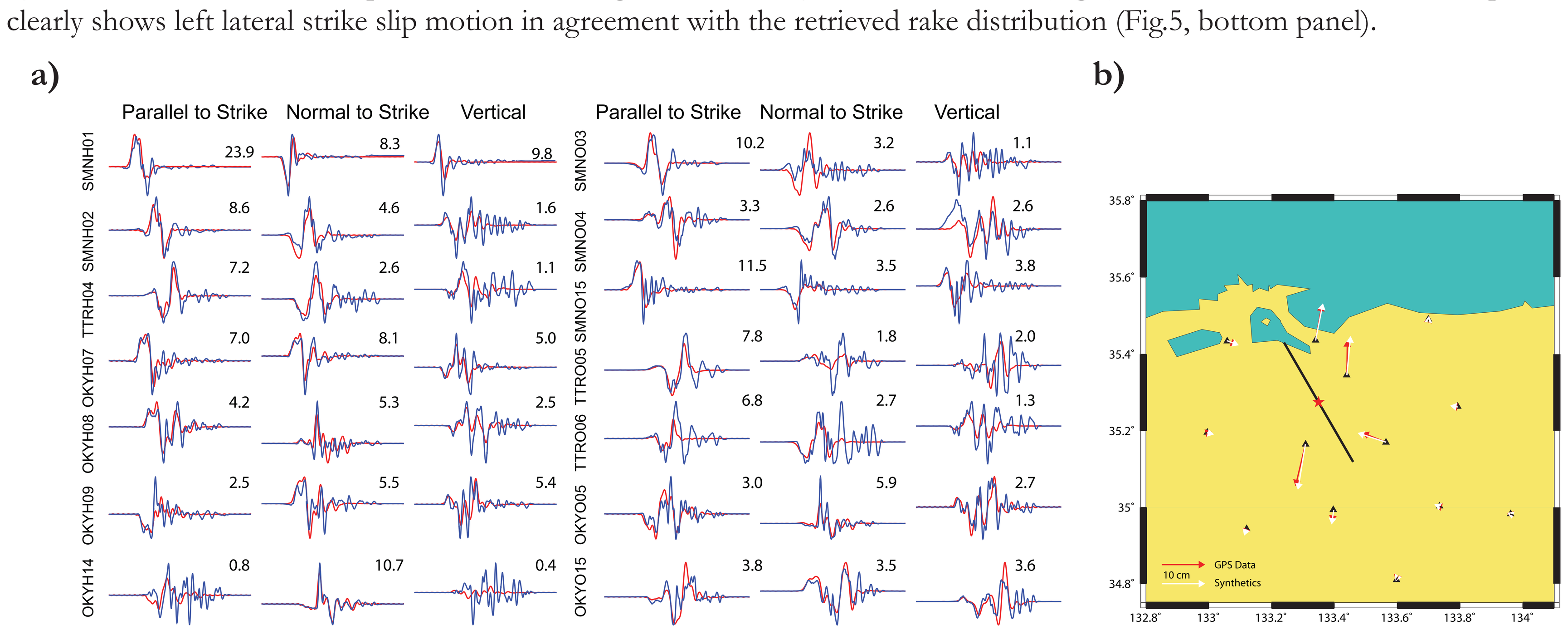

Figure 6. a) Comparison between the observed (blue lines) and the synthetic(red lines) waveforms; b) comparison between the recorded (red arrows) and computed (white arrows) GPS. Synthetic data refer to the retrieved model having the smallest cost function value (E(m)=0.19).This model is obtained from a regularized Yoffe with Tacc=0.400 sec (Fig.5d). Numbers with each trace are maximum peak velocity amplitude.

4.Dynamic Modeling

We compute the traction time histories on the fault plane by solving the elasto-dynamic equation (*Tinti et al.*, 2005b) and using the slip velocity time history as boundary conditions for each of the four retrieved kinematic models. Figure7 shows the traction versus slip curves for 15 subfaults around the maximum displacement on the fault plane. The different panels highlight the effect of the STFs during the weakening phase. It is evident the variability of the critical slip weakening distance (Dc) and the ratio Dc/Dtot: for the box-car STF (panel a) Dc is close to 90% of total slip and, as a consequence, the breakdown stress drop is reached at the end of the slipping phase. Only the two Yoffe STFs yield traction evolution versus slip curves similar to what expected from a slip weakening model and Dc is around 30% of total slip. Figure8 highlights the difference for the four models between the duration of the breakdown phase and the slip duration (rise time). In Figure 9 we show the distribution of dynamic stress drop: the box-car STF yields the highest values; the two Yoffe STFs give very similar stress drop distributions both in shape and in amplitude; finally, the cosine STF produces a rupture with lowest stress drop.

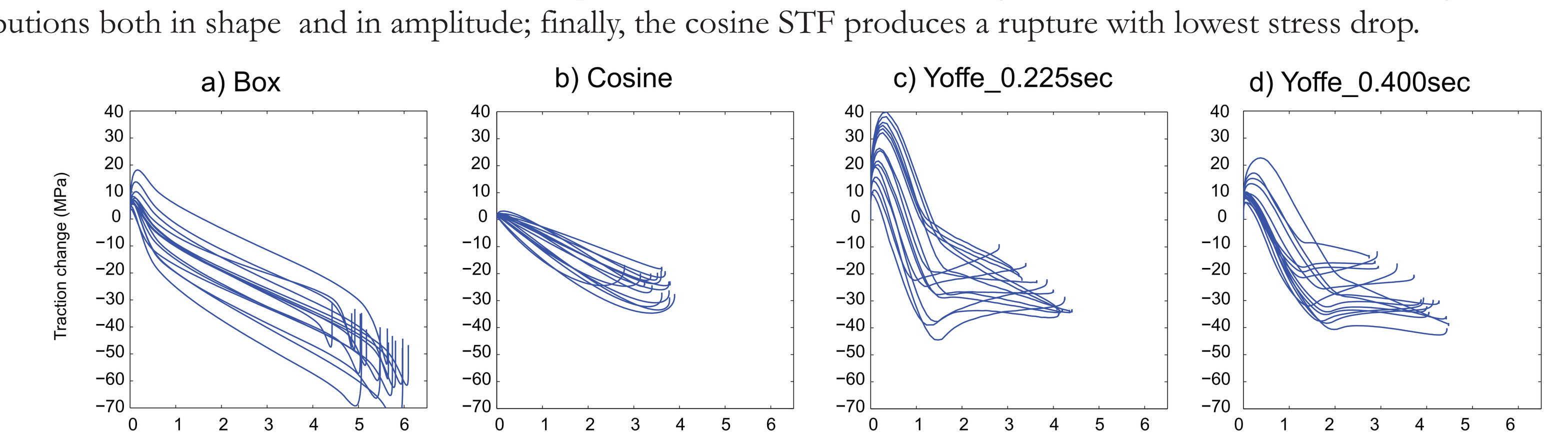

Figure 7. Traction versus slip curves for 15 subfaults around the maximum displacement for: a). a boxcar; b). a modified cosine; c). a Yoffe function with Tacc=0.225 sec; d). a Yoffe function with Tacc=0.400 sec.

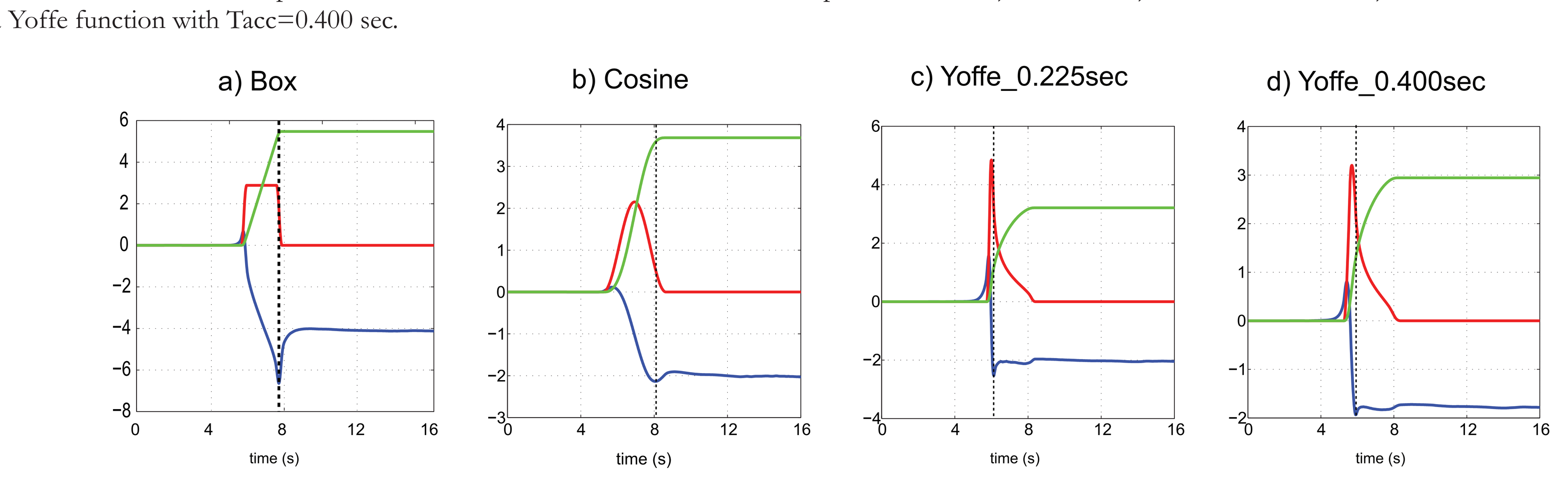

Figure 8. Traction change, slip and slip velocity time histories for one of the subfaul around the maximum slip for: a). a boxcar; b). a modified cosine; c). a Yoffe function with Tacc=0.225 sec; d). a Yoffe function with Tacc=0.400 sec.

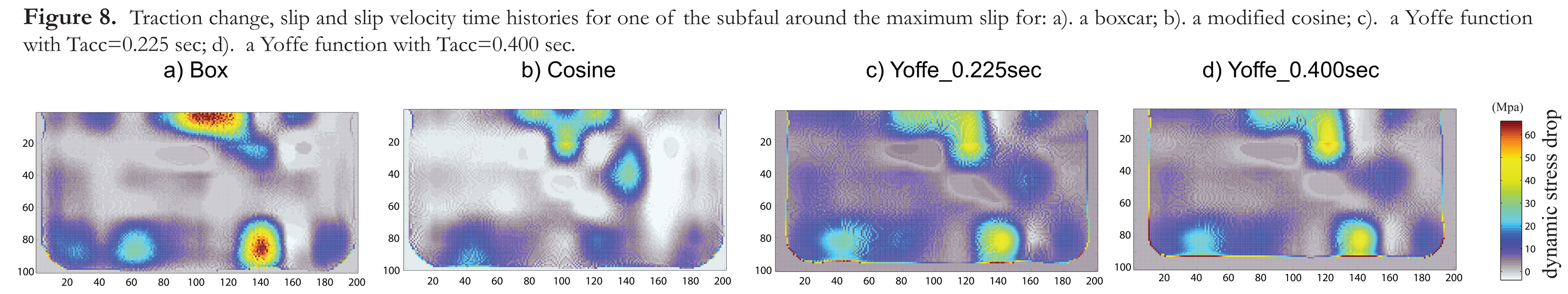

Figure 9. Dynamic stress drop for: a). a boxcar; b). a modified cosine; c). a Yoffe function with Tacc=0.225 sec; d). a Yoffe function with Tacc=0.400 sec.

6.Conclusive Remarks

Our results show that the choice of the STF affects the radiated waveforms within the frequency bandwidth (0-1 Hz) commonly used to invert ground motion waveforms. Moreover, this choice affects the high frequency (f > 0.5 Hz) radiated energy: a box-car slip velocity function underestimates the radiated energy at f > 2 Hz of nearly a factor 3 in respect to the radiated energy computed with the other STFs. The adoption of different STFs also modifies the imaged distribution of source parameters on the fault plane. In particular, we emphasize that peak slip velocity is quite variable also for inverted models having similar patterns of final slip. This has strong effects on the inferred dynamic traction evolution and on the scaling of Dc with final slip. Finally, our results suggest that breakdown work is less sensitive to the adopted STF.

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