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Supporting Information for

Rupture models of the 2016 Central Italy earthquake sequence from joint inversion of strong-motion and InSAR datasets: Implications for fault behavior

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Introduction

The auxiliary materials for this article consist of three texts supporting the main document.

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Text S1.

Inversion strategy

Geodetic data and seismic waveform data have complementary strengths in constraining earthquake sources. Geodetic data with dense near-field observations can provide a fine resolution for the slip distribution, while seismic waveform data with timing information permit the retrieval of the temporal evolution of the rupture processing. Combining these two different types of earthquake observations can undoubtedly expand the understanding of an earthquake event. We carried out the joint inversion in a multi-time window inversion scheme [30], where each fault patch is allowed to rupture many times, once in a time window. The source-time function in each time window is assumed to be a fixed shape and have overlap with neighboring time windows. In this study, an isosceles triangular source-time function with 50% overlap was adopted, following Kikuchi and Kanamori (1991) [27]. By unevenly distributing the slip in the time windows for each fault patch, the variation of both rupture velocity and source-time function can be accommodated. Assuming that the number of time windows is K and the fault plane includes M×N patches, the slip vector **S** to be inverted will be [28]:

$$\mathbf{S} = (\mathrm{S}_{1,1,1}, \mathrm{S}_{2,1,1}, \ldots \mathrm{S}_{M,1,1}, \mathrm{S}_{M,2,1}, \ldots \mathrm{S}_{M,N,1}, \mathrm{S}_{1,1,2}, \ldots \mathrm{S}_{M,N,K}) \quad \text{(s1)}$$

The joint inversion can be undertaken by solving:

$$\begin{pmatrix} \boldsymbol{d}_{geo} \\ \boldsymbol{d}_{seis} \end{pmatrix} = \begin{pmatrix} \boldsymbol{G}_{geo} \quad \cdots \quad \boldsymbol{G}_{geo} \\ \boldsymbol{G}_{seis} \end{pmatrix} \mathbf{S} + \begin{pmatrix} \boldsymbol{e}_{geo} \\ \boldsymbol{e}_{seis} \end{pmatrix} \quad \text{(s2)}$$

where $\boldsymbol{d}_{geo}$ and $\boldsymbol{d}_{seis}$ are the geodetic and seismic observations, and $\boldsymbol{e}_{geo}$ and $\boldsymbol{e}_{seis}$ are the geodetic and seismic observation errors. $\boldsymbol{G}_{geo}$ and $\boldsymbol{G}_{seis}$ are the geodetic and seismic kernel matrices. $\boldsymbol{G}_{geo} \quad \cdots \quad \boldsymbol{G}_{geo}$ is the K concatenations of the geodetic Green's functions $\boldsymbol{G}_{geo}$.

In order to avoid oscillatory solutions, a routine approach is to include regularization when retrieving an earthquake slip model, which is mostly in terms of a smoothing constraint. For the rupture model inversion, we need both spatial and temporal smoothing to make the slip features physically reasonable in both space and time. In this study, we used a 2-D finite difference Laplacian operator for the spatial smoothing, and a 1-D finite difference Laplacian operator for the temporal smoothing.

The mathematical framework for rupture model inversion was set up under Bayes' theorem. The constraints from the geodetic and seismic datasets were used to form the conditional probability, and the smoothing constraints were used to form the prior probability. The solution can be derived by maximizing the posterior probability obtained from the combination of the conditional probability and prior probability. To objectively determine the relative weighting for the datasets and smoothing constraints, we used the Akaike's Bayesian Information Criterion (ABIC) method, following previous studies [25]. The best estimate of the weighting parameters was achieved through minimization of ABIC. A numerical parameter grid search method was adopted to find the solution corresponding to the minimum ABIC.

Text S2.

Inversion setting

The static geodetic kernel matrix and the seismic kernel matrix were calculated by an elastic homogeneous half-space dislocation model [29] and the Frequency-Wavenumber (FK) synthetic seismogram package [31], respectively. For the latter, we first computed the Green's functions of a layered medium from a point source with a Dirac delta source-time function. We then computed the synthetic seismogram produced by an isosceles-triangular geometry source using these Green's functions. We filtered the seismogram between 0.02 and 0.5 Hz, in the same way as the processed velocity waveform data. Finally, the filtered synthetic seismograms were compiled to form the seismic kernel matrix.

During the inversion, we initialized a maximum rupture speed of 3.1 km/s and allowed the fault patch to slip in three neighboring time windows with a 0.8 s duration and a 0.4 s repeat interval. The Central Italian Apennines (CIA) velocity model [26] was used for the dynamic Green's functions calculation. The fault geometry setting conformed to the ones derived from previous studies based on abundant geodetic datasets [9], which can constrain fault geometry parameters well. Specifically, the fault for the 24 August event consists of two distinct 52^0 and 40^0 SW-dipping fault segments, both striking 161^0 SSE, with lengths of 12 km and 15 km, respectively. The 26 October and the 30 October event faults strike 160^0 SSE, dipping 40^0, with a 20 km length. We divided these faults into a number of ~1 km × 1 km rectangular patches. The bottom depths of all the faults were set to be 10 km.

Text S3.

Slip model comparison

Our derived joint slip models are in general agreement with the existing slip models, showing a normal faulting mechanism, high rupture speed, and mostly bilateral propagation. However, as the first source models for the sequence aimed at fast earthquake finite fault inversion and interpretation, many of them used strong-motion data or geodetic data only. Meanwhile, only a few studies have fully investigated all the major events in the earthquake sequence, and most work has focused on the Amatrice earthquake because it was the first and most serious event. Due to the data selection and model settings, the existing slip models differ from our joint inversion, to a certain degree.

The first notable difference is the fault geometry selection, mostly on the Amatrice earthquake. Chiaraluce et al. (2017) [10], Huang et al. (2017) [11], Liu et al. (2017) [13], Tinti et al. (2016) [14], and Xu et al. (2017) [16] preferred to consider a single fault segment, while Cheloni et al. (2017) [9] and Lavecchia et al. (2016) [12] adopted two segments. Because two lobes can be observed in the interferogram and the slips happened in two individual faults named MVF and MGF with different geometries, we followed the latter two studies to adopt distinct 52° and 40° SW-dipping fault segments for the Amatrice earthquake. The fault geometry selection for other two events agree quite well among all the slip models. We have also noted that Scognamiglio et al. (2018) [32] used two fault planes for the source inversion on the Norcia earthquake. However, the single fault plane is proved to fit quite well with the InSAR observations (Figure A1), so we preferred the single one with less complexity.

Another obvious discrepancy among these slip models is the slip distribution pattern of the three earthquakes. Early studies of the Amatrice earthquake using strong-motion data suggested a significantly larger slip in the south patch on the seismogenic fault plane [10,14], while other studies using InSAR or GPS data constraints have shown that the north patch slip more [9,12]. Our joint slip model shares more similarity with the latter results, where two separate major slip concentrations are derived with a maximum slip of 0.76 m (north) and 0.72 m (south), respectively. For the Visso earthquake, our joint slip model is closer to the model of Cheloni et al. (2017) [9] and Xu et al. (2017) [16], both of which were geodetic slip models with InSAR constraint, showing a single elongated slip concentration. However, the seismic slip model from Chiaraluce et al. (2017) [10], with only strong-motion data, shows a relatively complex slip distribution with a snake-like shape. For the Norcia event, the diagonally distributed slip concentrations revealed by our joint slip model are very close to another joint slip model using strong-motion and GPS data (Scognamiglio et al., 2018), and are also similar to a geodetic slip model [16]. However, our joint slip model differs a lot from other models [10,13], despite the fact that they may also adopts geodetic data. However, overall, the comparison of the existing results shows that the geodetic data, especially the InSAR-constrained slip models, share more similarities, implying that InSAR or geodetic data play an extremely important role in constraining the slip pattern. This is consistent with our finding that the InSAR-derived slip distribution is much closer to the joint slip distribution than that of strong-motion data.