

SCENARIO MODELING OF THE 2014 Mw6.0 SOUTH NAPA, CALIFORNIA, EARTHQUAKE USING AN ADVANCED BROADBAND KINEMATIC SOURCE MODEL

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Abstract

Strong ground motion simulations require physically plausible earthquake source model. Here we present application of such a kinematic model introduced by Ruiz et al. (2011). The model is constructed to inherently provide desired omega-squared spectral decay at high frequencies. The source is composed of randomly distributed overlapping subsources with fractal number-size distribution. Position of the subsources can be constrained by prior knowledge of major asperities (stemming, e.g., from slip inversions), or can be completely random. From earthquake physics point of view, the model includes positive correlation between slip and rise time as found in dynamic source simulations. Rupture velocity and rise time follows local S-wave velocity profile, so that the rupture slows down and rise times increase close to the surface, avoiding unrealistically strong ground motions. Rupture velocity can also have random variations, which results in irregular rupture front while satisfying the causality principle. This advanced kinematic broadband source model can be easily incorporated in any numerical wave propagation code as the source is described by spatially distributed slip rate functions, not requiring any stochastic Green's functions. Here we present a simple parametric study to illustrate the role of individual model parameters. Performance of the source model is shown on the very shallow unilateral 2014 Mw6 South Napa, California, earthquake. The model reproduces well the observed data including the near fault directivity, suggesting that main features of the earthquake rupture are correctly captured (Gallovič, 2015). We also present scenario simulation maps for this event, and comparison with existing ground motion prediction equations.

Key Words: 2014 Mw6 South Napa earthquake, kinematic strong ground motion modeling, scenario modeling, between-event ground motion variability, single-station sigma.

1. Introduction

Strong ground motion simulations require physically plausible earthquake source model. The method must be able to provide omega-square source spectrum in a broad frequency range, which is commonly observed in the real data. Moreover, the model must be compatible with basic characteristics observed in earthquake source studies of real events and with properties suggested by earthquake source dynamics.

For the strong ground motion modeling generally kinematic models are preferred to their dynamic counterpart for much better numerical efficiency. Here we apply one of the kinematic methods, which is based on evaluation of the representation theorem [1]. The source process is prescribed in terms of spatial-temporal evolution of slip along the fault. Numerically, the fault is discretized and the representation integral is substituted by a sum, so that the finite extent source is represented as a coherent superposition of point sources distributed regularly along the fault with spatial spacing small enough to avoid numerical problems in the integration. We note that this approach differs from the so-called composite modeling, which is based on

assumption that the modeled event can be described as a discrete sequence of individually-rupturing subevents that are treated as point-sources (e.g., [2]). Another viable approach to strong motion modeling is a hybrid combination of the latter two methods (e.g., [3], [4]). However, the disadvantage of such combination is the need for cross-over filtering of the synthetics simulated by the two techniques, which is typically performed ad-hoc.

Here we utilize method introduced by [5] (hereafter denoted as Ruiz Integral Kinematic, RIK, model) with some minor modifications. It has been recently applied to the broadband modeling of the observed velocity waveforms written by the 2014 Mw6 South Napa earthquake ([6]). We first explain basic characteristics of the source model, taking newly into account random variations of the rupture speed along the fault. We employ full-wavefield Green's functions calculated in a 1D velocity model. We validate the earthquake model against the observed data. Eventually, we perform scenario simulations to predict possible variability of ground motions due to varying hypocenter location, mean rupture speed and slip distribution. We compare the results with ground motion prediction equations (GMPes) and discuss spatial distribution of the between-event ground motion variability.

2. RIK Source model description

The RIK model has been developed by [5] for earthquake ground-motion simulations in order to provide omega-squared spectral decay at high frequencies. It utilizes the representation integral in the full frequency range (no composite modeling needed). In [6] some simplifications and minor modifications of the method have been introduced, such as taking into account the depth-dependence of the rupture velocity. Here we additionally introduce random variations of the rupture speed as discussed further.

The RIK model is composed of randomly distributed circular subsources with fractal number-size distribution with dimension $D=2$, which is considered also in other kinematic source models (e.g., [2], [4]). Kinematic properties (including the rupture propagation) are prescribed individually to each of the subsources, and thus each subsurface is characterized by its own slip rate functions along its areal extent. The total slip rates of the RIK model are eventually evaluated on a regular discretization grid along the fault by summing up slip rate contributions from all the subsources.

In particular, we consider that radii of the subsources, R , are integer fractions of the fault width W , i.e. $R=W/n$. For our number-size distribution the number of subsources at level n is then $2n-1$. The subsources are distributed randomly along the fault. In the scenario modeling we consider uniform distribution, but in the real data modeling we use slip distribution obtained from inversion of low-frequency data as a spatial probability density functions, see further.

The individual subsources have slip distributions corresponding to the crack model, i.e.

$$\Delta u^R(\rho) \sim \sqrt{R^2 - \rho^2} \text{ if } \rho < R; \quad \Delta u^R(\rho) = 0 \text{ otherwise,} \quad (1)$$

where ρ is the distance from the subsurface center. The constant of proportionality in (1) is determined so that the total seismic moment fits the prescribed scalar seismic moment M_0 . This fractal decomposition of the source model implies that the slip decays as k^{-2} at high wavenumbers k ([4], [2]). It implies physically plausible k^{-1} spectral decay of the stress distribution ([7]).

The rupture is assumed to propagate in form of a slip pulse of width L_0 with the Brune's pulse ([8]) as the slip rate function. If rise time were constant, the source spectrum would decay as omega-squared only up to the reciprocal of the rise time, decaying then faster due to the low-pass filtering effect of the slip rate function. To correct for this, [9] introduced the concept of

the k -dependent rise time. In the RIK model with subsources of varying sizes, the rise time is considered to depend on subsurface radius R as

$$\tau(R) = \tau_{max} = aL_0/v_r \text{ if } 2R > L_0; \quad \tau(R) = a(2R)/v_r \text{ otherwise,} \quad (2)$$

where a is a free parameter (of the order of 1). Rupture speed v_r follows the S-wave velocity profile, keeping the rupture speed to S-wave velocity ratio constant. This way we avoid too fast (even supershear) rupture propagation close to the surface and thus enhanced source radiation. The rise-time dependence on the subsurface radii (2) also implies a positive spatial correlation between the slip and the rise time as it is observed in dynamic rupture simulations (e.g., [10]).

[2] introduced a concept of small- and large-scale rupture fronts to decrease the coherency of the rupture front. [6] showed that taking this feature into account improved slightly the model performance in terms of explaining the azimuthal variability of the observed data. Instead, here we consider random variations of the rupture speed following a k^{-1} distribution. The rupture times are numerically evaluated using the solver of the eikonal equation by [11].

3. Application to the 2014 South Napa earthquake

The South Napa earthquake occurred on 24 August 2014 at 10:20:44 UTC in California, 6km NW of American Canyon and 9km SW of Napa ([12]). For this earthquake many high-quality recordings were written by many stations located at near-fault distances (see Fig. 1).

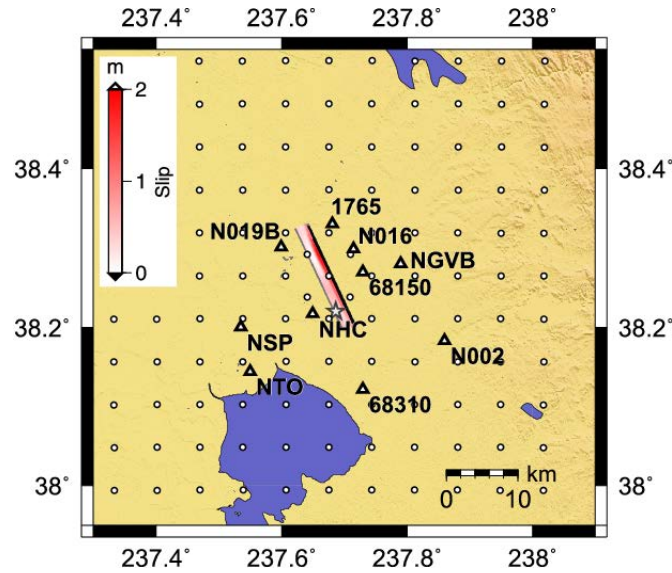


FIG. 1. Distribution of near-fault stations (triangles) that recorded the 2014 South Napa earthquake. Box represents the surface projection of the fault with superimposed slip distribution by [6]. Star denotes the nucleation point of the event. Small circles show position of phantom stations considered in the scenario simulations.

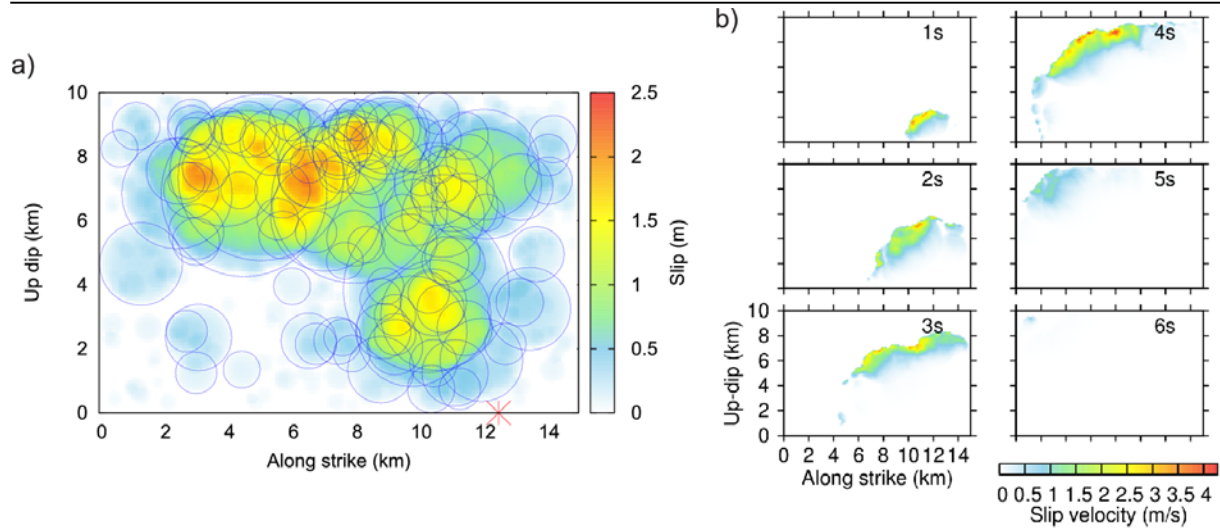


FIG. 2. Setup of the RIK model for simulation of the observed data. a) Distribution of RIK subsources (circles) composing the final slip distribution (color coded). Only the largest subsources are plotted for lucidity. b) Rupture evolution snapshots every 1s. Note the irregular rupture front due to the random variations of the rupture velocity.

[6] present a slip inversion of the South Napa earthquake utilizing method by [13] and near-fault stations (Figure 1). The model is in agreement with other models published so far ([14]; [15]; [16]; [17]), showing a unilateral northward rupture propagation towards the city of Napa, having significant asperity at shallow depths (<5 km) with longer rise times at the place where 40-46cm slip was observed at the surface ([12]).

3.1. Modeling the observed data

Raw accelerometric data from stations located within 15km from the fault were downloaded from the database of the Center for Engineering Strong Motion Data (Fig. 1). After detrending, bandpass filtering using one-way (causal) Butterworth filter of the 4th order, the data were integrated to velocity and eventually undersampled. The high-pass filtering at 0.05Hz removes the low-frequency part of the wavefield that is corrupted by the instrumental noise. The low-pass filter at 5Hz is sufficient for the velocity recordings, while limiting the computational expense. The horizontal components were rotated to the fault-parallel (F-P) and fault-normal (F-N) components.

We adopt RIK model parameters from [6]. In particular, the distribution of the subsources of the RIK model is constrained by slip model from the low-frequency data inversion by [6], see Fig. 2a. The mean rupture velocity is considered also as 0.8 times the local rupture velocity. We add random variations to the rupture speed to distort the coherent rupture front obtained when a constant rupture velocity is considered. Fig. 2b shows snapshots of the slip rates along the fault illustrating the irregular shape of the rupture front.

The model is used to simulate ground motions at all the receiver sites (Fig. 1). For the wave propagation modeling we use a modification of the 1-D layered velocity model GIL7 ([18]), with two additional layers with subsurface velocity representing soft-rock site properties (see Table S2 in [6]). Full wavefield Green's functions (GFs) are calculated using the discrete wavenumber technique (Axitra code, [19]; [20]). No stochastic GFs are used throughout the whole study.

Fig. 3 shows comparison between observed and synthetic velocity waveforms, showing relatively good fit despite the simplicity of the modeling, especially in terms of the wave propagation modeling (considering just a 1D velocity model in the full-frequency range). Generally, both the shapes of the waveforms and their peak values are correctly reproduced. In particular, the model successfully explains the long-period directivity pulses observed at the F-N components of the stations located in the forward direction from the rupture propagation (N019B, N016). Interestingly, it also reproduces the double peak character of the F-N component observed at station 1765, located just across the fault from station N019B.

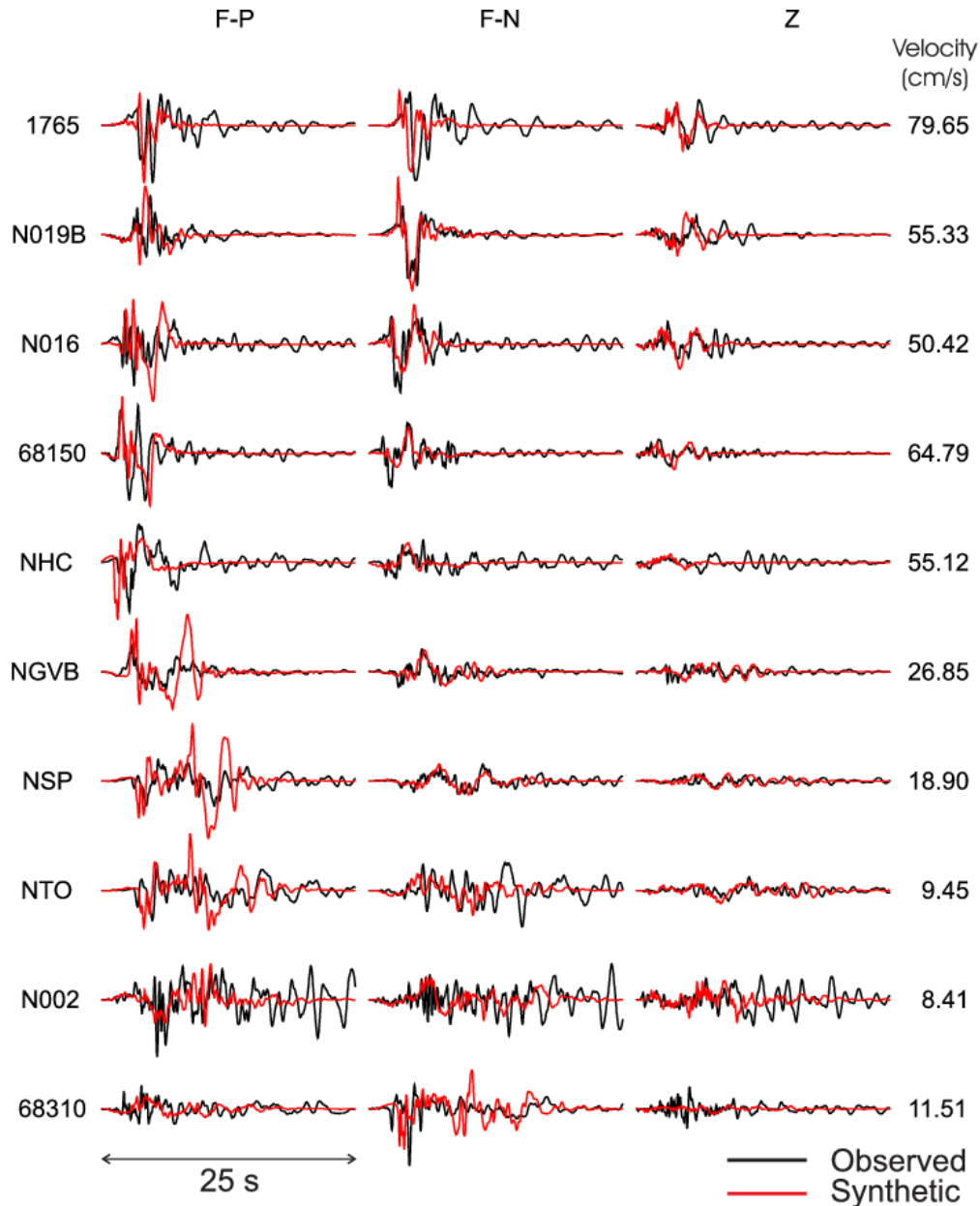


FIG. 3. Comparison between observed and synthetic velocity data simulated by the RIK model (frequency range 0.05-5Hz).

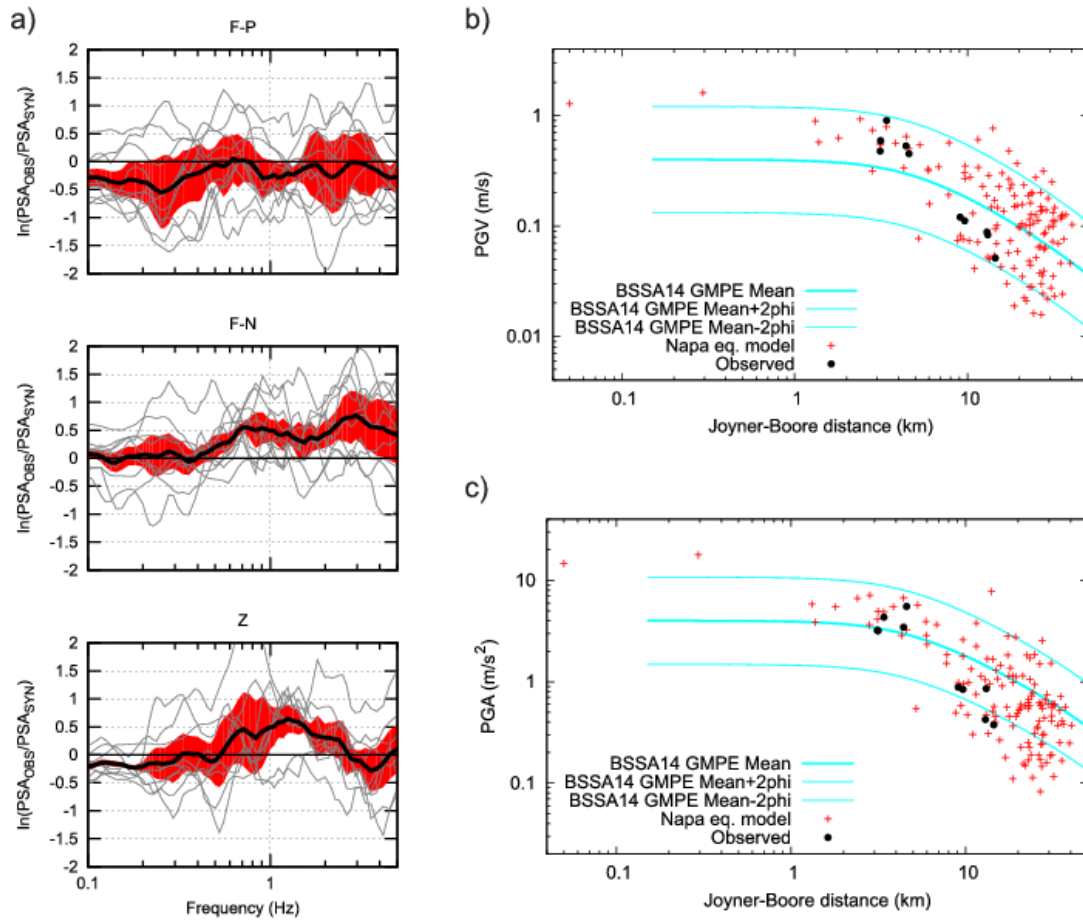


FIG. 4. a) Modeling bias in terms of the response spectra. b) Comparison between simulated (red points) and observed (black points) PGV values collected from all the real and phantom stations (Fig. 1). Lines represent mean (thick) and mean $\pm 2\phi$ (thin), where ϕ is the within-event standard deviation of the GMPE ([21]). c) Same as b) but for PGA.

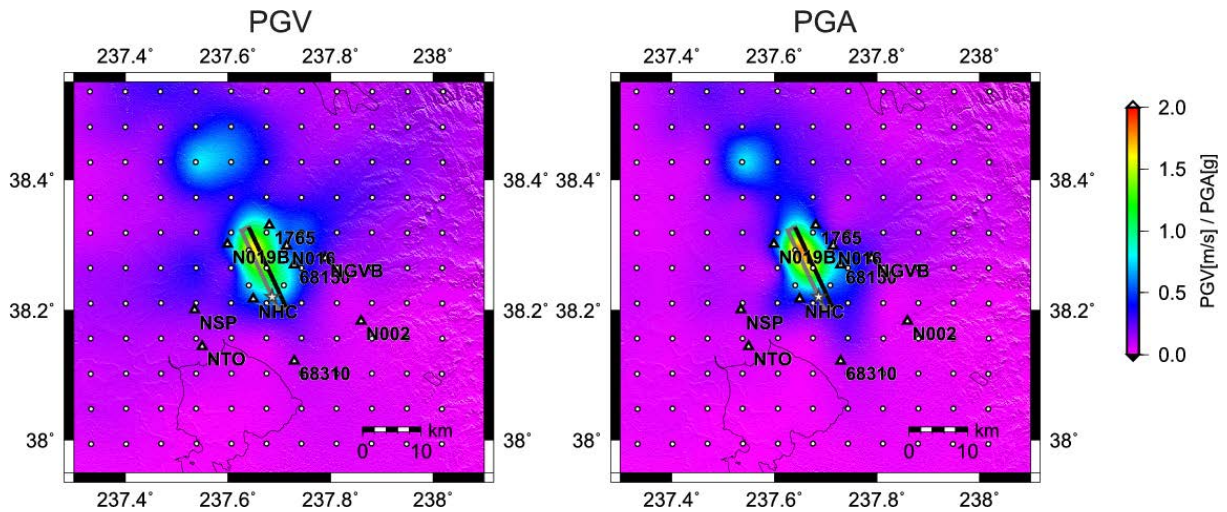


FIG. 5. Map view of the simulated PGV and PGA values interpolated from all the real and phantom stations (triangles and circles, respectively).

Fig. 4a displays the modeling bias in terms of the acceleration response spectra at the individual components. The mean bias (black curve) is generally close to zero, suggesting minor overestimation (-0.2) and underestimation (0.3) at the F-P and F-N components, respectively. The variance of the bias is also rather low (0.2-0.4).

The simulations are carried out not only for the real stations, but also for a regular distribution of phantom stations (see Fig. 1). Fig. 5 shows map view of the simulated PGA and PGV values. Red points in Fig. 4b and 4c show the simulated PGV and PGA values, respectively, as a function of the Joyner-Boore distance. The plots are complemented by the real-data peak values and GMPEs adopted from [21]. Note that the real data overshoot the mean GMPE curves, especially in terms of PGV, while at larger distance the observed values are smaller than those predicted by GMPEs. This behavior, which results in a seemingly stronger attenuation with distance than suggested by the GMPE curves, is well captured by the strong motion simulations. We ascribe this particular behavior to the very shallow location of the major asperity, which is a rather peculiar feature of the present event (Fig. 2).

3.2. Scenario modeling

In deterministic seismic hazard assessment one is typically interested in strong ground motion prediction for a hypothetical earthquake on an assumed fault. Typically, mechanism and geometry of a causative fault can be estimated a priori with some epistemic uncertainty. However, details of the rupture process, such as position of the nucleation point, asperity, or rupture velocity, are generally not known in advance, representing source of aleatoric uncertainty. In such a case, scenario simulations are performed to take into account possible variations of the source parameters.

To estimate the variability related to the a priori unknown rupture scenario, we assume the following variations of the source parameters: two ratios between the mean rupture speed and S-wave velocities (0.6 and 0.8), six positions of the nucleation point on the fault and six slip distributions, see Fig. 6a. Regarding the latter, we actually consider three different slip distributions as shown in Fig. 6a and then their horizontal mirror image to improve the symmetry of the simulated scenarios. Considering all combinations of the rupture parameters, we thus generate 72 rupture scenarios in total. For each of the scenarios we consider a unique distribution of the rupture speed variations. Fig. 6b shows examples of three of source scenarios in terms of rupture evolution snapshots. The rupture propagation is characterized by similar complexity as the model used for modeling the observed data (see above).

Fig. 7 displays the resulting PGV and PGA values picked from the simulated seismograms (red dots) against the Joyner-Boore distance. For reference, the GMPEs and real data are plotted as well. Scatter of the simulated values is relatively large, having standard deviation of approximately 1.0 (in natural log units). This value is much larger than the standard deviation of the GMPEs (including both within- and between- event variability), which is approximately 0.6-0.65 and roughly constant for our distance range ([21]). We ascribe this discrepancy to the abundant number of earthquake scenarios and seismic station density considered in the simulations, which by far exceeds any standard number of observations in real cases. We suppose that scarce real observations might not capture all systematic features of the earthquake ground motions as suggested by the simulations (see also further).

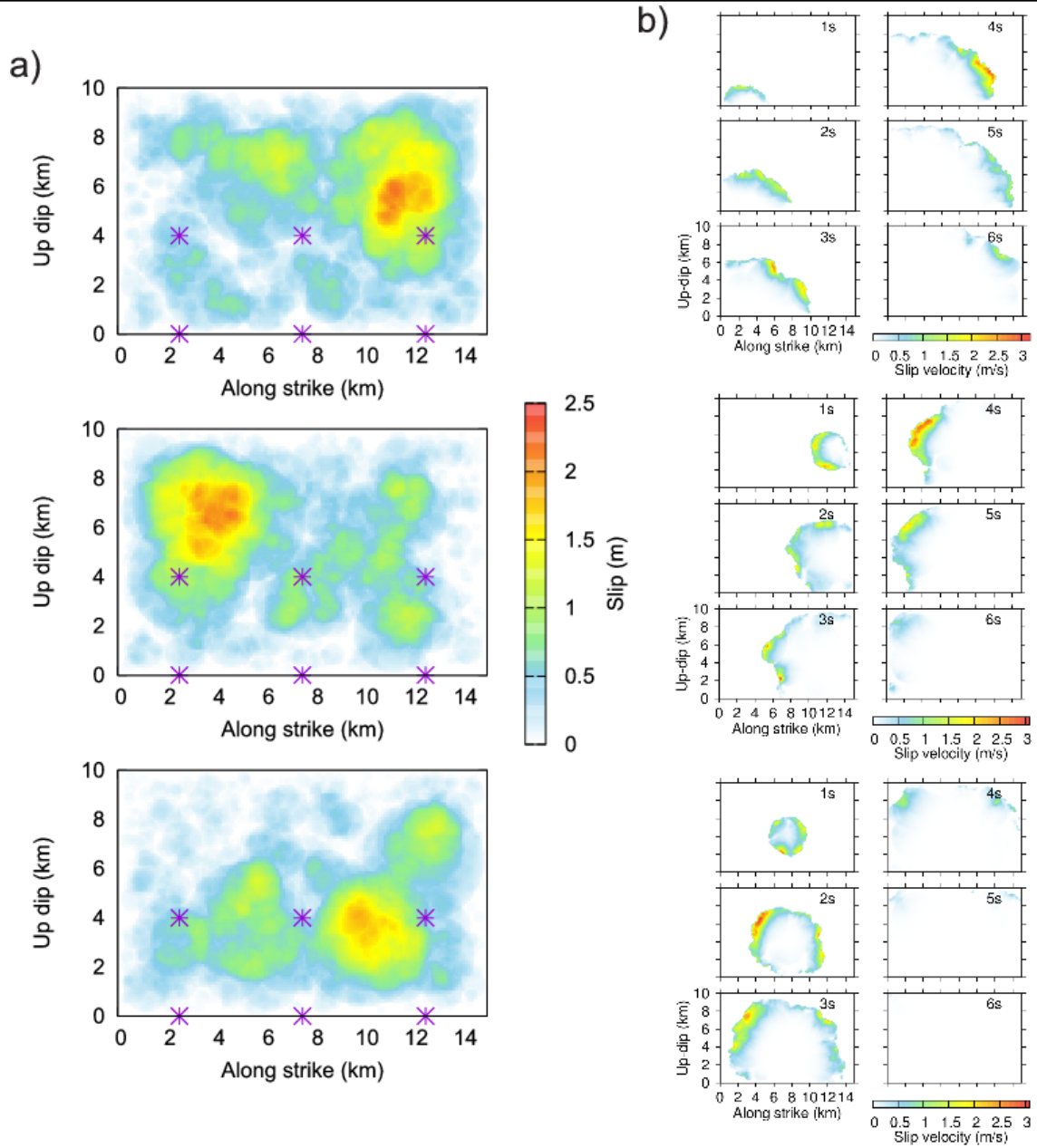


FIG. 6. Setup of the scenario modeling. a) Three slip distribution models with considered positions of nucleation points (stars). b) Three examples of the rupture propagation scenarios.

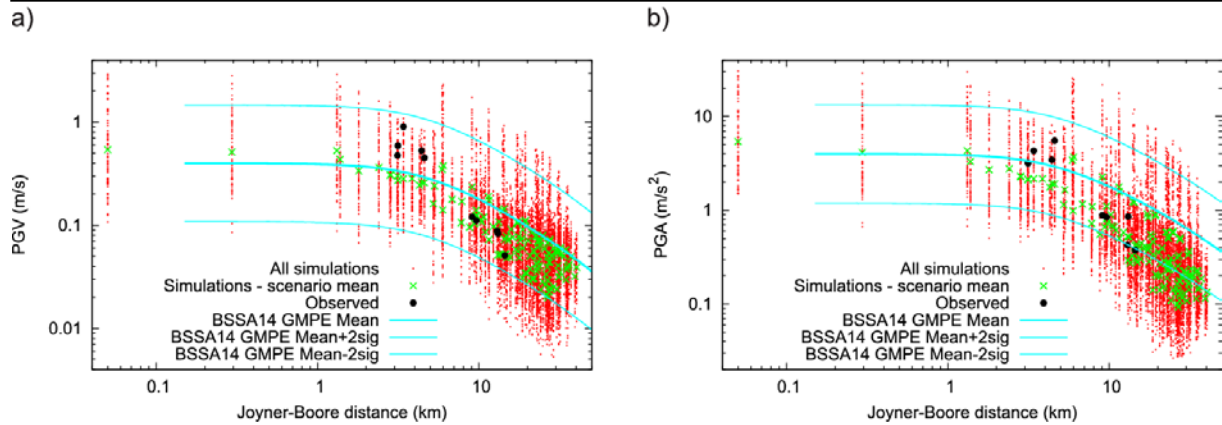


FIG. 7. Results of the scenario simulations. Red points are simulated PGV (a) and PGA (b) from all scenarios and stations. Lines represent mean (thick) and mean $\pm 2\sigma$ (thin), where σ is the complete standard deviation of the GMPE ([21]) including within- and between-event variabilities. Green crosses show mean values over scenarios for each of the stations considered.

Fig. 7 shows also mean values of the peak values evaluated at each of the stations over all the scenarios. The mean peak values have smaller scatter. They decay slightly faster with distance (especially in terms of PGA), which resembles the faster decay of the observed data. In the case of modeling the real data we have ascribed it to the superficial character of the slip distribution. In this case we cannot use this argument although there is a larger number of models having shallower slip (see Fig. 6). Instead, the 1D velocity model seems to attenuate the seismic waves more strongly than what is suggested by the empirical data (GMPEs). It is also possible that our velocity model lacks some superficial structure that would enhance the seismic waves at larger distances.

Fig. 8 shows spatial distribution of the simulated PGV and PGA values in terms of their mean and standard deviations (in natural log units). The mean values have elongated shape following the geometry of the fault. In the along strike direction at larger distances the mean values are larger than at perpendicular direction. Minor effect of the radiation pattern can be also seen, being expressed by the cross-like character of the peak-value maps.

Regarding the ground motion variability, the simulations suggest spatially inhomogeneous standard deviation (also called single-station between-event sigma) ranging from approximately 0.35 to 1.1. Indeed, the corresponding maps in Fig. 8 have fan-like shape with the largest values located in the along the directions of the fault. This is due to the directivity effect, which is mostly pronounced in the along-fault direction. Indeed, the variability is lowest in the directions perpendicular to the fault, where the ground motions are not much affected by the direction, in which the rupture front propagates. Root-mean-square of the variability over all the stations is 0.65 and 0.75 for PGV and PGA, respectively.

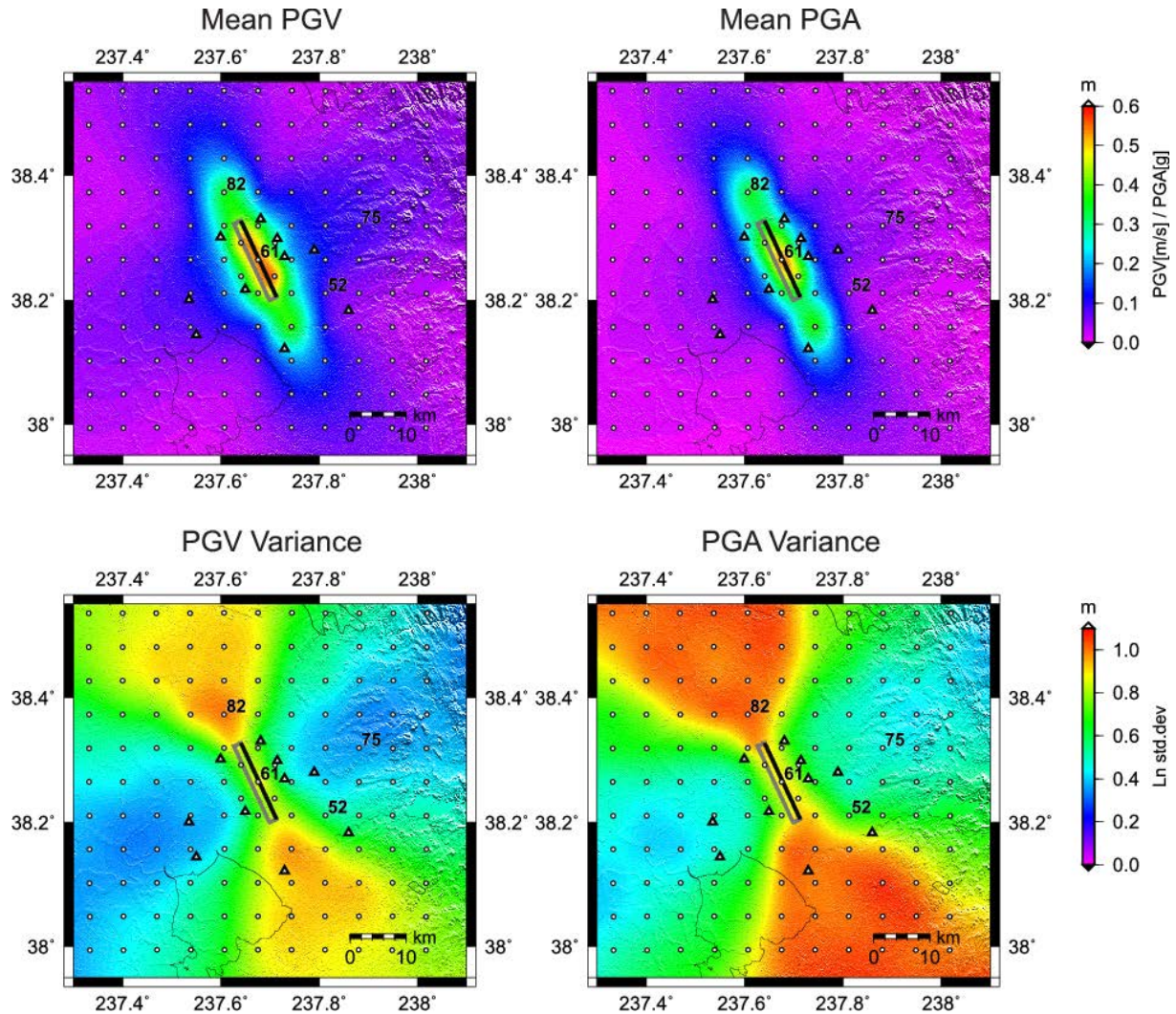


FIG. 8. Results of the scenario simulations plotted in terms of mean values of PGA and PGV evaluated over all the scenarios and their variability. Triangles and small circles denote real and phantom stations, respectively. For the numbered phantom stations Fig. 9 shows histograms of PGA values.

For four selected phantom stations depicted in Fig. 8, we show histograms of the simulated PGA values in Fig. 9. The histograms have varying shape, resembling normal distribution (e.g., station 75). In some cases (stations 82 and 52) they have a bimodal character, having more than one peak. We observe the bimodal shape generally at stations lying in the along-strike direction. They are perhaps imprints of the significant difference between the peak values simulated in the forward and backward directivity directions.

The plots in Fig. 9 show also PGA values obtained considering the source model used to simulate the observed data (crosses). They fall within the histograms from the scenario simulations. However, one can see that the values obtained for the constrained source model do not fall to the same part of the histograms for various stations; in some cases they fall at the margin of the distribution (stations 75 and 61), while in other cases they are located approximately in their centers (stations 82 and 52).

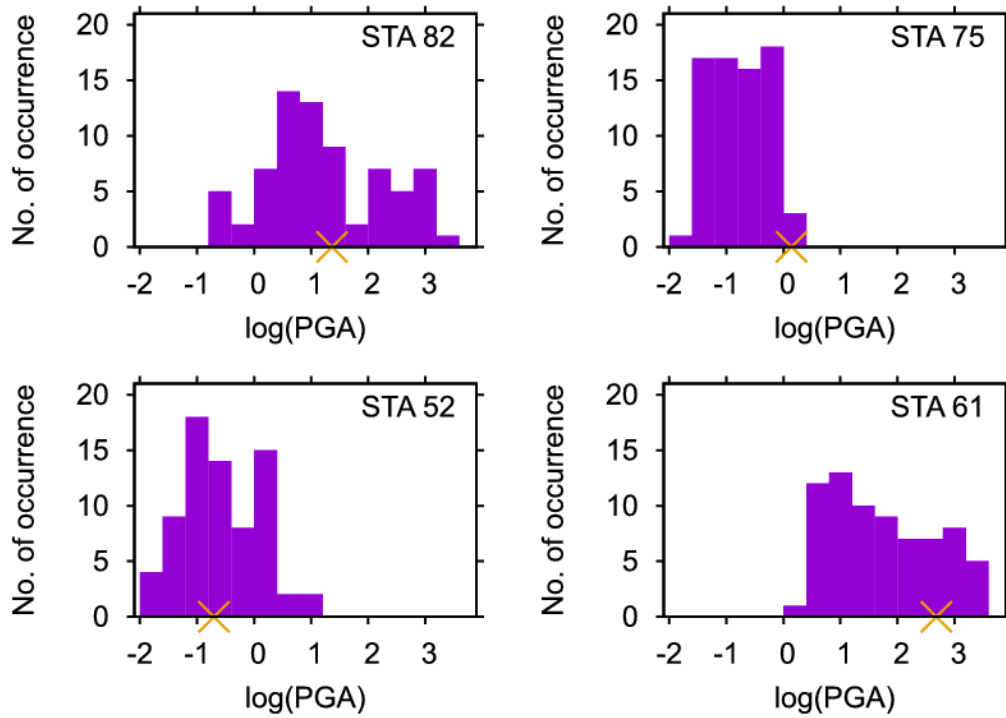


FIG. 9. Histograms of (natural log) PGA values corresponding to the numbered phantom stations in Fig. 8. Crosses denote values obtained from the model used to simulate the observed data.

4. Discussion and Conclusions

In this study we have employed an advanced broadband kinematic source model originally introduced by [5]. It is characterized by k^{-2} slip distribution and k -dependent rise time, providing correctly omega-squared source spectrum in a broad frequency range. We have introduced several minor modifications, such as dependence of the rupture speed on the 1D velocity profile to avoid too fast (even supershear) rupture propagation close to the surface. We have also included random variations of the rupture speed to distort the otherwise too coherent rupture front.

The approach is validated against near-fault high-quality recordings of the 2014 Mw6 South Napa earthquake. Slip model inferred by [6] (having a major slip patch located at depths shallower than 5km) is used to constrain a source model to predict the velocity waveforms (0.05-5Hz). Full-wavefield Green's functions calculated in a 1D velocity model roughly corresponding to a hard-rock site are taken into account in the whole frequency range (no stochastic Green's functions were utilized). The model correctly reproduces the major characteristics of the observed data including their peak values and broad directivity pulses in the velocity waveforms.

We have performed scenario simulations for the South Napa causative fault. To this end, we have generated 72 source models varying rupture speed, nucleation point position and slip distribution in order to evaluate within-event uncertainty of the ground motions. The resulting maps of the average peak motions have elongated shape due to the finite extent of the fault.



PGA and PGV values decay slightly more rapidly with increasing distance than suggested by the empirical GMPEs ([21]). The variability of the ground motions (in terms of single-station between-event standard deviation) show a peculiar fan-like shape with largest values in the along-strike directions. We ascribe this to the effect of directivity, which is most pronounced in those directions. The directivity effect is also imprinted in the histograms of the peak values at stations in the along strike-directions, having rather a bimodal character.

The simulated single-station between-event standard deviations range from 0.35 to 1.1 with root-mean-square value (over all stations) of 0.65-0.75, which is larger than the between-event standard deviations of GMPEs (0.35). We note that the standard GMPEs take into account only distance-dependence of the observed motion, and thus do not capture the systematic azimuthal dependence of the ground motion variability as suggested by the simulations.

Although the present application utilizes just a 1D velocity model to evaluate ground motions, the source model can be easily implemented in any code simulating wave propagation in generally 3D media. In terms of scenario simulations, we expect that the 3D model would mainly affect the mean ground motions and perhaps also the variability at further distances in directions perpendicular to the fault. Contrarily, we suppose that close to the fault and in the along-strike directions the source effect plays a dominant role in controlling the within-event ground-motions variability. The simulations may thus help to introduce new types of functional forms of GMPEs that would take into account the ground motion variability due to the source effect.

5. Acknowledgement

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