

Effects of complicated 3-D rupture geometries on earthquake ground motion and their implications: a numerical study

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SUMMARY

We present a numerical study of the effects of geometrically complicated 3-D ruptures on near-source ground motions. In most of the kinematic and dynamic rupture modelling studies or seismic moment tensor and slip inversions the strong assumption of a perfectly planar fault is made. However, it is known from geological field studies that real fault traces are not planar but characterized by relatively strong deflections, bends and other irregularities. In this paper we, investigate the effects of such non-planar earthquake ruptures on ground motion modelling in comparison to their equivalent planar ones. For this purpose we apply the highly accurate Discontinuous Galerkin method that is capable of incorporating the geometry of complicated non-planar rupture surfaces by a set of double couple point sources that do not have to coincide with the mesh vertices. We generate a set of kinematic rupture models characterized by random spatial deflections with various correlation lengths and root mean square values. These deflections then determine the associated spatial strike and dip variations. We find that the deflected rupture models have the same seismic moment tensor as the perfectly planar one, however, with a reduced scalar moment, which we correct for. After a sound validation of our modelling approach, we present the effects of the deflections on synthetic velocity seismograms computed in the vicinity of the rupture. We observe that these geometrical irregularities do not just lead to high frequency effects but can strongly affect the synthetics in the whole frequency band. Finally, we discuss our observations in detail and conclude that the correct incorporation of the geometrical properties such as local strike and dip variations of the rupture surface is an important issue. We also discuss possible implications for some seismological fields, such as strong-motion simulations or seismic moment tensor and slip inversions, where these results might have significant consequences.

Key words: Numerical solutions; Earthquake ground motions; Computational seismology; Wave propagation; Fractures and faults.

1 INTRODUCTION

In the dynamic and kinematic modelling of ground motions close to an earthquake rupture the source is often considered to be *perfectly planar* and characterized by constant strike and dip angles. However, field observations at the Earth's surface commonly show that geological faults are much more complicated at all scales (Bonilla 1979, <http://earthquake.usgs.gov/regional/qfaults/>). Studies of the deeper Earth's crust using techniques such as fault-zone guided waves (Li *et al.* 1994) and aftershock mechanism variations (Hardebeck 2000) suggest that the faults' geometrical complexities extend even to seismogenic depths. Just recently, researchers have started using geological information and advanced numerical methods to model rupture propagation on geometrically more complicated faults.

Dynamic rupture propagation is classically simulated on a planar fault. However, also in this field the attention was recently shifted to non-planar ruptures (Cruz-Atienza & Virieux 2004). Since the dynamic problem is difficult itself, the actual complicated fault geometry is usually approximated by a few planar segments, for example (Harris & Day 1999; Aochi & Madariaga 2003). These studies emphasize that geometrical discontinuities have an important effect on rupture propagation in terms of decreasing rupture speed, rupture arrest and generation of strong seismic wave radiation. Other studies, yet rather theoretical, concern dynamic rupture propagation on a piecewise planar rupture containing one or more kinks, that is, sharp changes of the rupture fault direction, (Bouchon & Streiff 1997; Aochi *et al.* 2000; Adda-Bedia & Madariaga 2006). In particular, Adda-Bedia & Madariaga (2006) found that the dynamic rupture propagation across the kink generates a special type

of circular *SH*-wave which is centred at the kink and related to the starting and stopping phases at this kink. However, such waves are induced by the very sudden change of the rupture geometry, which may not be realistic itself.

Although slip inversions of seismic ground motions has made considerable progress in recent years, still most of these inversions use planar source models. This is on one hand due to the lack of geometrical details of the faults, and on the other hand to simplify numerical computations. In the case of very large earthquakes again the rupture surface is approximated by a few planar segments of different orientations (Wald & Heaton 1994; Delouis *et al.* 2002; Zeng & Chen 2002) but with piecewise constant strike and dip angles on each segment. In some studies the rake (slip) angle is allowed to vary along the rupture plane during the inversion, showing significant rotations of the slip vector in the rupture plane (Delouis *et al.* 2002; Zeng & Chen 2002). Nevertheless, these studies do not try to retrieve the possible strike and dip variations related to the rupture's non-planar geometry.

Furthermore, in the forward modelling of strong ground motions mainly planar ruptures or at most a few planar segments (Pulido *et al.* 2004) are usually considered even though such an approximation may have significant consequences on the synthetic seismograms. For example, some authors report problems related to large amplitude differences at horizontal components in their synthetics, which are not observed in real data. To solve this problem Zeng *et al.* (1995) suggest to include rake variations in the synthetic ground motion calculation. They illustrated the effect on ground motions only for one station for the Uttarkashi thrust fault earthquake of 1991 October 19, showing that the synthetics then have comparable amplitudes at the horizontal components. Others, for example, Pitarka *et al.* (2000) or Satoh (2002), suggest to use a radiation pattern that vanishes with increasing frequency to get a better fit of synthetic and observed data. We hypothesize that such a need may be induced by neglecting geometrical complexities in terms of strike and dip variations of the rupture.

In summary, although it is well understood that the geometrical complexities of a rupture are able to significantly influence both the rupture dynamics and the generated ground motions, they are commonly neglected or, as in the case of geometrically very complicated ruptures, the planar fault approximation is extended by using a few planar rupture segments to capture the overall geometrical structure. Such studies however do not take into account the rupture topology that may be very complicated at all scales as it is observed in the field and, therefore, may bias important conclusions. To our knowledge, a thorough quantitative study of the implications of complicated 3-D ruptures is still missing. It is also not clear if strike and dip variations projected on a perfectly planar fault may serve as a satisfying representation of a truly 3-D non-planar rupture surface in terms of the radiated wavefield.

Therefore, we present in this paper a systematic analysis of the effects of different kinematic models of finite-extent rupture sources with complicated rupture geometries on synthetic velocity seismograms and the corresponding amplitude spectra. The rupture topology is assumed to be a continuous surface with random deflections without any sharp kinks, that is, with varying but continuous strike and dip angles. Since we are interested in the effects of the non-planarity itself, we define a set of kinematic earthquake models characterized by the same seismic moment and duration but with various correlation lengths and amplitudes of the deflections. This way, the models are similar regarding their kinematic properties, while we remark that their underlying dynamic models may be substantially different. On this set of earthquake rupture models, we ap-

ply the highly accurate Discontinuous Galerkin method (Dumbser & Käser 2006) to numerically simulate ground motions on a number of receivers surrounding the rupture. After validating our numerical approach, we show the influence of the ruptures' non-planarities on the resulting ground motions with respect to the radiation from the perfectly planar rupture. Finally, we discuss possible implications of the observed effects for some seismological applications, namely strong ground motion simulations or seismic moment tensor and slip inversions.

2 MODELLING SETUP

2.1 Source–receiver geometry and the crustal model

The setup of our model is similar to the well-defined 3-D test problem Layer Over Half-space (LOH.2) proposed in the final report of the *LIFELINES PROGRAM TASK 1A01* (Day 2001) of the Pacific Earthquake Engineering Research Center. This test case was part of a multi-institutional code validation project with reference and quasi-analytical solutions. Our computational domain has a lateral extent of 60×60 km and reaches 30 km depth as sketched in Fig. 1(a). Note, that for clarity we only show one quarter of the computational domain. The material parameters of the top 1 km (Medium 1) and the half-space beneath (Medium 2) are also given in Fig. 1(a).

The seismic wavefield is recorded up to a simulation time of 15 s at 59 receivers on the free surface as indicated in Fig. 1(c). We remark, that the first 10 receiver locations are identical to the original setup of the LOH.2 test case (Day 2001), that is, $(x_i, y_i, z_i) = (i \cdot 600, i \cdot 800, 0)$ m, for $i = 1, \dots, 10$. Receivers 11–20 are positioned equidistantly along the x -axis from $x = -1$ to -10 km, receivers 21–30 have the mirrored positions of the first 10 receivers with respect to the x -axis and receivers 31–59 are located equidistantly along the y -axis from $y = -10$ to 18 km, extending 10 km to the left-hand side and to the right-hand side of the rupture plane. This way, we sample different directions with respect to the rupture orientation and also cover various distances in the fault-normal and fault-parallel directions.

2.2 The ADER-DG method

The computational domain described in Section 2 is discretized by an unstructured, tetrahedral mesh of 336 049 elements. The discretization on the free surface is shown in Fig. 1(b). Furthermore, the mesh is generated in a problem-adapted manner, so that in the zone of interest, where the source and receivers are located, the seismic waves travel through a very fine tetrahedral mesh with an average edge length of 350 m. Towards the model boundaries the mesh is rapidly coarsened up to edge lengths of 3500 m to reduce the number of total elements and, therefore, computational cost. Even though absorbing boundaries are applied, waves grazing almost parallel along numerical model boundaries still can produce numerical artefacts that could pollute the seismograms. Such effects are avoided by the enlarged computational domain and the mesh coarsening towards the boundaries as weak artificial reflections disappear due to numerical diffusion (Käser *et al.* 2007). The refined zone reaches a depth of 7 km to include the entire rupture surface.

The numerical simulations are carried out by the highly accurate ADER-Discontinuous Galerkin scheme (ADER-DG) using Arbitrary high order DERivatives. The ADER-DG method has been recently introduced to the field of numerical seismology (Dumbser & Käser 2006; Käser & Dumbser 2006). It solves the heterogeneous elastic wave equations formulated as a linear hyperbolic system (velocity–stress formulation) with arbitrary high order of

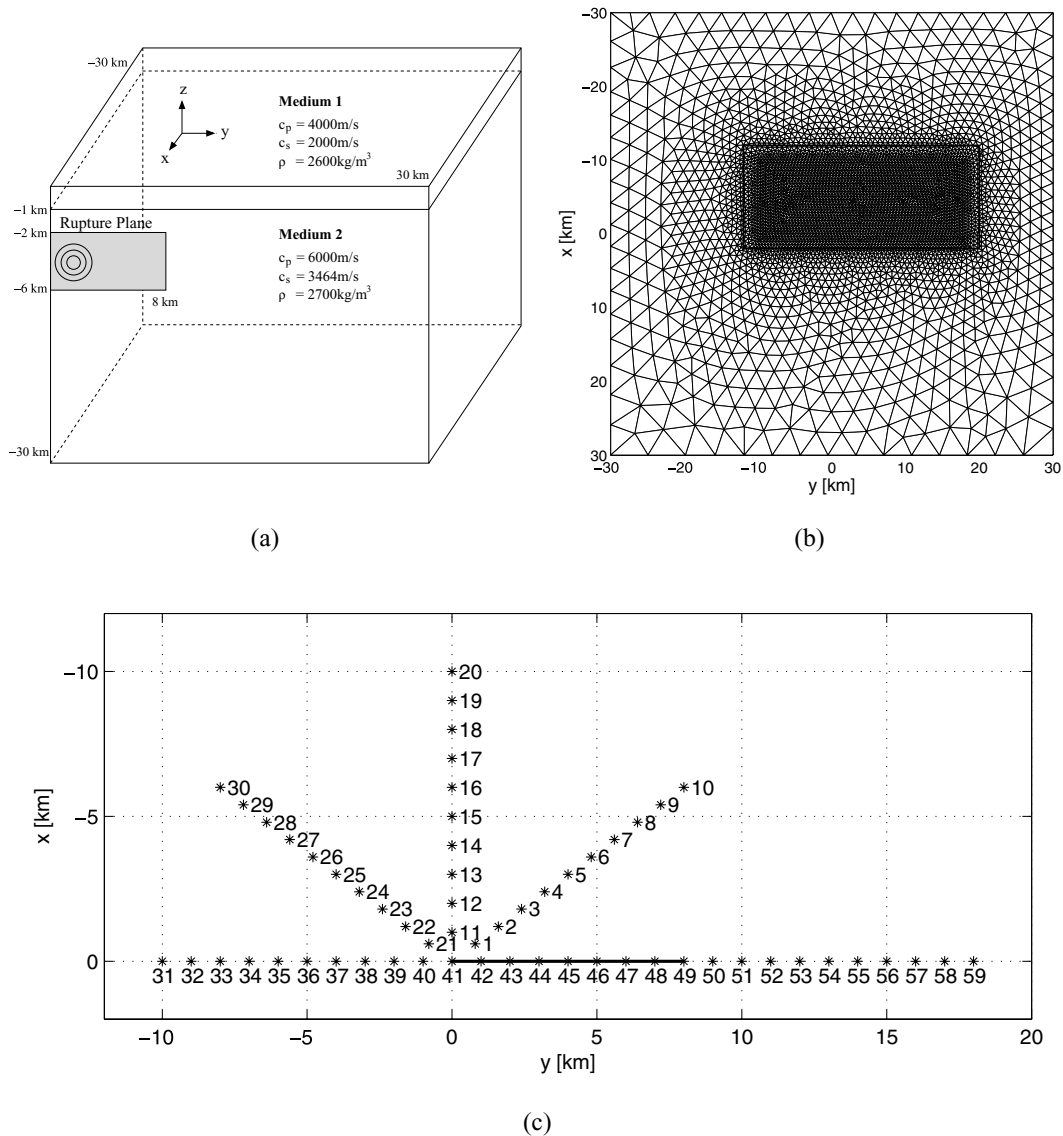


Figure 1. (a) Sketch of the model setup of the modified LOH.2 test case, corresponding to one quarter of the actual computational domain. (b) View of the gradually refined tetrahedral discretization of the computational domain from the top. We also indicate the zoomed section (thick rectangle) displayed in (c), where we show the map of the 59 receiver locations (stars) and the projection of the planar rupture on the surface (thick line).

accuracy in space and time on 3-D unstructured tetrahedral meshes. To this end, the numerical scheme combines the Discontinuous Galerkin Finite Element method with the ADER approach (Titarev & Toro 2002) using high order approximation polynomials and their derivatives for accurate time integration. In the DG framework the variables, that is, the velocities and stresses, are approximated by piecewise polynomials which allow for the introduction of discontinuities at element interfaces. Therefore, the well-established theory of numerical fluxes across element interfaces obtained by the solution of Riemann problems can be applied as in the finite volume framework (Toro 1999).

The main idea of the ADER approach is then a Taylor expansion in time in which all time derivatives are replaced by space derivatives using the so-called Cauchy–Kovalevski procedure which makes recursive use of the governing partial differential equation (Titarev & Toro 2002). The basis functions of the approximation polynomials are orthogonal in the tetrahedral reference element and, there-

fore, lead to diagonal mass matrices. Furthermore, increasing the polynomial approximation order exhibits spectral convergence on tetrahedral meshes (Dumbser & Käser 2006). The application of the ADER-DG method to a number of test cases (de la Puente *et al.* 2006; Dumbser & Käser 2006) and various comparisons to analytical and reference solutions obtained by other well-established methods confirm the performance of the ADER-DG method.

In particular, source terms and their heterogeneous properties in space and time as given by a kinematic rupture model of finite extent can be accurately included into the tetrahedral mesh due to the high resolution of the polynomial approximation inside each element. Hereby, the rupture surface is represented very generally by a set of point sources distributed arbitrarily in the computational domain and the space–time integration of the source contribution is accurately computed at each time step (Käser *et al.* 2007).

Let us emphasize that for the application of the ADER-DG method neither the source location nor the receiver locations have to

coincide with nodes of the tetrahedral mesh. This greatly simplifies the process of mesh generation when considering the non-planar rupture models as the mesh does not have to be aligned with the rupture surface. In fact, we are using the same tetrahedral mesh for all our non-planar rupture models.

2.3 Kinematic parameters of the finite source models

As stated above, for the ADER-DG method any kinematic rupture model is approximated by a grid of double couple (DC) point sources. Such an approximation for *perfectly planar* ruptures is a well-known problem in elastodynamics. It can be understood as approximative numerical solution of the representation theorem (Aki & Richards 2002). The theorem states that the i th component of displacement u measured at receiver location $\mathbf{x}$ can be obtained by an integral over the rupture surface S as

$$u_i(\mathbf{x}, t) = \int_S G_{ip,q}(\mathbf{x}, \mathbf{x}, t) * m_{pq}(\mathbf{x}, t) dS, \quad \text{with } i, p, q \in [1, 2, 3] \quad (1)$$

where $m_{pq}(\mathbf{x}, t)$ is the moment tensor density depending on time t and position $\mathbf{x}$ on the rupture surface and $G_{ip,q}(\mathbf{x}, \mathbf{x}, t)$ represents the elastodynamic Green's tensor. The last subscript after the comma denotes the spatial derivative with respect to x_q (i.e. $G_{ip,q} = \partial G_{ip}/\partial x_q$). Note that classical tensor notation is used, which implies the summation over each index that appears twice. The symbol '*' means the time convolution. For simplicity, we will restrict ourselves to DC sources, so that we can consider the quantity $m_{pq} dS$ in eq. (1) as an infinitesimally small DC source.

The integral over the whole rupture area S in eq. (1) can be divided into a sum over N usually equally sized rupture elements S_n , such that

$$u_i(\mathbf{x}, t) = \sum_{n=1}^N \int_{S_n} G_{ip,q}(\mathbf{x}, \mathbf{x}, t) * m_{pq}(\mathbf{x}, t) dS. \quad (2)$$

Assuming that the rupture element is small enough that the Green's tensor spatial derivatives do not change much with respect to $\mathbf{x}$ within each rupture element S_n , $G_{ip,q}$ can be taken out of the integral in eq. (2), leading to

$$\begin{aligned} u_i(\mathbf{x}, t) &\approx \sum_{n=1}^N G_{ip,q}(\mathbf{x}, \mathbf{x}'_n, t) * \int_{S_n} m_{pq}(\mathbf{x}, t) dS \\ &= \sum_{n=1}^N G_{ip,q}(\mathbf{x}, \mathbf{x}'_n, t) * M_{pq}^n(t), \end{aligned} \quad (3)$$

where $\mathbf{x}'_n$ denotes a particular location in the n th rupture element, usually its centre. When a planar fault is considered, the integral over the rupture element S_n in eq. (3) can simply be substituted by an equivalent DC moment tensor $M_{pq}^n(t)$ characterized by the corresponding total seismic moment, duration, etc. This way, the representation integral in eq. (1) over infinitesimally small DC sources is substituted by a sum over a finite number of elementary DC sources of finite size.

Let us explain the source geometry models adopted in our study. As stated in Section 1, we are dealing not with independent segments or sharp kinks, but with smooth, continuous rupture surfaces. We start with a *perfectly planar* vertical fault at $x = 0$ extending from $y = 0$ to 8 km and $z = -2$ to -6 km with the hypocentre located at $(x_h, y_h, z_h) = (0, 1, -4)$ km as shown in Figs 1(a) and (c). We discretize the rupture plane by a regular grid of 128×64 rupture elements in y - and z -direction, respectively, each consisting of a DC point source of size 62.5×62.5 m as discussed also in Section 2.4.2

Note that this spatial discretization is independent of the tetrahedral discretization of the computational domain. The rupture represents a right-lateral strike-slip earthquake with strike $\phi = 90^\circ$ and seismic moment $M_0 = 1.04 \times 10^{18}$ Nm. We associate the rupture (onset) time τ of each of the rupture elements proportional to the distance from the hypocentre assuming a constant rupture propagation speed of $v_r = 3$ km s $^{-1}$, that is,

$$\tau = v_r^{-1} [(y - y_h)^2 + (z - z_h)^2]^{1/2}. \quad (4)$$

Each rupture element has the same seismic moment $m_0 = M_0/(128 \times 64) = 1.27 \times 10^{14}$ Nm and the slip-rate function

$$s(t) = \frac{t - \tau}{T^2} \exp\left(-\frac{t - \tau}{T}\right) H(t - \tau), \quad (5)$$

where H is the Heaviside step function and $T = 0.1$ s is a parameter controlling the rise time.

Regarding the non-planar rupture models we use the same discretization as in the planar case. However, each of the rupture elements is now characterized by its local fault parameters and a so-called deflection, that is, the distance of the element's centre from the perfectly planar surface at $x = 0$ as shown in Fig. 2. These deflections are created using a random field generator following a similar approach as previously applied for heterogeneous slip distributions (Gallovič & Brokešová 2004). First, random numbers are prescribed to each of the rupture elements. Then this white noise is transformed to the spatial Fourier domain. Here the amplitude spectrum is modified by a k^{-3} function

$$P(k_y, k_z) = \left[1 + \sqrt{\left(\frac{k_y L}{K}\right)^2 + \left(\frac{k_z W}{K}\right)^2} \right]^{-3}, \quad (6)$$

where k_y and k_z are wavenumbers in the strike and dip directions, respectively. Parameter K controls the ratio between the correlation length of the random field and the rupture length $L = 8$ km and width $W = 4$ km. The modified spectrum is then high-cut filtered just below the Nyquist wavenumber and Fourier transformed back to the spatial domain. Finally, the random field root mean square (rms) responsible for the strength of the deflection in x -direction is adjusted afterwards according to the desired value. As we are considering approximations of a smooth rupture, the spatial variations of strike and dip due to the source geometry are computed for each rupture element by the spatial derivative of the deflection field in the strike and dip directions, respectively. As there are no discontinuities in the rupture geometry, the strike and dip variations are also continuous, characterized by k^{-2} decay in the strike and dip direction, respectively.

Concerning the remaining kinematic properties of the rupture elements of all non-planar rupture models (i.e. rupture time, seismic moments, slip velocity function), we keep them as in the case of the perfectly planar rupture. Let us remark that depending on the non-planarity of the rupture surface, the rupture propagation speed, in fact, varies slightly between different elements. This way, however, all source models have clearly the same total duration.

Let us discuss the final scalar seismic moment of the non-planar rupture models. We find that they are not the same as for the perfectly planar rupture. To analyse this, we sum up all the seismic moment tensors $M_{pq}^n(t = 0)$, see eq. (3). In all cases the final moment tensor corresponds again to a pure right-lateral vertical strike-slip earthquake as for the planar rupture model, however with lower scalar seismic moment. Therefore, we define a so-called *moment correction factor* as the moment ratio between the given planar model and each non-planar one. Then, in order to analyse ground motions

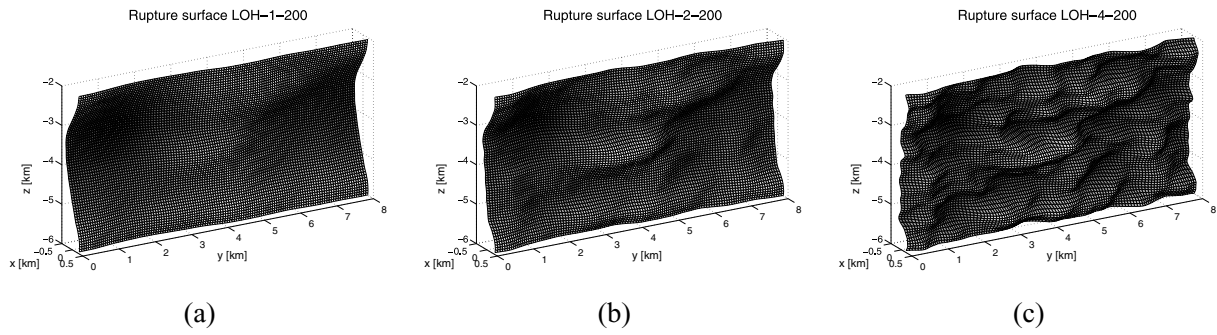


Figure 2. Rupture surfaces with different correlation lengths. Note that the rms value and the Fourier phase spectrum are the same for all three cases (a), (b) and (c). The top end of the rupture surface could be considered as a fault trace that would be visible on the surface if the rupture reached it.

Table 1. Spatial variations of the rupture model parameters with respect to the perfectly planar model adopted in this study.

Name	K	Deflections (m)		Strike ($^{\circ}$)		Dip ($^{\circ}$)		Rake ($^{\circ}$)		Moment correction factor
		rms	Max	rms	Max	rms	Max	rms	Max	
LOH-0-000	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	1.00
LOH-1-200	1	200	513	7.4	20.5	17.0	37.4	0.0	0.0	1.09
LOH-2-200	2	200	640	12.9	38.4	23.9	56.0	0.0	0.0	1.20
LOH-4-050	4	50	164	6.6	23.5	11.8	35.8	0.0	0.0	1.05
LOH-4-100	4	100	327	12.8	41.0	21.6	55.3	0.0	0.0	1.19
LOH-4-200	4	200	654	23.3	60.1	35.3	70.9	0.0	0.0	1.72
LOH-4-200P	4	0	0	23.3	60.1	35.3	70.9	0.0	0.0	1.72
LOH-4-015R	4	0	0	0.0	0.0	0.0	0.0	15.0	46.0	1.03

caused by earthquake models characterized by the same seismic moment, we correct the seismograms by multiplying them by the corresponding moment correction factor.

Note that preserving the same rupture times, corrected seismic moments and slip functions for the rupture elements of the different rupture models ensures the representation of *equivalent* earthquake sources in terms of the total seismic moment and duration. Therefore, we can separately study the effects of different rupture geometries themselves.

In Table 1 we show the variations of the parameters of the different rupture models adopted in this study. The models differ in their correlation lengths given by parameter K of eq. (6) and rms of the deflections. The models are denoted as LOH- K -XXX, where XXX denotes the rms value in metres. The model LOH-0-000 represents the original perfectly planar rupture of the LOH.2 test case. Table 1 also gives the corresponding Moment correction factors discussed above. To have a consistent set of source models, we use the same initial random number distribution (see the random field generation above) for all the models. To illustrate the effect of the parameter K , Fig. 2 displays three different rupture surfaces characterized by the same rms value and various values of K . The reader can easily imagine how the rms value alters the deflections as it acts simply as a multiplicative factor on the deflections in x -direction.

Additionally, our study employs two other models given in Table 1. The model LOH-4-200P corresponds to the model LOH-4-200, where the local strike and dip variations are projected onto the perfectly planar rupture model, that is, the deflections are set to zero. The model LOH-4-015R is similar to the perfectly planar model LOH-0-000, however, instead of generating various deflections the random field is used to generate rake variations with $K = 4$ and an rms value of 15° .

2.4 Validation

2.4.1 ADER-DG versus discrete wavenumber

To confirm our statements about the accurate treatment of the geometrically complicated rupture models, we first validate the ADER-DG approach for the intended study as shown in the following section.

The ADER-DG method for tetrahedral meshes has been validated thoroughly by a number of model problems, for example, the original LOH test cases (Day 2001), in previous papers (de la Puente *et al.* 2006; Dumbser & Käser 2006; Käser *et al.* 2007). Nevertheless, to underline the accuracy and performance of the scheme, we also validate the method for this special case of kinematic non-planar rupture models presented here. Therefore, we compare the velocity seismograms obtained by the ADER-DG $\mathcal{O}4$ scheme, that is, fourth order of accuracy in space and time, for the LOH-4-200 model with the roughest rupture geometry with reference solutions computed by the Discrete Wavenumber (DWN) method (Bouchon 1981). We remark that the seismograms of both methods are filtered by the same low pass filter at 5 Hz. As an error norm we define the relative seismogram misfit energy

$$E = \sum_{j=1}^{n_t} (s_j^{\text{ADER-DG}} - s_j^{\text{DWN}})^2 / \sum_{j=1}^{n_t} (s_j^{\text{DWN}})^2, \quad (7)$$

where $n_t = 1501$ is number of time samples in the seismograms, $s_j^{\text{ADER-DG}}$ is the j th value of numerical ADER-DG $\mathcal{O}4$ seismogram and s_j^{DWN} is the corresponding reference value of the Discrete Wavenumber seismogram.

In Fig. 3, we show the results of E for the three velocity components obtained at all 59 receivers as indicated in Fig. 1(c). We

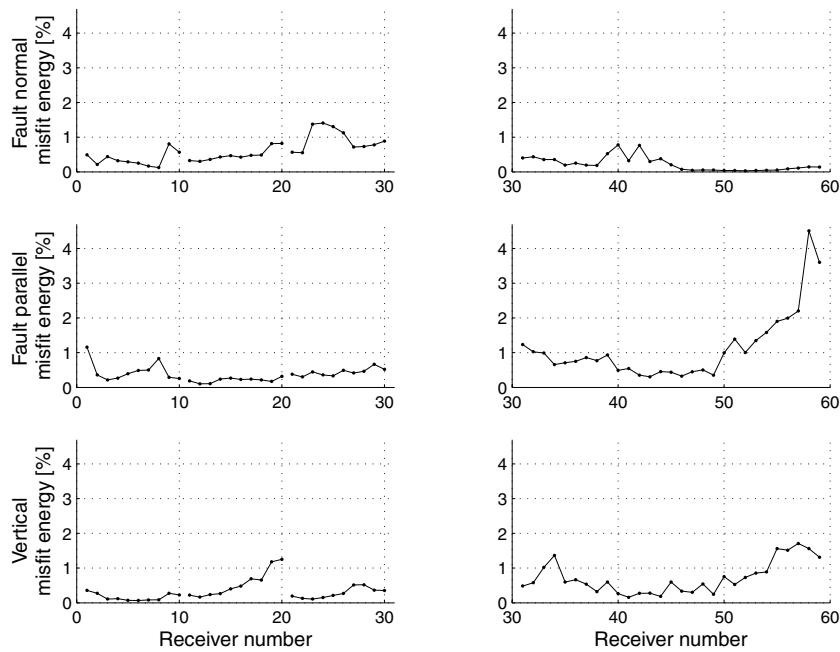


Figure 3. Seismogram misfit energy E between the Discrete Wavenumber method and the ADER-DG $\mathcal{O}4$ method for the rupture model LOH-4-200.

observe that E typically has values around 1 per cent, however, an increase of errors away from the rupture is visible especially from receiver 50 to 60. Based on these observations, we choose four receivers, namely no. 1, 20, 34 and 58, where relatively large misfits E appear and which cover different directions and distances with respect to the rupture position. For these receivers, Fig. 4 shows the comparison of the ADER-DG $\mathcal{O}4$ and the DWN seismograms indicated by the model notation LOH-4-200. As one can see, the fit is almost perfect, which is in agreement with the low values of E . To further support our statement that the ADER-DG $\mathcal{O}4$ method correctly takes into account the non-planar rupture, we compare these seismograms also with those obtained for the model LOH-4-200P where the strike and dip variations are the same, but the locations of the rupture elements are projected onto the perfectly planar surface (see Table 1). As shown in Fig. 4 the ADER-DG $\mathcal{O}4$ method correctly resolves the differences between the truly deflected LOH-4-200 model and the projected one LOH-4-200P although these differences are relatively small. We remark, that these differences will be further discussed later in the text.

We summarize that the above comparisons confirm that even in the discussed cases of relatively large misfits the ADER-DG $\mathcal{O}4$ results are very satisfying and, therefore, our results will be reliable at least up to a frequency of 5 Hz. The validation demonstrates that the highly accurate ADER-DG $\mathcal{O}4$ method is well suited for this study as it correctly resolves important details in the synthetic seismograms.

2.4.2 Rupture geometry approximation

As stated above, we approximate the non-planar rupture geometry by a grid of elementary DC point sources. However, it is not straightforward how dense this grid spacing should be chosen to correctly account for the deflections effects on the recorded ground motion signals. In other words, we have to be sure that our approximation of the continuous, deflected rupture surface corresponds to the model we claim to study in terms of the radiated wavefield.

Concerning the error related to the approximation in eq. (3), Spudich & Archuleta (1987) have shown that the error is given mainly by neglecting the time variations of $G_{ip,q}$ within each rupture element. The associated error then depends, among others, on the temporal resolution (frequency) and the receiver location (source directivity). Given a maximum considered frequency, Spudich & Archuleta (1987) have shown that the fault has to be sufficiently sampled by the elementary DC sources at the shortest wavelength considered in the model, which is given by the maximum frequency and the lowest velocity in the source area, that is, usually the rupture velocity. Additionally, they have shown that although the discretization error also depends on other factors such as the receiver position, the error generally decreases with decreasing frequency.

In our case of the *non-planar* rupture, the situation is even more complicated due to the fact that the elementary DC sources with an associated moment tensor $M_{pq}^n(t)$ should approximate non-planar elements of a deflected rupture surface as defined by eq. (3). As such, the non-planar elements do not radiate as single DC sources but in fact represent a superposition of infinitesimally small DC sources of slightly varying orientation, that is, of varying moment tensors. Therefore, their radiated wavefield corresponds rather to a point source characterized by a tensorial sum of the infinitesimal DC moment tensors. Therefore, the approximation using DC point sources could bias the resulting wavefield in the whole frequency band in addition to the frequency dependent error discussed above. On the other hand, since the representation theorem in eq. (1) is a linear function of $m_{pq}(\mathbf{x}, t)$, the approximate solution in eq. (3) will still converge with increasing refinement of the rupture discretization, that is, with increasing N .

Being aware of this issue, we validate the chosen approximation of the rupture geometry (128×64 rupture elements) by comparing the synthetic seismograms with those obtained for a refined discretization of the rupture model. Therefore, we refine the model with the roughest rupture geometry LOH-4-200 by Fourier interpolation on a 4×4 denser grid. Fig. 5 shows the seismogram misfit energy E between the resulting seismograms in a similar way as for

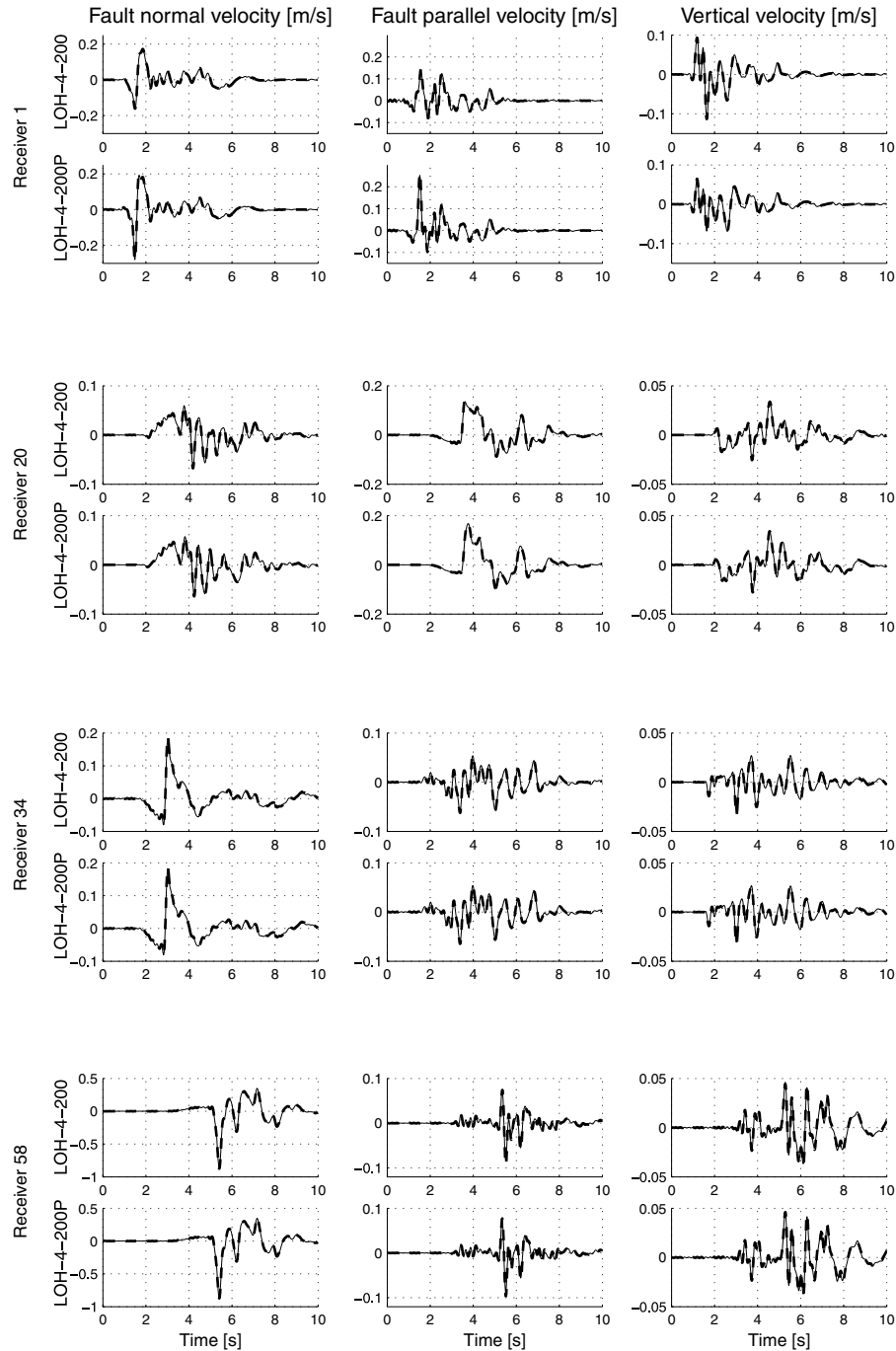


Figure 4. Validation of the numerical computations by comparing the ADER-DG $\mathcal{O}4$ (solid) and the Discrete Wavenumber (dashed) results for receivers 1, 20, 34 and 58 for the rupture surface models LOH-4-200 (non-planar) and LOH-4-200P (projected).

the case of ADER validation in Fig. 3. The plot exhibits a relatively strong dependence of E on the receiver position, which however does not follow a clear systematic trend. The maximum E reaches about 7 per cent with a typical value around 1–2 per cent, which is relatively small and comparable to the misfits between the ADER-DG $\mathcal{O}4$ and DWN method presented in Section 2.4.1

As an example, we present in Fig. 6 the comparison of velocity waveforms and their Fourier spectra for receiver 1, which is characterized by a large misfit value E at the fault parallel component as observed in Fig. 5. As one can see, the fit between the seismograms

for our actual discretization of 128×64 rupture elements and the refined one is almost perfect at the fault normal and vertical component, while the first significant fault parallel velocity amplitude deviates clearly. This can be also seen in the corresponding Fourier spectra comparison shown in Fig. 6 bottom. The overall fit is, as in the time domain, almost perfect. However, let us emphasize the spectral difference for the fault parallel and especially for the vertical component in the low-frequency range. As discussed above, we attribute these effects to the error caused by the approximation of the non-planar rupture elements by pure DC sources. This effect

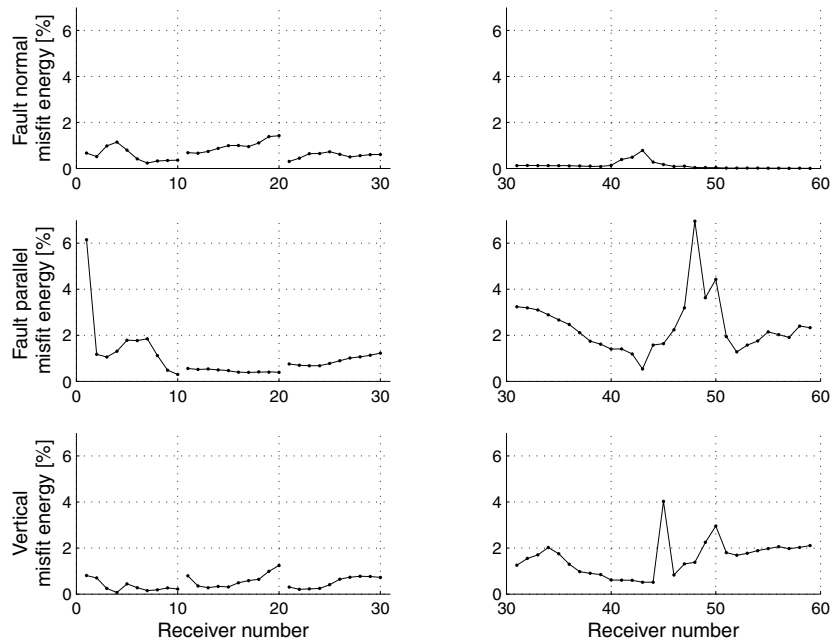


Figure 5. Seismogram misfit energy E between the used discretization of the rupture surface LOH-4-200 and its 4×4 finer discretization.

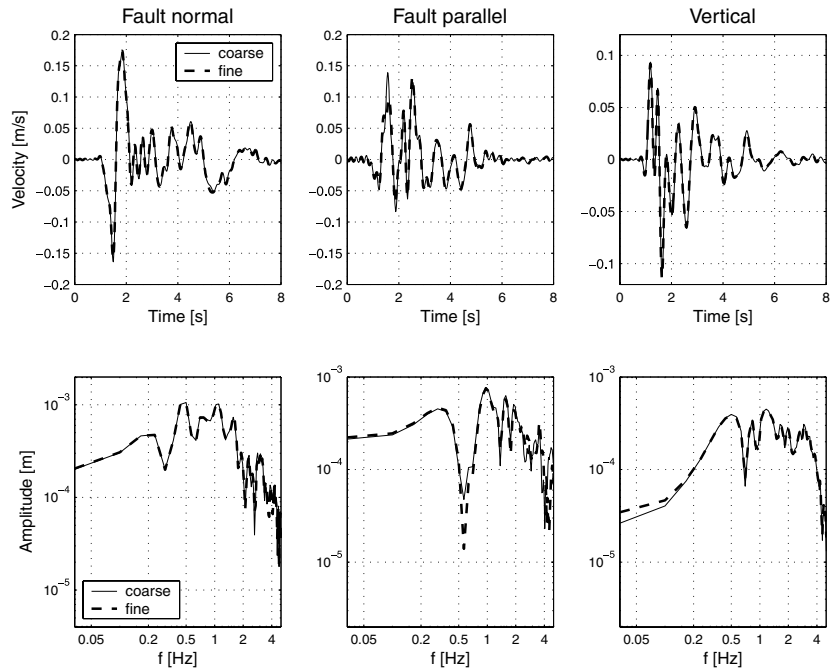


Figure 6. Comparison of seismograms (top) and spectra (bottom) of the used approximation for model LOH-4-200 and the 4×4 refined discretization of the rupture surface for receiver 1.

is also related to the sensitivity of the low-frequency motion to the rupture deflections and is discussed in more detail in the following section.

Despite the observed but small differences between the seismograms obtained with our actual discretization of the rupture model and the refined one, we consider the coarser discretization very satisfactory. Therefore, we will use the discretization into 128×64 rupture elements in all of the following simulations.

3 EFFECTS OF RUPTURE GEOMETRY VARIATION

After validating our numerical approach in the previous section, we present in the following our main results obtained by the ground motion simulations considering the different rupture models discussed above and summarized in Table 1. We choose the velocity seismograms and the corresponding amplitude spectra for receivers 1, 20,

36 and 54 to cover various distances and directions with respect to the rupture and to highlight the differences between off-fault and on-fault receivers. Note that the word on-fault is to be understood in a more general sense since by on-fault receivers we mean those located along strike direction as shown in Fig. 1(c). For convenience, in the following we will refer to the fault normal, fault parallel and vertical velocity components as FN, FP, and V components, respectively.

3.1 Effect of rms on the seismograms

In our first investigation, we keep the correlation length fixed at $K = 4$ and analyse the influence of the rms value of the deflections. The different components of the velocity seismograms presented in Fig. 7(a) show the changes in the waveforms when the rms value is gradually increased, that is, when the amplitude of the rupture model deflections is increased. Furthermore, for comparison we present the seismograms of the equivalent perfectly planar rupture model LOH-0-000 in Fig. 7(a). Note that for the on-fault receivers 36 and 54 the FP and V components for the LOH-0-000 case should theoretically be exactly zero, however, a very small signal can be observed, which is due to the irregularity of the tetrahedral mesh. However, the amplitude of these numerical artefacts is very small and does not affect the following investigations. Furthermore, we remark that all four seismograms inside each of the 12 panels are plotted on the same scale with zero referring to the onset of the LOH-0-000 seismogram. All other seismograms corresponding to increasing rms values are shifted by a constant to facilitate the visual comparison of the waveforms.

As we can see in Fig. 7(a), the introduction of the rupture non-planarity changes the seismograms significantly compared to the planar LOH-0-000 case for most of the receiver components. In particular, we observe that the waveforms of the FN and V components of the off-fault receivers 1 and 20 change gradually with increasing rms and show richer structure for enhanced geometrical complexity. An interesting observation in the FP and V components of receiver 1 is that the energy is released in a longer time window for the geometrically more complicated models. For the perfectly planar model LOH-0-000 we see a more pulse-like energy release on these components. As regards the on-fault receivers 36 and 54, the introduction of deflections, compared to the planar LOH-0-000 case, results in the generation of signals on their FP and V components. Their amplitudes increase with increasing rms values. On the other hand, at the same receivers the amplitudes and waveforms on the FN components remain almost unchanged.

3.2 Effect of correlation length on the seismograms

In Fig. 7(b) we show the results when keeping the rms values constant at 200 m and increasing the correlation length by decreasing K , that is, reducing the spatial wavelength of the geometrical variations as displayed in Fig. 2. In addition, we show again the synthetics obtained for the planar LOH-0-000 model. For better comparison the individual plots for a given receiver and component in Fig. 7(b) are scaled in the same way as in Fig. 7(a). We can see that introducing deflections of any correlation length has a significant effect on most of the seismograms as the waveforms change their characteristics compared to the perfectly planar model LOH-0-000. However, these effects appear to a different degree at different stations and components. A remarkable feature is that the behaviour of the FN components of all the receivers is very similar when changing K or

rms values (compare Figs 7a and b). Their waveforms do not change rapidly when the non-planar fault is introduced regardless the actual value of K . The maximum amplitudes of the FN component seem to be only slightly affected by variations in K , but the waveforms show richer structure at the off-fault receivers 1 and 20, similar to Fig. 7(a). On the on-fault receivers 36 and 54 the amplitudes and waveforms of the FN component remain basically unchanged with increasing K . Similarly, the behaviour of the FP and V components of the most distant receiver 20 is almost the same when changing the K value (Fig. 7b) or the rms value (Fig. 7a). This suggests that the discussed components are sensitive to the actual correlation length almost in the same way as to the rms values. As regards the waveforms for other receivers and components, they change rapidly when the non-planar fault is introduced regardless of the actual value of K . For example, note the originally zero amplitudes of the FP and V components at the on-fault receivers show some signal when the non-planar fault is introduced regardless of the particular K value. Concerning the latter, the dependence of the waveforms on the K value is rather modest. Perhaps most interesting is the richer structure of the seismograms on the FP component of station 36 for increased K .

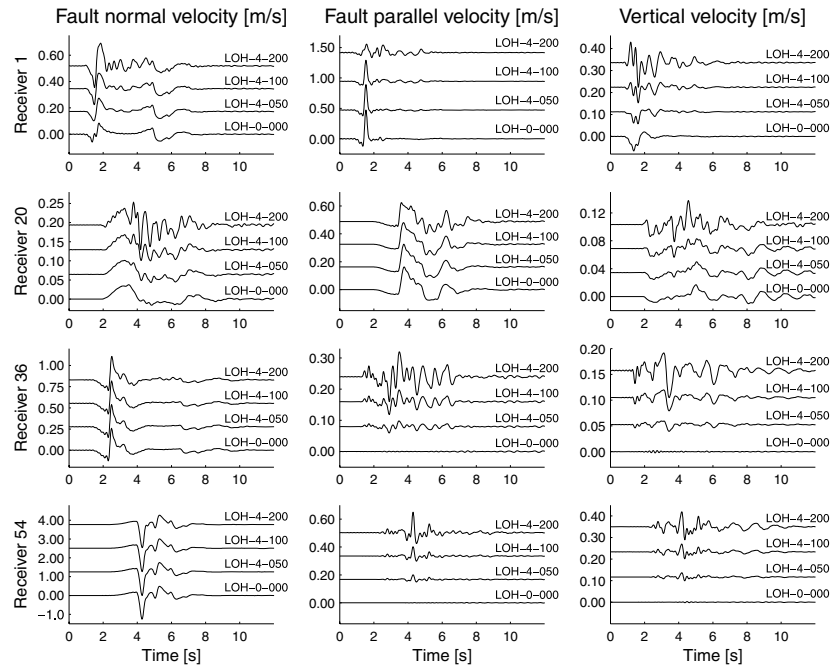
3.3 Effect of rms on the frequency spectra

Here, we are investigating the Fourier spectra of the seismograms discussed above. In Fig. 8(a) we display the amplitude spectra of the velocity seismograms shown in Fig. 7(a). Note, that the blue lines for the LOH-0-000 model at the FP and V components of the on-fault receivers 36 and 54 should theoretically again be zero. However, we leave them in the plots for completeness as they show the small numerical effects due to the irregular tetrahedral mesh. However, they will not be discussed in the following.

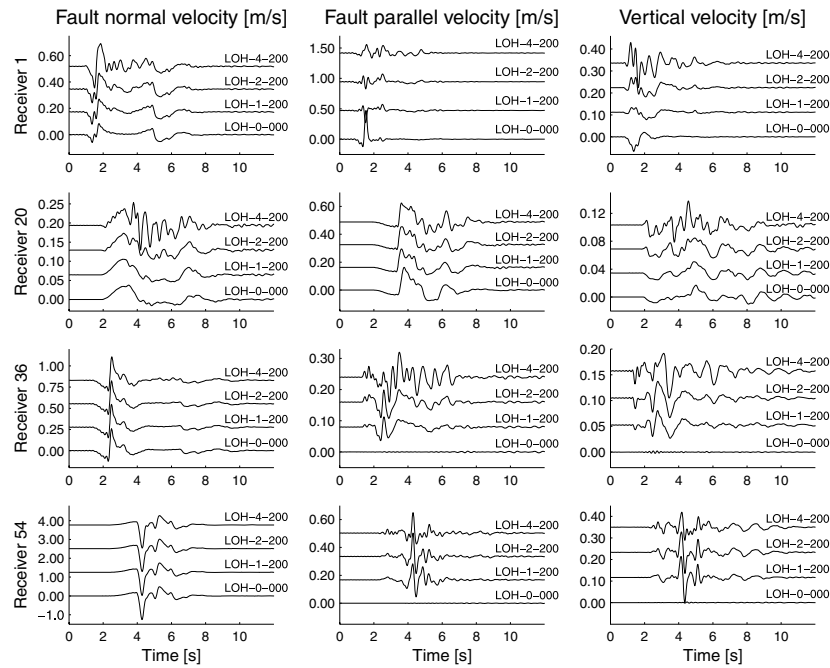
As in the previous plots of Fig. 7(a) we first keep the correlation length fixed ($K = 4$) and vary the rms value. The first and most important observation is that introducing deflections of the rupture surface can affect the whole frequency band at some receivers and not only the high-frequency range. In particular, at receiver 1 close to the rupture the amplitudes of the FN and V components in the high-frequency range approximately above 0.5 Hz are increasing with increasing deflections. The FP component shows the opposite trend in this frequency range. On receiver 20, much further away from the rupture, the low-frequency amplitudes of all components are not affected by the geometrical variations via the rms values, whereas the high-frequency amplitudes are systematically increased. For the on-fault receivers 36 and 54 the amplitude spectrum of the FN component remains basically unaffected by deflections. However, the spectra of the FP and V components show a very clear trend as the amplitudes in the whole frequency band strongly increase with higher rms values.

3.4 Effect of correlation length on the frequency spectra

In Fig. 8(b), we display the amplitude spectra of the velocity seismograms shown in Fig. 7(b) where we keep the rms value fixed and vary K . Again, the first and most important observation is that the geometrical complexity can affect the whole frequency band in some cases. In the high-frequency band above 0.5 Hz at the off-fault receivers 1 and 20 we observe increasing amplitudes for increasing K on the FN and V components. This trend is less clear at the FP component. In the low-frequency band especially the V component of receiver 1 is strongly affected where amplitudes decrease



(a)



(b)

Figure 7. Synthetic velocity seismograms obtained for rupture surfaces of various geometrical parameters with (a) different rms value of the deflections and (b) different correlation lengths.

systematically with increasing K . However, we mention that this is not the case if different random numbers are used to generate the rupture model. At the distant receivers 20 the low-frequency band is again almost unaffected. The spectra of the FN component at the on-fault receivers 36 and 54 remain basically unchanged with varying K , similar to the rms variations. However, the situation is less clear

at their FP and V components at these receivers as the increase of K does not show any clear systematic trend in the spectra in contrast to the previous case of fixed K and varied rms value in Fig. 8(a). Finally, let us emphasize that similar to the seismograms themselves (compare Figs 8a and b) also the spectra of the FN components at all receivers and the spectra of all components at the distant receiver

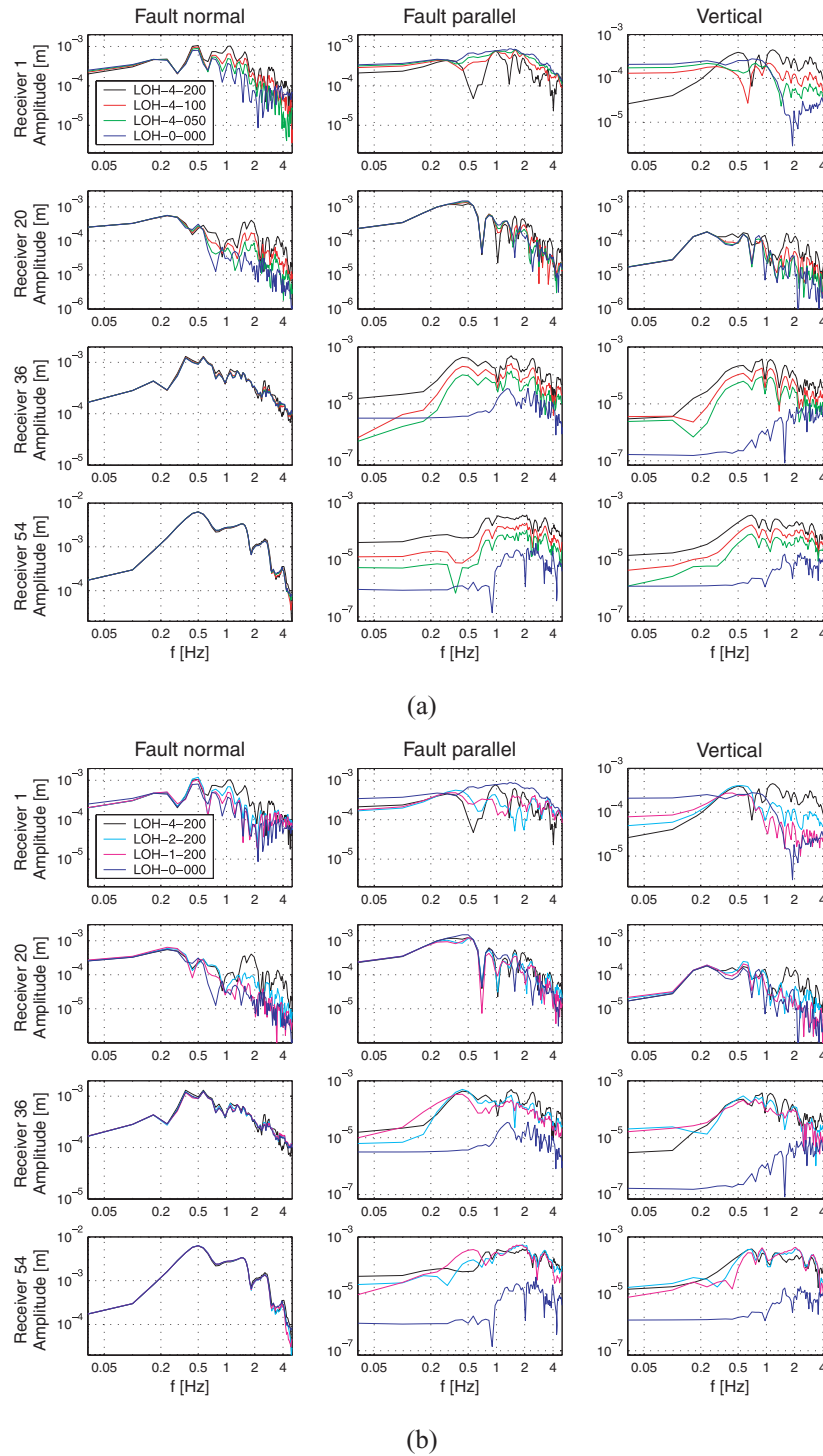


Figure 8. Comparison of the Fourier amplitude spectra of the synthetic velocity seismograms shown in Fig. 7, obtained for the rupture surfaces with a variation of the geometrical rupture parameters using (a) different rms value of the deflections and (b) different correlation lengths.

20 are remarkably insensitive to whether the rms or K values are changed as both variations seem to have very similar effects.

3.5 Effect of rms on the peak ground velocity

Furthermore, we examine the peak ground velocity (PGV) values of the three velocity components obtained at all 59 receivers. For

the case of varying rms values, Fig. 9(a) shows that the PGV values of the 30 off-fault receivers in the left panels predominantly decrease with increasing distance from the hypocentre. Furthermore, increasing the geometrical complexity by means of increasing rms values leads to a better balance of FN and FP components at basically all receivers. In particular, at the off-fault receivers we can observe a gradual reduction of higher PGV values, for example, of

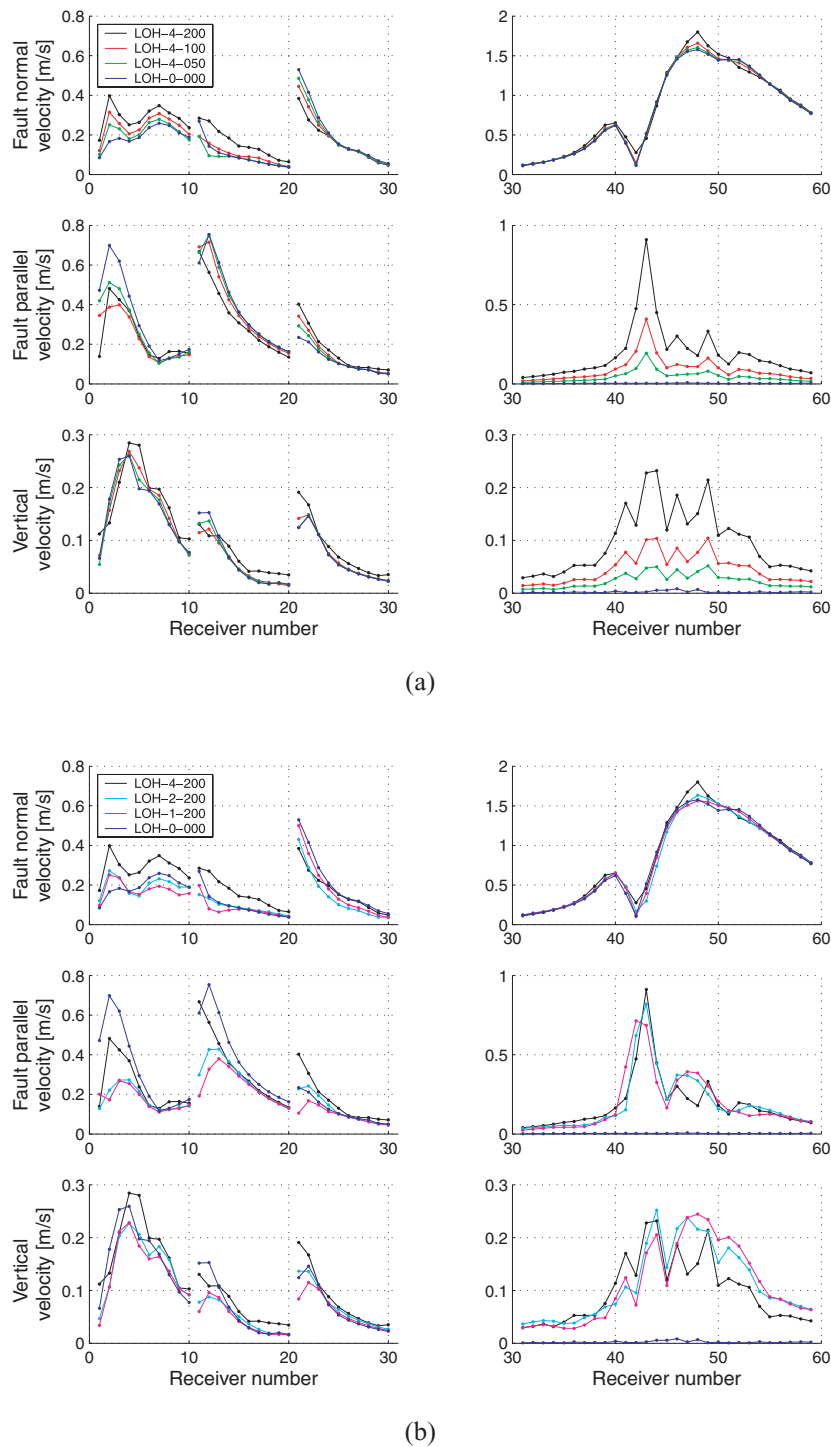


Figure 9. Comparison of the peak ground velocity of the synthetic seismograms, obtained for the rupture surfaces with a variation of the geometrical rupture parameters using (a) different rms value of the deflections and (b) different correlation lengths.

the FP components at receivers 1–20 and the FN components of receivers 21–30. In contrast, the smaller PGV values, for example, of the FN components at receivers 1–20 and the FP components of receivers 21–30 are gradually increased. However, the V component at off-fault receivers only shows a systematic trend at receivers 1–10. The on-fault receivers 31–59 originally have FP and V components of zero amplitudes for the perfectly planar model LOH-0-000, but adding deflections of increasing rms values increases the amplitudes

in a very regular manner. These effects are more pronounced above the rupture from receiver 41 to 49 and rapidly decay with distance along the fault line, see also Fig. 1(c). The FN component, however, is less affected and shows slightly increased PGV values with increasing rms mainly above the right end of the rupture plane, that is, at receivers 47–49. Furthermore, the local minimum of the PGV values at receiver 42 nicely indicates the location of the hypocentre. Generally, Fig. 9(a) confirms our previous statement that the

increasing complexity of the geometrical model tends to balance the PGV differences in the three velocity components of all receivers.

3.6 Effect of correlation length on the peak ground velocity

Considering the results obtained for the rupture models with varying K in Fig. 9(b), the behaviour of the PGV values is less clear compared to the previous case in Fig. 9(a). However, the roughest model LOH-4-200 leads to larger PGV values of the FN component at the off-fault receivers 1–20 and the FP component at receivers 21–30. In contrast, the strongest reduction of PGV values of the FP component at receivers 1–20 and FN component at receivers 21–30 is observed for lower K values. Again no obvious trend can be observed for the V component. In strong contrast to the previous rms variations in Fig. 9(a) the K variations also do not show systematic changes at the on-fault receivers 31–59. Regarding the FN component the behaviour with increasing K is similar to the one of increasing rms values. However, the amplitudes of the FP and V components along the fault seem to jump from exactly zero for the LOH-0-000 case to some larger values when introducing rather smooth rupture complexity with $K = 1$, whereas a further increase of K has no systematic effect on the amplitudes. Finally, in analogy to Figs 7 and 8, the PGV values change less systematically with varying K than with varying rms values.

A quite surprising observation in both Figs 9(a) and (b) is also the behaviour of the PGV amplitudes of the FP components for the planar LOH-0-000 model. Moving just slightly away from the fault line (e.g. from 41 or 42 to receivers 1, 11 or 21), the PGV values basically *jump* from zero values on the fault to values that are even larger than those of the corresponding FN component. However, they quickly decay with increasing distance from the fault. This effect is less pronounced for geometrically more complicated rupture surfaces.

3.7 Real versus projected geometry variations

For completeness, our next test case concerns the question of whether the differences in the seismograms obtained for planar and non-planar ruptures are driven predominantly by the actual rupture geometry or by the strike and dip variations only. In other words, one can ask if a planar model including the actual geometrical complexities of the rupture only in terms of strike and dip variation will give the same results, or, if it is really necessary to correctly take into account the deflections in x -direction. This might be important for many numerical methods that have difficulties in following a deflected rupture surface with their discretization, for example, regular Cartesian Finite Difference grids. Therefore, we simplify our roughest rupture model LOH-4-200 in the way that we project the locations of all the elementary DC sources representing the rupture to a perfectly planar surface at $x = 0$, while keeping the strike and dip variation of the original LOH-4-200 model. This way, all spatial deflections are zero, however, each rupture element still carries the strike and dip variations of the LOH-4-200 model.

The results for the projected model are shown in Fig. 10 and are denoted as LOH-4-200P. We observe, that the differences between the projected LOH-4-200P and the deflected LOH-4-200 model are very small. However, coming back to Fig. 4 of the validation Section 2.4 and having a closer look at some seismograms, we observe some interesting details. The seismograms obtained for the LOH-4-200 and LOH-4-200P models at receivers 1 show quite clear amplitude differences. Furthermore, we observed that at receiver 20 the error is mainly due to small phase shifts of up to 0.05 s in the first half of the seismograms. The fit at receivers 36 and 54, however, is almost perfect.

To further investigate the errors associated with the projection approximation, we plot the relative seismogram misfit energy E of eq. (7) for all 59 receivers in Fig. 11 in a similar manner as for the validation in Section 2.4. We observe that the largest misfit is obtained for the off-fault stations 1–30. Looking closer on the

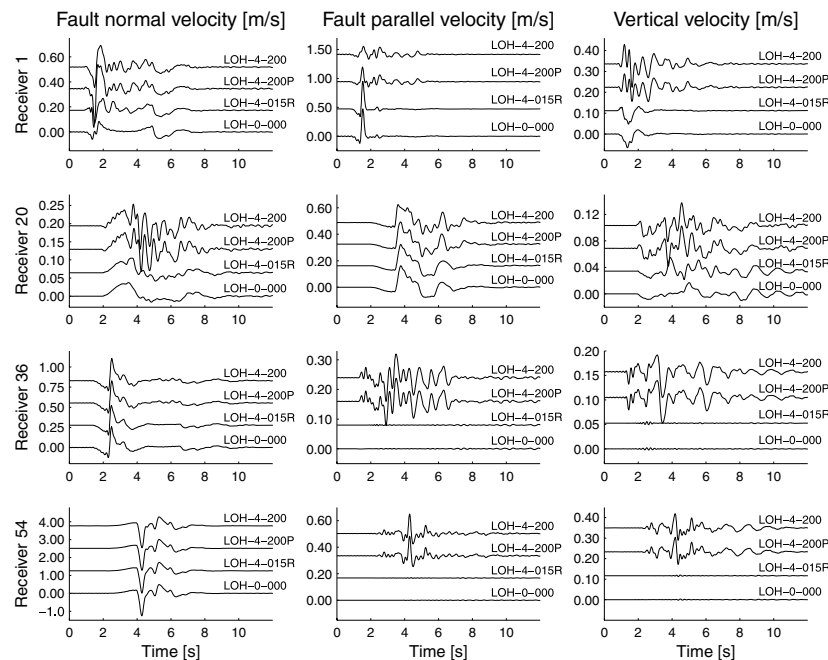


Figure 10. Comparison of the effect of rake variations and the projection of the strike and dip parameters to a planar rupture surface. Note that the seismograms for models LOH-4-200 and LOH-4-200P at receivers 1 and 20 are the same as in Fig. 4.

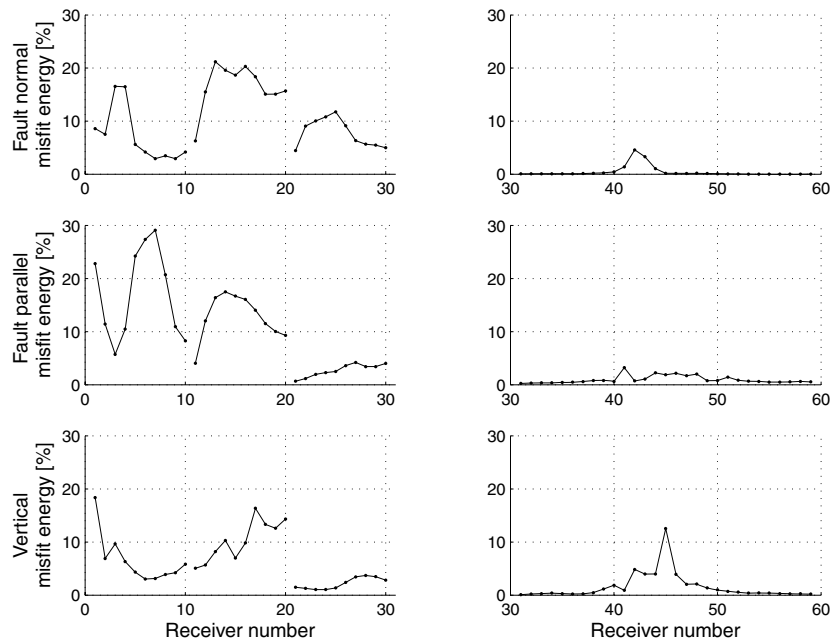


Figure 11. Seismogram misfit energy between the truly deflected rupture surface LOH-4-200 and the projected one LOH-4-200P.

differences of the corresponding waveforms, we observe that with increasing perpendicular distance from the rupture the misfit at some components is more and more dominated by small phase shifts of up to 0.05 s, for example, at receivers 7, 13 and 20 in approximately the first half of the seismogram. Contrary to that, the misfit E for the on-fault receivers is remarkably smaller. The seismograms at the on-fault receivers obviously show larger difference between the truly deflected LOH-4-200 and the projected, perfectly planar LOH-4-200P models only above the rupture location between receivers 41 and 49. We consider this as surprising since it means that the waveforms are less sensitive to the actual rupture geometry, in terms of the misfit energy E , right above the fault, while they become more sensitive with larger perpendicular fault distance. We have checked this result by the DWN method coming to the same conclusion. Nevertheless, despite the fact that we cannot easily explain this behaviour, we claim that the major properties of a geometrically complicated deflected rupture surface can be taken into account even with a simpler projected model. However, care has to be taken if very high accuracy is required or amplitudes and waveforms want to be analysed or interpreted in detail.

3.8 Effect of rake variations

For our final test case, we have computed a set of synthetic seismograms for the perfectly planar rupture, that is, no deflections in x -direction and constant strike and dip, where we apply the random field to generate rake variations with $K = 4$ and rms value of 15° . This model is indicated by LOH-4-015R as discussed in Section 2.3. The results are shown in Fig. 10 together with the seismograms obtained for the planar LOH-0-000 model for comparison. Note, that the scaling of the amplitude axes is identical to Fig. 7. In particular, only the FN component at receiver 1 and the FN and V components at receiver 20 show slightly richer structure, whereas the other components and receivers basically remain unchanged. Especially, the on-fault receivers do not show any signal on the FP and V components as the rupture is still perfectly planar like for the LOH-0-000

case. Therefore, it seems that pure rake variations do not affect the seismograms to the same extent as the introduction of deflections leading to non-planar rupture surfaces.

In summary, we have systematically examined a set of geometrically different rupture models (Table 1) by observing their effects on all three components of the velocity seismograms obtained at a number of receivers covering various distances and directions with respect to the source location. Furthermore, we have evaluated the influence of increasing geometrical complexity on the amplitude spectra and the PGV values. In the following we discuss our observations and draw conclusions regarding the possible implications for various fields of seismology.

4 DISCUSSION AND IMPLICATIONS OF THE RESULTS

We have presented a numerical study of the influence of possible geometrical complexities of rupture surfaces on the generated wavefield. To this end, we have created a set of rupture models characterized by different degrees of the geometrical complexity. We emphasize, that we also used different random numbers for the random field generator discussed in Section 2.3 to study the effects of different realizations of deflected fault models. As they qualitatively lead to the same results they confirm the results of our numerical study and our derived conclusions. Note that these deflected rupture models have the same seismic moment tensor as the perfectly planar one, however, with a reduced scalar moment, which we correct for. We remark, that of course the developed non-planar rupture models used in this study could still be far from reality. None of the parameters describing the random rupture deflections, namely the spectral decay, the correlation lengths or the rms values are precisely known. Moreover, these parameters can vary among different earthquakes and/or tectonic regions. Therefore, our models have to be understood as speculative test cases. As shown by the results above, it is not always possible to distinguish whether the variations in the seismic wavefield are caused by changes in the rms or K values, for

example, FN component in Fig. 9. Nevertheless, we believe that the determination of possible models characterizing typical geometrical properties of earthquake ruptures is of great importance.

Let us emphasize that here we are dealing only with kinematic and not dynamic models. This could be considered as a deficiency in our approach. However, the restriction to kinematic rupture modelling allows us to perform the study much more consistently. This means that all the rupture models, apart from their geometrical differences, are characterized by same kinematic properties, such as total seismic moment, rupture velocity, duration, slip velocity function, etc. Moreover, as we mention in Section 2.3, the different kinematic models considered may even have completely different underlying dynamic models. On the other hand, the dynamic models might theoretically constrain the range of the possible geometrical rupture models.

Our study shows that perhaps the most typical behaviour of velocity amplitudes of different components at a given receiver is their tendency to be more balanced as more geometrical complexity is introduced (see Fig. 9a). Moreover, the larger the differences between the components of the perfectly planar rupture are, the more sensitive are the amplitudes to the rupture deflections (see receiver 2, 12, 22 or 31–59 in Figs 9a and b.)

In the frequency domain in Figs 8(a) and (b) we observe that for increasing rms or correlation length, the whole spectrum can be affected, for example, for the FP and V components at receivers close to the rupture. This suggests that the energy between the components is distributed more equally in the whole frequency band when enhancing the geometrical irregularities of the rupture model. However, for the distant off-fault receiver 20 in Figs 8(a) and (b) the Fourier amplitudes at low frequencies typically are not affected by increasing rms or K values, while at high frequencies the amplitudes increase with geometrical complexity. This is due to the constraint seismic moment of all our rupture models that is governing the low-frequency motion. Moreover, we observe that the geometrical complexity introduces changes in the seismogram spectra starting almost always at the same frequency. In other words, we do not see any systematic dependence of this frequency on rms or K .

In the following we want to draw the readers attention to possible implications of the discussed observations for a number of different field in seismology affected by the effects of non-planar rupture geometries.

4.1 Implications to strong ground motion simulations

In strong ground motion simulations it is quite common that the synthetic seismograms exhibit large amplitude differences in the horizontal components, which are not observed in real data records. This experience is clearly supported by our study (see Fig. 9) and is a consequence of the strong effect of the radiation pattern. We show that gradually adding complexities to the rupture geometry balances these maximum values of the synthetics. Zeng *et al.* (1995) suggested to include rake variations in the simulations to overcome this problem of unrealistically large differences between the horizontal components in strong ground motion predictions. They illustrated the effect for one station for the Uttarkashi thrust fault earthquake showing that their synthetics then have comparable amplitudes at horizontal components. They also state that the strike and dip variations do not have such a strong effect. In our experience such a statement should depend on the position of the particular station with respect to the rupture (distance and azimuth). Moreover, we attribute this disagreement to the different principal source mecha-

nisms assumed in the calculations. While Zeng *et al.* (1995) used a thrust fault, we only consider a strike slip fault, where, on the contrary, the rake variations in the LOH-4-015R model basically did not affect the amplitudes of the horizontal components.

Pitarka *et al.* (2000) or Satoh (2002), suggested the use of a radiation pattern that vanishes with increasing frequency to explain observed data. To our knowledge, this observation is not yet theoretically fully understood. Based on our numerical study we cannot fully explain this particular behaviour. In fact, our results show that the geometrical variations of the adopted source models can affect the seismograms in the whole frequency band depending on the receiver location and the analysed velocity component. Therefore, not all signals exhibit such a systematic frequency dependence, especially not those recorded at close fault distances (see Fig. 8). Another, rather high-frequency effect might have to be studied in order to explain this general behaviour observed in real data. Perhaps the most promising phenomenon that could exhibit such frequency-dependent effects is the scattering due to random medium properties. Since the ADER-DG method seems to be suitable for studying wave propagation in a random medium, this will be the subject of our further studies.

Generally speaking, we state that the small-scale geometrical variations of a 3-D non-planar rupture can be approximated by a mean planar fault, on which the rupture elements are projected, however, taking into account their actual strike and dip variations. Referring to Figs 4 and 11 this approximation will lead to satisfying results in terms of the radiated wavefield and misfits for many cases. From the practical point of view, this allows most numerical methods that are possibly not capable of incorporating the geometrical complexities of non-planar ruptures in their mesh to resolve most of the discussed effects. However, we emphasize that the small-scale variations in strike and dip should not be neglected even if projected onto a planar surface. This might be important for many numerical methods that have difficulties following a deflected rupture surface with their discretization, for example, regular Cartesian Finite Difference grids. Precisely speaking, this approach will lead to minor amplitude and phase discrepancies in comparison to a truly deflected rupture surface. Therefore, the modeller should be aware of the significance of the possibly introduced errors with respect to the desired accuracy of his synthetics. However, we remark that we only considered smooth geometrical variations of the rupture surface with respect to its mean, perfectly planar surface. Significant deviations from a mean, planar trend, such as bends, should definitely be approximated by separate rupture segments.

4.2 Implications to seismic moment tensor inversions

Zahradnik *et al.* (2007) show that two pure shear earthquakes of different orientations can introduce a non-DC component in the retrieved moment tensor if such a double event is considered as a single one in the inversion. Here, we represent our non-planar rupture surfaces by a grid of differently oriented elementary DC point sources. However, as mentioned above, the final moment tensor of the whole earthquake obtained as a sum of the moment tensors of all rupture elements has the same character as for the planar case, that is, the same strike, dip and rake angles with no non-DC component. However, as mentioned above the total scalar moment is lower and has to be corrected for.

We attribute the fact that our non-planar ruptures keep the character of a planar rupture in terms of the seismic moment to our particular generation of random distributions of strike and dip. They

vary randomly around a mean value always corresponding to the same planar rupture. Therefore, we state that for seismic moment tensor inversions, which are typically based on low-frequency data of stations of regional or teleseismic distances, the geometrical complexity as introduced in this paper does not seem to have an effect (see Fig. 8).

4.3 Implications to slip inversions

Our study shows that taking into account the non-planar character of a rupture surface could be of major importance, especially if the real rupture deflections were characterized by even larger rms values. Generally, the non-planar character of a rupture is neglected in slip inversions. Only if the rupture is clearly bent (e.g. Landers earthquake), the rupture is divided into several planar segments. In some cases, rake variations are also retrieved together with slip. However, strike and dip variations are still neglected. Considering our study, this can significantly bias the resulting slip image since the actual strike and dip variations have strong effects on the waveforms as shown in Fig. 7. Once again it has to be emphasized that the effects introduced by geometrical complex rupture surfaces can influence the whole frequency band depending on the receiver location with respect to the rupture distance and orientation, so that they cannot generally be avoided, for example, by simply low-pass filtering of the waveforms.

5 CONCLUSIONS

We have presented a numerical study of the effects of geometrically complicated 3-D ruptures on the radiated wavefield in the vicinity of the source. As currently most kinematic and dynamic rupture models are still based on the assumption of perfectly planar ruptures, we show how the variations of the geometrical rupture parameters at different scales can significantly influence the synthetic seismograms. The results show that the correct incorporation of the rupture complexity is important as the observed effects due to local variations of the rupture geometry parameters can strongly affect the waveforms and the corresponding Fourier spectra of the synthetics in the whole frequency band. We conclude that the observations of this study might have important implications for strong ground motion simulations or seismic moment tensor and slip inversions when realistic earthquake scenarios with very heterogeneous rupture kinematics are considered.

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