Construction of equivalent single planar fault model for strike-slip stepovers

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ARTICLE INFO

Article history:
Received 23 February 2014
Received in revised form 21 May 2014
Accepted 20 June 2014
Available online 28 June 2014

Keywords:
Fault geometric discontinuity
Equivalent single planar fault
Numerical simulation
Radiated seismic waveform

ABSTRACT

Non-planarity is a common and natural characteristic of seismic faults that strongly affects the rupture dynamics and the associated seismic waves. Geometrically uniform planar fault model is widely used in studies of kinematic source inversion, seismic hazard estimation and rupture dynamic simulation because of the simplicity and computational efficiency of this method. The influence of the geometric heterogeneity of faults on rupture dynamics and associated seismic waves may under some circumstances be reasonably approximated by an appropriate heterogeneous distribution of shear strength of planar faults, particularly for the case with uniform initial stress distribution. An outstanding issue is how to approximate the dynamic behavior of a non-planar fault by means of heterogeneous properties on a planar fault. Thus, we propose the construction of an equivalent planar fault model for a given stepover fault through the introduction of a heterogeneous distribution of static friction coefficient. Our study shows that the distribution of static friction coefficient on the equivalent planar fault model is mainly controlled by the geometric irregularities of the stepovers regardless of the initial shear stress, thereby providing a way to quantify the effect of fault geometry, particularly the step width effect in seismic hazard estimation. Moreover, our results indicate that the influence of geometric discontinuity of stepovers on rupture dynamics is equivalent to a barrier of the planar fault model.

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1. Introduction

A seismic fault is geometrically heterogeneous at all scales, i.e., non-planarity is a common and natural characteristic of seismic faults (Fukuyama and Madariaga, 1998; Shi and Day, 2013). Such geometric heterogeneity of faults strongly affects the rupture dynamics and the associated seismic waves. A geometrically uniform planar fault model has been widely used in studies of kinematic source inversion (e.g., Beroza and Spudich, 1988; Hartzell and Heaton, 1983; Ji et al., 2002; Xu and Chen, 1997), seismic hazard estimation (Aki, 1987, 1993; Kamae et al., 1998; Mai, 2009; Somerville et al., 1999; Wald et al., 1991), and rupture dynamic simulation (e.g., Aki, 1979; Aochi et al., 2000; Chen and Zhang, 2006; Das and Aki, 1977; Das and Kostrov, 1987; Day, 1982; Day et al., 2005; Madariaga, 1976) because of the simplicity and computational efficiency. The influence of the geometric heterogeneity of faults on rupture dynamics and associated seismic waves might be approximated by an appropriate heterogeneous distribution of shear strength of planar faults.

For a given non-planar fault model, the planar fault with an appropriate heterogeneous shear strength can be regarded as an equivalent single planar fault model (ESPFM). Here, equivalence indicates that the single planar fault model would be best matched to the original non-planar fault model in terms of total fault size, final slip distribution, dynamic rupture process, and associated seismic waves. Nonetheless, even if the ESPFM matches well with the original non-planar fault model, these two models can never be exactly the same because they are essentially different.

To date, inadequate effort has been exerted on systematic studies on constructing an ESPFM whose dynamic rupture behavior and associated seismic waves are best matched to the real dynamic rupture of a given non-planar fault, on the ideal observation distance for using the ESPFM, and on the relationship between the geometric heterogeneities of the actual non-planar fault and the effective shear strength of the corresponding ESPFM. Therefore, this study investigates these issues. Our study will be limited to the stepover fault model because this model is one of the most common types of non-planar fault models.

2. Construction of equivalent single planar fault model

We used a specific example to describe the construction of an ESPFM for a given stepover fault model (SoFM) (Fig. 1). The SoFM consists of
two parallel right-lateral strike-slip vertical planar sub-faults; each one is 16 km long along the strike direction (x direction) and 15 km wide along the vertical dip direction (z direction). Both of the top sides of the two sub-faults reach the free surface. The two sub-faults are separated along the fault perpendicular direction (y direction) with a 0.5 km overlap, along the x direction with a 4 km overlap, composed of two vertical parallel 16 km × 15 km sub-faults embedded in a homogeneous half space and both top sides reach the free surface. The coordinates of the center point in the 3 km × 3 km square asperity is (6 km, 0 km, −7.5 km).

A total of 18 receivers (black triangles) with a 20 km interval are placed along a radial line with the azimuth of 14° with respect to the x direction on the free surface. These receivers are denoted with the character Π plus the epicenter distance.

Step 1 Determining the geometry of the ESPFM
First, we set up a single planar fault model whose geometric dimension is the projection of the SoFM on the plane OZX shown in Fig. 1. In addition to geometric similarity, the dynamic aspect of the ESPFM must also be best matched with that of the SoFM. Such matching is achieved by constructing heterogeneous dynamic parameters for the ESPFM.

Step 2 Determining the pseudo slip rate distribution of the ESPFM
To determine the dynamic parameters of the ESPFM, we first conduct a dynamic simulation of the SoFM with initial shear stress aligned with the x-axis. We then obtain the spatial-temporal slip rate distribution \( V_x^{\text{SoFM}}(x, z, t) \) of the SoFM (Fig. 2a), which consists of two parts, namely, \( V_x^{\text{II};\text{SoFM}}(x, z, t) \) and \( V_x^{\text{I};\text{SoFM}}(x, z, t) \), i.e., the slip rate occurred on sub-faults I and II, respectively. We then project the slip rate distributions of each sub-fault of SoFM onto the fault plane of the ESPFM to form pseudo slip rate distribution for the ESPFM, i.e.,

\[
V_x^{\text{pseudo};\text{ESPFM}}(x, z, t)_{y=0} = V_x^{\text{II};\text{SoFM}}(x, z, t)_{y=0} + V_x^{\text{I};\text{SoFM}}(x, z, t)_{y=0}.
\]

where the pseudo slip rate \( V_x^{\text{pseudo};\text{ESPFM}} \) is not a real slip rate of the ESPFM, but only an approximate one (Fig. 2b). For the SoFM, dynamic parameters such as background stress field, critical slip distance \( d_0 \) and static and dynamic frictional coefficients \( \mu_s \) and \( \mu_d \) are considered uniform constants in this study for simplicity. In the ESPFM, all dynamic parameters are assumed to have the same constants as those of the SoFM except for static friction coefficient \( \mu_s \), which is determined by the pseudo slip rate \( V_x^{\text{pseudo};\text{ESPFM}} \).

Step 3 Determining the static friction coefficient distribution of the ESPFM
To construct the distribution of \( \mu_s \) of the ESPFM, we apply the discrete form of the boundary integral equation (BIE) for the problem of rupture dynamics in half-space (Chen and Zhang, 2006; Zhang and Chen, 2006a,b):

\[
\begin{align*}
\sum_{i \leq j \leq k} C_{ijk}^{0,lmn} &\cdot V_{x;\text{ESPFM}}^{\text{lmn}}(y) \\
&= \frac{\tau_{ij}^{0,lmn}}{C_{12}^{0}} + \sum_{i \leq j \leq k} \frac{\tau_{ij}^{0,lmn}}{C_{12}^{0}} \cdot V_{x;\text{ESPFM}}^{\text{lmn}}(y) + \sum_{i \leq j \leq k} \frac{\tau_{ij}^{0,lmn}}{C_{12}^{0}} \cdot V_{x;\text{ESPFM}}^{\text{lmn}}(y),
\end{align*}
\]

where \( \tau_{ij}^{0,lmn} \) and \( \tau_{ij}^{0,lmn} \) are the shear and normal stresses, respectively, and \( \tau_{ij}^{0,lmn} \) and \( \tau_{ij}^{0,lmn} \) are the initial shear and normal stresses of the background stress field. The upper scripts ‘ijk’ denote the observational point (\( \Delta s \), \( \Delta t \)) and time \( n \Delta t \). The initial stresses for the ESPFM are of the same constants as those for the SoFM because the normal directions for both fault models are the same. \( C_{ijk}^{0,lmn} \) is the coplanar integral kernel of BIE for half-space derived by Zhang and Chen (2006a). \( V_{x;\text{ESPFM}}^{\text{lmn}}(y) \) should be the slip rate of ESPFM at spatial point (\( \Delta s \), \( \Delta m \), \( \Delta s \)) at time \( n \Delta t \); however, this value cannot be determined until the ESPFM’s static friction coefficient \( \mu_s^{\text{ESPFM}} \) is known. At the current stage, \( \mu_s^{\text{ESPFM}} \) is not yet known and is currently being determined. To determine...
μ_{ESPFM} \cdot V_{\text{inm:ESPFM}}^{\text{lmn}} was approximated by \( V_{\text{inm:ESPFM}}^{\text{lmn}} \) defined as Eq. (1). Thus Eq. (2) can be used to determine \( \mu_{s}^{\text{ESPFM}} \) by incorporating the slip-weakening law (Andrews, 1976; Ida, 1972). First, by incorporating slip-weakening law, we rewrite Eq. (2) as follows:

\[ \delta_{ij} \delta_{ml} \geq \tau_{ij}^{0} + \sum_{l,m,n} C_{ijkl mn} \tau_{ij}^{\text{inm:ESPFM}}^{\text{lmn}}(l, m, n), \]  

with

\[ \mu_{l}(l) = \begin{cases} \frac{\mu_{s}^{\text{ESPFM}} - \mu_{s}}{d_{0}}, & \text{for } 1 < d_{0} \\ \mu_{s}, & \text{for } 1 \geq d_{0} \end{cases} \]  

where \( l \) denotes the slip, \( d_{0} \) is the critical slip distance, and \( \mu_{s}^{\text{ESPFM}} \) and \( \mu_{s} \) are the static and dynamic friction coefficients for the ESPFM. Notably, \( d_{0} \) and \( \mu_{s} \) are the same as those of the SoFM, whereas \( \mu_{s}^{\text{ESPFM}} \) is not and is determined by Eq. (3). The equality in Eq. (3) pertains to points encountered on the rupture front, and the \( \mu_{s}^{\text{ESPFM}} \) at those points can be determined by solving Eqs. (3) and (4) simultaneously. After the rupture front of \( V_{\text{inm:ESPFM}}^{\text{lmn}} \) sweeps through the entire fault plane of the ESPFM, the distribution of \( \mu_{s}^{\text{ESPFM}} \) on the ESPFM is obtained (Fig. 2c).

3. Numerical examples and tests of ESPFM

3.1. Rupture dynamics of SoFM

To check the validity of the ESPFM, we first calculate the rupture dynamics of the SoFM whose geometrical configuration is the same as that shown in Fig. 1. We consider two cases with different initial shear stresses, which correspond to the subshear and supershear ruptures. Table 1 shows the initial stress and friction coefficients used in the simulations of the two cases. The asperity (i.e., initial rupture patch) of the SoFM is a 3 km × 3 km square area located at 7.5 km deep from the free surface and 6 km apart from the left boundary on fault I. The background medium is homogeneous with a P wave velocity of 6 km/s, S wave velocity of 3.464 km/s, and a density of 2670 kg/m³.

Dynamic rupture simulations on stepovers were first proposed by Harris et al. (1991), who used 2D finite difference method (FDM). Eventually, 3D FDM (Harris and Day, 1999; Kase and Kuge, 2001) became widely used in simulations of dynamic rupture on stepovers (Das and Aki, 1977). In this study, all the dynamic rupture simulations are performed by collocated-grid finite difference method (Zhang and Chen, 2006; Zhang et al., 2012; Zhang et al., 2014) with a uniform spatial interval of 0.05 km and a 0.005 s time step. Fig. 3 shows the snapshots of the simulated rupture slip of the SoFM for the supershear and subshear cases. For the supershear case, the rupture on fault I became supershear at 2 s, swept through the entire fault I at 3 s, triggered the rupture on the fault II at 4 s and swept over it at approximately 6 s. For the subshear case, however, the rupture propagated slower than the supershear case, and did not reach the end of fault I at 3 s. Fault II was triggered to rupture between 5 s and 8 s, and entirely swept over at 8 s. These rupture scenarios clearly show that the secondary fault (fault II) was triggered in approximately 1 s after the rupture front completely reached the right end of fault I. The step jump of the SoFM acts as a “barrier” in the rupture dynamics of planar faults (Das and Aki, 1977).

3.2. Distribution of static friction coefficient for ESPFM

The distribution of the static friction coefficient of the ESPFM \( \mu_{s}^{\text{ESPFM}} \) can be obtained from the dynamic modeling results of the two SoFMs presented above and the constructing procedures of ESPFM described earlier. To illustrate the difference between \( \mu_{s}^{\text{ESPFM}} \) and \( \mu_{s} \), \( \gamma^{i} \) is defined by the following relation:

\[ \mu_{s}^{\text{ESPFM}} = \mu_{s}(1 + \gamma^{i}) \]  

where \( ij \) denotes the spatial location (\( \Delta s_{i}, \Delta s_{j} \)) on the ESPFM, \( \gamma^{i} \) represents the incremental percentage of \( \mu_{s}^{\text{ESPFM}} \) compared with \( \mu_{s} \). The distribution of \( \gamma^{i} \) for the supershear and subshear cases is shown in Fig. 4a and b, respectively. Although the two cases have different initial shear stresses (Table 1), the distributions of \( \gamma^{i} \) exhibit a good coincidence. A high \( \mu_{s}^{\text{ESPFM}} \) zone exists between 12 km and 16 km along the strike direction. This high \( \mu_{s}^{\text{ESPFM}} \) located on the overlapped area of the projection of

<table>
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<th>Table 1 Stress and frictional parameters.</th>
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<td>Parameters</td>
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<tr>
<td>Initial shear stress ( \tau_{0} ) (Mpa)</td>
</tr>
<tr>
<td>Initial normal stress ( -\tau_{n} ) (Mpa)</td>
</tr>
<tr>
<td>Shear stress in the asperity (Mpa)</td>
</tr>
<tr>
<td>Static friction coefficient ( \mu_{s} )</td>
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<tr>
<td>Dynamic friction coefficient ( \mu_{d} )</td>
</tr>
<tr>
<td>Critical slip distance ( d_{0} ) (m)</td>
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two sub-faults of the SoFM forms a vertical belt on the ESPFM. For both cases, the highest value of $\mu_{\text{ESPFM}}$ occurred at 16 km, i.e., the location of the end of fault I. This high $\mu_{\text{ESPFM}}$ belt on the equivalent planar fault behaves like a barrier for rupture propagation along the strike direction (i.e., $x$ direction). To quantitatively analyze the property of the “barrier”, $\gamma^i$ was averaged along the dip direction ($z$ direction), i.e., $\bar{\gamma}^i = \frac{1}{N} \sum_{j=1}^{N} \gamma^i_{j}$, where $N$ is the number of spatial grids along the dip direction. The results showed that, for both supershear and subshear cases, $\bar{\gamma}^i_{16\text{ km}}$ reached nearly the same value of 0.34 at the location of $x = 16$ km, i.e., $\bar{\gamma}_{16\text{ km}} = 0.34$. Since the geometries of both SoFMs are the same, the similar feature of $\gamma^i$ and consistency of $\bar{\gamma}_{16\text{ km}}$ indicate that the barrier of ESPFM is, if not completely, mainly controlled by the geometry feature of SoFM.

### 3.3. Rupture dynamics of ESPFM

Using the distribution of static friction coefficient $\mu_{\text{ESPFM}}$, we can simulate the rupture dynamics of the ESPFM. Simulation was also performed by FDM (Zhang et al., 2014) with a 0.05 km uniform spatial grid and a 0.005 s time step. All of the dynamic parameters for this simulation are the same as those for the two SoFMs discussed in the preceding section, except for the distribution of $\mu_{\text{ESPFM}}$ that contains a high-value “barrier” belt. Fig. 5 shows the simulated results of the rupture dynamics of ESPFM for the two cases. For the supershear case, the rupture front is obstructed for a while at 2 s by the barrier belt with high $\mu_{\text{ESPFM}}$, continues to propagate at approximately 4 s, and finally sweeps over the entire plane of ESPFM at approximately 6 s (Fig. 5a). For the subshear case, however, the entire rupture process is slower and the fault slip is weaker than that of the supershear case (Fig. 5b). For instance, the rupture front did not sweep over the entire fault plane until the 8 s, and the peak slip is only about half that of the supershear case. Comparison of the dynamic rupture scenarios of ESPFM (Fig. 5) and SoFM (Fig. 3) reveals that the overall features of rupture speed and slip distribution for both supershear and subshear cases are quite similar for each comparison counterpart.

### 4. Seismic waves excited by the ESPFM

On the basis of rupture scenario of the ESPFM, the corresponding seismic waves can be calculated by FDM (Zhang and Chen, 2006c; Zhang et al., 2012). The simulated volume is a 360 km $\times$ 240 km $\times$ 21 km homogeneous cube with free surface at the plane of $z = 0$, as shown in Fig. 1. The inner boundaries are treated with perfectly matched layer (PML) approach (Berenger, 1994; Marcinkovich and Olsen, 2003; Zhang and Shen, 2010). Other parameters for the simulation are listed in Table 2. The results are shown in Figs. 6 and 7.

First a group of receivers are traced along a radial line from the epicenter with the 14° azimuth with respect to the fault plane of ESPFM or fault I of the SoFM (Fig. 1). Three-component velocity waveforms of the supershear and subshear cases are shown in Fig. 6a and b. A 0.5 Hz low-pass filter is applied, and each waveform pair is normalized to their maximum value. The numbers labeled on the left and right sides of each comparison pair of waveforms denote the maximum amplitudes and the correlation coefficient of each comparison pair, respectively. The correlation coefficients are calculated by Pearson’s correlation coefficient, i.e., $\rho_{X,Y} = \frac{\text{Cov}(X,Y)}{\sigma_X \sigma_Y}$, where $X$ and $Y$ are the two waveforms, $\mu_X$ and $\mu_Y$ are the mean of $X$ and $Y$, respectively, $\sigma_X$ and $\sigma_Y$ represent the standard deviation of $X$ and $Y$. For this low frequency situation, these comparisons show good coincidence in both the amplitudes and the arrival times for both the supershear and subshear cases regardless of epicenter distance.

### Table 2

Parameters for wave-field simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>P wave velocity (km/s)</td>
<td>6.0</td>
</tr>
<tr>
<td>S wave velocity (km/s)</td>
<td>3.464</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2670</td>
</tr>
<tr>
<td>Spatial grid (km)</td>
<td>0.20</td>
</tr>
<tr>
<td>Time step (s)</td>
<td>0.025</td>
</tr>
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</table>
Moreover, coincidences in the horizontal components are better than those in the vertical components, and the coincidences in the supershear case are better than those in the subshear case. The amplitudes of vertical components are substantially smaller than those of the horizontal ones; therefore, the relatively lower correlation coefficients shown in the comparisons of the vertical components suggest that the relative differences of the seismic waves radiated from ESPFM and SoFM for the three components are in the same order.

Fig. 7a and b shows the detailed comparisons of velocity waveforms with a 2.0 Hz low-pass filter in the supershear and subshear cases at the near-field receiver R30 (located at 30 km epicenter distance) and the far-field receiver R290 (located at 290 km epicenter distance), respectively. In view of the wider frequency band, particularly the high frequency band, more detail features of the waveforms of both models are shown. Accordingly, the correlations of waveforms between the two models for both supershear and subshear cases are decreased, although the correlation for the supershear case is better than that for the subshear case. Moreover, the amplitudes of fault-parallel (FP) component of both models at near-field (e.g., R30) for the supershear case are not smaller than those of fault-normal (FN) component, whereas at the far-field (say, R290), the amplitudes of FP component are much smaller than those of the FN component. For the sub-shear case, however, the amplitudes of FP component of both models are smaller than those of the FN components at both near and far field receivers. For the far-field receiver R290, the comparison was started at 80 s because the arrival time and amplitudes of the P waves of SoFM and ESPFM agree very well for all station. Major differences were observed at the amplitudes, although the arrival time of each phase has good coincidence.

Thus, the waveforms have good coincidence with a 0.5 Hz low-pass filter and slight amplitude differences can be noticed with a 2.0 Hz low-pass filter.

5. Discussions and conclusions

In this study, we developed a method for constructing an ESPFM for a given SoFM, and the equivalence of the ESPFM to the SoFM was tuned by a heterogeneous distribution of static friction coefficients. Our study shows that the distribution of static friction coefficient on the ESPFM may under some circumstances has a similar effect in controlling rupture dynamics with the effect of geometric irregularities of the SoFM, thus providing an alternative insight to quantify the effect of fault geometry in rupture dynamics. The rupture dynamics and final slip distribution of the ESPFM are similar to those of the SoFM because of the heterogeneous static friction coefficient distribution on the ESPFM.
Moreover, our results indicate that the influence of geometric discontinuities on rupture dynamics is approximately equivalent to a barrier of the planar fault model. Furthermore, velocity waveforms radiated by the ESPFM agree quite well with velocity waveforms from both the planar fault and 3D numerical simulations. We also found that in all aspects the coincidence between the ESPFM and SoFM is better than that of the subshear case.

Acknowledgments

This study is supported by the Nature Science Foundation of China (41274073, 41004029).

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