Effects of low-velocity fault zones on dynamic ruptures with nonelastic off-fault response

Benchun Duan

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[1] Using a finite element method for elastoplastic dynamic analysis, we examine the effects of a low-velocity fault zone (LVFZ) surrounding a fault on a spontaneous dynamic earthquake rupture. A Mohr-Coulomb failure criterion is used to characterize nonelastic off-fault response to earthquake ruptures. We find that the presence of a LVFZ alters the distribution of off-fault plastic strain and results in larger final slip and larger peak slip velocities on the fault. These effects show a LVFZ-width dependency. A supershear transition is observed with a LVFZ width of 400 m or larger (relative to the shear wave velocity of country rocks) rupture is limited by off-fault plastic yielding. But LVFZs have not been included in these models. LVFZs are expected to have effects on off-fault plastic yielding, and thus on dynamic ruptures in a manner probably different from that revealed by Harris and Day [1997]. In addition, effects of LVFZs on near-field ground motion have not been explicitly examined. This study is to examine effects of LVFZs on rupture dynamics and near-field ground motion with off-fault elastoplastic response.

2. Method and Model

[4] We use a finite element code [Duan and Day, 2006] to simulate a spontaneous dynamic rupture on a fault surrounded by a LVFZ and wave propagation in an elastoplastic medium. A general description of an earlier version of the code has been given by Duan and Oglesby [2006, 2007], which solves an elastodynamic problem with a linearly elastic medium. The modification to this earlier version of the code is to allow material in the medium to yield when the stress state reaches a Mohr-Coulomb yield surface. The criterion is given by \( \tau \leq c - \sigma_n \tan \phi \), where \( \tau \) and \( \sigma_n \) are shear and normal (positive in tension) stresses in any orientation at a point in the medium, \( c \) and \( \phi \) are cohesion and the internal frictional angle. The implementation of plastic yielding in the code follows Andrews [2005] and the code has been verified against Andrews [2005] on an identical faulting model. A linear slip-weakening friction law with a critical slip distance of \( D_0 \) [e.g., Ida, 1972; Andrews, 1976; Day, 1982] is used to govern the spontaneous rupture propagation on the fault in this study.

[5] We work on 2-D plane strain problems in the x-y plane (see the inset of Figure 1a). The relevant stress components are \( \sigma_{xx}, \sigma_{yy}, \sigma_{xy} \). A 20-km long fault is modeled as a planar frictional surface embedded in an elastoplastic continuum. The fault bisects a LVFZ with a width of \( w \). We vary \( w \) to examine width-dependence of LVFZ effects. The case of \( w = 0 \) m is the reference model in which...
material is homogeneous and elastoplastic. Static and dynamic frictional coefficients on the fault are 0.6 (except at the ends) and 0.4, respectively. A very high static frictional coefficient is assigned at the two ends of the fault to stop the rupture. Right-lateral fault slip is assumed in this study. A uniform stress field is assigned in the entire model with $s_{xx} = s_{yy} = 100$ MPa and $s_{xy} = 50$ MPa. Table 1 gives material properties in the medium. A velocity reduction of 30% in the LVFZ is chosen based on observations along the SAF at Parkfield [Li et al., 2006]. The stress level and cohesion for country rocks correspond to a depth of about 6 km [Ben-Zion and Shi, 2005]. Within the LVFZ, internal friction and cohesion are chosen to be smaller than those of country rocks, based on the observation that a higher level of fracture density is usually associated with a fault damage zone [e.g., Chester et al., 2005].

Rupture is initiated artificially within a nucleation patch (a half length of 750 m in this study) in the middle of the fault, by forcing rupture to grow bilaterally at a fixed speed and dropping the frictional coefficient from static to dynamic values. Outside of this nucleation patch, the simulated rupture propagates spontaneously. Square elements with a side length of 10 m are used in the main region surrounding the fault. A much larger buffer region within which the element size increases by a ratio of 1.02 away from the main region is used to prevent reflections from the model boundaries from contaminating results we will examine. A slip-weakening critical distance value of 0.2 m is chosen to ensure good resolution of the cohesion zone at the rupture front for the given 10 m element size. Simulations are terminated at 8 seconds.

3. Results

Figure 1 shows the distribution of plastic strain magnitude for six cases with different LVFZ widths. Different scales among subplots in the y axis are used for clearer illustrations. Also notice that the scales in the x and y axes are different in each subplot. The fault is along $y = 0$ m and runs between $x = -10$ km and 10 km. Figure 1a is the reference case in which the LVFZ is excluded ($w = 0$ m). The features reported by Andrews [2005] are obtained in this case: Under the given initial stress condition, plastic yielding occurs only on the extensional side of the (right-lateral) rupture; the magnitude of plastic strain is largest adjacent to the fault, and it decreases smoothly away from the fault with a thickness proportional to rupture propagation distance. Strong plastic strain bands associated with the fault ends reflect significant nonelastic deformation due to sudden stop of rupture.

The presence of a LVFZ alters the above features significantly and the LVFZ width has obvious effects on the distribution of plastic strain. Under the given Mohr-Coulomb parameter values in LVFZs and country rocks, the plastic strain in the LVFZ is significantly higher than that in country rocks.

Table 1. Material Properties in the Models

<table>
<thead>
<tr>
<th></th>
<th>Vp, m/s</th>
<th>Vs, m/s</th>
<th>$\rho$, kg/m$^3$</th>
<th>$\tan \phi$</th>
<th>c, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country rocks</td>
<td>6000</td>
<td>3464</td>
<td>2670</td>
<td>0.85</td>
<td>45</td>
</tr>
<tr>
<td>LVFZ</td>
<td>4200</td>
<td>2425</td>
<td>2670</td>
<td>0.7</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 1. Distribution of plastic strain magnitude at the end of simulations (8 s) for six cases with different LVFZ widths. The case of $w = 0$ m is the reference model in which the LVFZ is excluded, resulting in a homogeneous, elastoplastic medium in the model. Inset in Figure 1a schematically illustrates the model setup.
rocks (Table 1), plastic yielding is limited within the LVFZ in the cases of a wide LVFZ ($w \geq 400$ m), while it penetrates into country rocks in the cases of a narrow LVFZ ($w \leq 200$ m). The cases of $w = 100$ m and 200 m exhibit a similar pattern of the plastic strain distribution with the following features: (1) the largest plastic strain magnitude occurs adjacent to the LVFZ/country-rock boundary, not adjacent to the fault ($y = 0$ m), (2) plastic yielding occurs in both the LVFZ and surrounding country rocks, and (3) the thickness of plastic yielding zone in country rocks is proportional to rupture propagation distance. At the fault ends, strong plastic yielding along the boundary extends several km beyond the fault ends and weaker plastic yielding occurs on the compressional side of

Figure 2. Rupture time along the fault strike for six cases shown in Figure 1. $V_{s1}$ and $V_{s2}$ are shear wave velocities of country rocks and LVFZ, respectively. $V_{r1}$ and $V_{r2}$ are corresponding Rayleigh wave velocities. They are shown as references to rupture velocity. A narrow LVFZ (200 m or narrower) slows down the rupture a little, while a wide LVFZ (400 m or wider up to 2 km) causes a supershear (relative to the shear wave velocity of country rocks) transition at a propagation distance proportional to the LVFZ width.

Figure 3. Distribution of final slip on the fault at the end of the simulations (8 seconds) for the six cases shown in Figure 1. A wider LVFZ results in larger fault slip, probably due to the trapped energy within the LVFZ.
the fault. With a LVFZ width of 400 m or larger, plastic yielding occurs only within the LVFZ. Plastic strain tends to develop within the LVFZ in a similar trend to that in the reference case. However, this trend is interrupted due to a supershear rupture (faster than the shear-wave velocity of the country rock) transition as shown in Figure 2.

Figure 2 shows rupture time along the fault strike for the six models. We define rupture time as the moment at which the shear stress reaches the yield stress (the product of the frictional coefficient and normal stress) at a point on the fault. In the reference case \((w = 0 \text{ m}, \text{ black curve})\), rupture speed approaches the Rayleigh wave speed of the country rock \((V_{r1})\) at the end of the rupture. A narrow LVFZ (i.e., \(w = 100 \text{ m} \text{ and } 200 \text{ m}, \text{ blue curves}\)) slows down the rupture a little. For widths of 400 m or larger, the rupture velocity first slows down at the early stage and then becomes supershear (relative to the shear wave velocity of the country rock) after a certain propagation distance that is proportional to the LVFZ width. For example, the transition occurs at rupture propagation distances about 3 km with \(w = 400 \text{ m}\), about 4.5 km with \(w = 1000 \text{ m}\), and about 8 km with \(w = 1800 \text{ m}\). This transition in rupture speed causes the interruption of off-fault plastic strain generation discussed above. A rupture jump can be also observed in the cases of \(w = 1000 \text{ m} \text{ and } 1800 \text{ m}\). The supershear transition and the rupture jump must be a result of complex interference between dynamic stresses at the rupture front and ahead and stress waves reflected from the LVFZ/country-rock boundary. This interference appears LVFZ-width dependent. The supershear transition due to the reflected wave effect was also observed in the elastic analysis by Harris and Day [1997].

Fault slip at the end of simulations of 8 s (at which slip does not increase obviously, thus it may be considered as the final slip) are compared in Figure 3. It is clearly seen that the final slip increases with the LVFZ width. The maximum slip in the case of \(w = 1800 \text{ m}\) (about 7.8 m) is about 1.4 times of that (about 5.6 m) in the reference case \((w = 0 \text{ m})\). If the increase in fault slip with the LVFZ width can be mainly attributed to the trapped energy within the LVFZ, this result indicates more energy will be trapped within a wider LVFZ. The presence of a LVFZ also results in larger peak slip velocity (not shown) on a fault. Furthermore, a LVFZ with a width of 200 m or wider causes peak slip velocity to fluctuate with the rupture propagation distance, maybe due to effects of reflected waves from the LVFZ/country-rock boundary. This feature is different from the reference case \((w = 0 \text{ m})\) in which peak slip velocity increases quickly with rupture propagation distance at the early stage of rupture and then levels off due to off-fault plastic yielding.

Figure 4 shows x- and y-velocity seismograms at 3 stations from three models with different LVFZ widths. The location of stations can be found by referring to Figure 1. Due to supershear rupture in the case of \(w = 400 \text{ m}\), waveforms from this model are significantly different from the other two, with a much higher peak value in the x component and a lower peak value in the y component at the same station. Under the condition of subshear ruptures on the fault, the presence of the LVFZ enhances the
magnitude of ground shaking at stations within the LVFZ. The y-component shows strong trapped wave modes at stations within and near the LVFZ. The trapped wave modes become weaker with increase of distance from the fault outside of the LVFZ, indicating diminishing of the LVFZ effect on near-field ground motion under the condition of subshear ruptures on the fault.

4. Discussion and Conclusions

References

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B. Duan, Department of Geology and Geophysics, Texas A&M University, College Station, TX 77843–3115, USA. (bduan@tamu.edu)