Short Note

Dynamic Rupture Simulation of the 2008 $M_w$ 7.9 Wenchuan Earthquake with Heterogeneous Initial Stress

by Yi-Ying Wen,* David D. Oglesby, Benchun Duan, and Kuo-Fong Ma

Abstract The rupture process and tectonic surroundings of the 2008 Wenchuan, China, earthquake are both complex in a way that might be related to the heterogeneous stress field of the Longmen Shan region. In this study, we construct dynamic models with heterogeneous initial stress to reproduce a kinematic inversion result by Wen et al. (2012) and investigate the physical mechanisms of the variable slip pattern and rupture velocity in this event. The results show that, for the 2008 Wenchuan earthquake, (1) the rupture behavior and slip pattern can be explained by heterogeneities in initial stress and (2) the variations of rupture velocity and ground-motion pattern are strongly affected by both stress drop and fault strength. Our preferred dynamic model agrees with the kinematic model that the 2008 Wenchuan earthquake initiated with a slow velocity in the southwest, sped up in the segment with the largest slip, and then slowed down for the remaining propagation to the northeast.

Introduction

The 2008 $M_w$ 7.9 Wenchuan earthquake struck the eastern margin of the Tibetan Plateau in the vicinity of the Sichuan basin, causing a 300-km-long surface rupture (Fig. 1a). The Longmen Shan region is composed of not only the typical thrust faults, but also active dextral-slip structures. Field investigations indicate that the faulting mechanism of this event varied along strike (Lin et al., 2009; Xu et al., 2009), with more thrust-oriented slip in the south near the hypocenter and more right-lateral slip in the north.

Several kinematic models (e.g., Nakamura et al., 2010; Wang et al., 2008) indicate the presence of a large asperity near the epicenter. However, for the segment between Beichuan and Qingchuan, these models derive slip, the location of asperity, or a fault length that is inconsistent with field observations (Lin et al., 2009; Xu et al., 2009). On the other hand, a recent study of this earthquake using teleseismic and regional surface waveforms (Wen et al., 2012), which shows great consistency with the field observations in slip pattern and location, indicates a quite variable rupture velocity in this event. The variation of the rupture velocity appears to be correlated with the segmentation of the fault observed in the field, which in turn might be related to the heterogeneous stress field of the Longmen Shan region. Several studies of past earthquakes have suggested that variation of rupture velocity might be related to variation of strength or shear stress on the fault (e.g., Archuleta, 1984; Vallée et al., 2008; Wen et al., 2009). Dynamic models of historical earthquakes can help shed light on the physical processes taking place during the rupture and slip processes, and many studies have modeled the spontaneous rupture of earthquakes based on inverted slip models (e.g., Mikumo and Miyatake, 1995; Olsen et al., 1997; Oglesby et al., 2004; Ma et al., 2008). In the present work, we attempt to investigate the physical origin of both the variable slip pattern and rupture velocity in the 2008 Wenchuan earthquake. We perform dynamic forward modeling to match the kinematic slip model of Wen et al. (2012) and investigate the rupture velocity pattern of this event. Because our model is simplified, we do not attempt to reproduce the seismic waveforms of strong-motion stations. Rather, we focus on investigating whether strength or stress heterogeneity is most responsible for the heterogeneous slip and rupture pattern and whether a model that is designed to fit slip can also fit rupture velocity with a minimum of assumptions.

Method, Fault Model, and Prestress Field

We use the explicit finite-element code EQdyna (Duan and Oglesby, 2006; Duan and Day, 2008; Duan, 2010) and a time-weakening frictional law (Andrews, 2004) to perform 3D dynamic spontaneous rupture simulations of the 2008 Wenchuan earthquake. Field evidence (Lin et al., 2009; Xu et al., 2009) indicates that this earthquake occurred on a geometrically complex fault system, with two overlapping
branches over a portion of its length along strike. In this study, to match the kinematic inverted model of Wen et al. (2012) and to follow the study of Duan (2010), we simplify this model to a single planar dipping fault segment embedded in a uniform 3D half-space with a flat surface. Consistent with the kinematic model, we set up a fault plane that is 350 km long along strike and 40 km wide down-dip, with a dip angle of 33°. For computational efficiency, we use a grid size of 1000 m on the fault, and inspection of slip rate pulses suggests that we resolve the weakening process adequately. We nucleate rupture by assigning a fixed initial rupture velocity of 1.7 km/s (obtained from kinematic modeling) in a circular region with a radius of 5 km, and then the rupture propagates spontaneously outside this patch. The computational parameters of this study are listed in Table 1.

The deformation of the Longmen Shan region isaccommodated by partial reactivation of a complex network of preexisting faults and is composed of both thrust faults and dextral-slip structures due to the strongly rotational and three-dimensional deformation field (Li et al., 2003; Densmore et al., 2010). Duan (2010) pointed out that the rotations in the principal stress orientation along strike might be responsible for the faulting style changes observed in the 2008 Wenchuan earthquake. In this study, we initially assume a constant normal stress $\sigma_n$, static friction coefficient $\mu_s$, and sliding friction coefficient $\mu_d$ on the fault for simplicity; our shear stress direction varies by segment in a manner consistent with the slip inversion of Wen et al. (2012). To account for decreased stress near the free surface, the shear and normal stresses are reduced to 0.1 times their ambient value at the free surface in all models, with a linear decrease in stress in the top 1 km. We then relax these assumptions to investigate different prestress models, based on the inverse kinematic result, for the dynamic simulation.

In the inverse kinematic modeling (Fig. 1b), the fault is divided into three segments, based on the geological and seismological data, with constant rupture velocity assumed for each segment. The slip model shows smaller-scale heterogeneous pattern with obvious asperities. Our goal was to match the inverted slip pattern and investigate the rupture velocity with a minimum of unconstrained assumptions.

Therefore, we considered four stress field parameterizations. (1) For model-SEG, we used the same fault segmentation as Wen et al. (2012). We calculated the average static stress drop, $\Delta \sigma = 2.44 \times M_0/A^{1.5}$, by assuming a circular fault model for each segment. For each segment, the moment ($M_0$) and area ($A$) were obtained by integrating only those subfaults with nonzero slip. From this calculation, the average static stress drops are 4.3, 4.6, and 1.6 MPa for segments S-1 to S-3, respectively. In addition, because the fault slip was composed of dip-slip and strike-slip components, the static stress drop was also calculated in two components, $\Delta \sigma_{ds}$ (dip-slip) and $\Delta \sigma_{ss}$ (strike-slip), which correspond to the inverted slip model. (2) Model-ASPE, in which the fault was more finely divided into five fault segments along strike according to the asperities in Figure 1b. The average static stress drop then varies over the fault with values of 4.3, 8.8, 2.9, 4.1, and 2.3 MPa for segments 1–5, respectively. (3) Model-HETERO has a more spatially heterogeneous (depth-dependent) stress field that is more comparable with the inverted slip distribution. For these three models, the assumption is a constant normal stress on the fault plane, with various initial shear stresses corresponding to the static stress drop. Such an assumption leads to variation in the relative fault strength parameter ($S = (\tau_y - \tau_0)/(\tau_0 - \tau_f)$), where yield stress $\tau_y = \sigma_n\mu_s$, sliding frictional stress $\tau_f = \sigma_n\mu_d$, and $\tau_0$ is initial shear stress; Das and Aki (1977)), which is a dimensionless ratio for quantifying how near the initial stress field is to failure and largely controls the rupture velocity variation during faulting. (4) For comparison, we consider a model with constant relative fault strength, model-COMP, which has heterogeneous normal stress and shear stress field corresponding to the static stress drop pattern from model-HETERO but with a constant $S$ value over the entire fault. The initial stress fields of these four models are depicted in Figure 2.

### Results

Figure 2 shows the slip distribution and rupture times of the four models described in the preceding section (Method, Fault Model, and Prestress Field). The final slip pattern is strongly controlled by the assumptions about the initial stress field. For model-SEG, the main asperity is smeared out due to the constant stress being applied to areas in the inverted model with nonzero but very small slip in segment S-2; thus no obvious asperity can be identified in this model (Fig. 2a). When we further separated the asperities along strike, as shown in Figure 2b (model-ASPE), the more realistic spatial variability in stress resulted in a clearer main asperity with a slip direction closer to that of the inverted model. Although we did not consider the changes in the principal stress orientation as done by Duan (2010), our model also displays variations of slip during rupture propagation due to variations in the initial shear stress direction set from the inverted model. However, because the stress was a fixed value (along the down-dip direction) in each segment, model-ASPE still

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Model Parameters Used in This Study</th>
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<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
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<td>P-wave velocity</td>
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<td>S-wave velocity</td>
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<td>Fault element size</td>
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<td>Critical radius $r_c$</td>
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<td>Static friction $\mu_s$</td>
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<tr>
<td>Dynamic friction $\mu_d$</td>
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<td>Time step $\Delta t$</td>
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<td>Termination time</td>
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results in a relatively smooth slip pattern and significantly larger slip and moment than in the inverted model. Therefore, in model-HETERO, we used a stress field that is heterogeneous along both strike and dip directions and attempted to match the general pattern of kinematic model by trial-and-error. Mikumo and Miyatake (1995) pointed out that the stress drop estimated from an inverted model is actually the local static stress drop, which could differ from the dynamic stress drop ($\tau_0 - \tau_f$). In their study, considering the possible overshooting of fault slip (in theory, the static stress drop could be 30% larger than dynamic stress drop; Kikuchi and Fukao, 1976; Madariaga, 1976), they used 90% of static stress drop as the dynamic stress drop. Model-SEG and model-ASPE both reflect this overshoot. Thus, to set the overall stress level of model-HETERO, we decreased both the normal and shear stresses to 0.9 times the values of model-ASPE. Then, we adjusted the dimension of each patch to fit the asperities in the kinematic model. In addition, we set up the initial shear stress with a background stress drop of the entire fault (1.4 MPa) for the area around those high-stress patches and with a very low stress drop of 0.05 MPa for the nonslipping areas in the kinematic model. Figure 2c displays our best-fit model, and shows that the slip pattern and amplitude are much closer to the final kinematic model, with asperities that can be clearly identified.

From Figure 2a–c, we can see that the rupture propagation speeds up in high-stress-drop areas but slows down as the stress drop decreases, an effect attributable to variations in the strength parameter $S$. To distinguish the influence of stress drop and fault strength, we set up an additional model (model-COMP with constant fault strength ($S = 1.7$, which is the average $S$ value of the high-stress patches in

Figure 1.  (a) Location (star) and surface rupture (thick black lines) of the 2008 Wenchuan earthquake. The focal mechanism and epicenter are determined by the Global Centroid Moment Tensor (CMT) solution and the U.S. Geological Service (USGS), respectively. The squares show the locations of some major cities. (b) Slip model from kinematic inversion (Wen et al., 2012). The star shows the hypocenter location, and the arrows and contours indicate the slip vectors and rupture time, respectively. The fault was divided into three segments (S-1 to S-3), with the rupture velocity of each segment also shown. The observed fault trace and offsets from Xu et al. (2009) are also shown above the slip distribution for reference.
model-HETERO) by varying both initial normal and shear stresses, while the stress drop distribution is the same as in model-HETERO. As shown in Figure 2c,d, model-COMP and model-HETERO display similar slip distributions but very different rupture time histories. In model-COMP, the rupture slows down as it enters high-stress regions and speeds up as it enters low-stress regions. This effect occurs because, for a constant $S$ condition, the absolute level of stress increase needed to reach failure stress is higher where the stress drop is larger (i.e., both the denominator and numerator in $S$ are large); the seismic waves radiated by low-stress-drop areas are only barely sufficient to trigger slip in neighboring high-stress areas. In addition, the slip magnitudes in the asperities of model-COMP are slightly larger than that of model-HETERO, most likely because of the differences in rupture propagation and thus dynamic overshoot.

In Figure 3 we show the coseismic surface deformation for these four models. Model-SEG and model-ASPE display an overly large vertical displacement area along the thrust fault segment, while model-HETERO and model-COMP both show similar patterns with two distinct large vertical displacement areas (one near the epicenter and the other near Beichuan), consistent with the model retrieved from Interferometric Synthetic Aperture Radar (InSAR) data (de Michele et al., 2010). Compared with the variation of rupture velocities from kinematic modeling (Wen et al., 2012), model-HETERO (Fig. 2c) matches the pattern with a slow initiation, a high rupture speed (> 3 km/s) in the segment with the largest slip, and a decreased speed farther north along strike. Overall, model-HETERO is our preferred dynamic model. The total seismic moment is $12.73 \times 10^{20}$ N·m with a magnitude of 8.0, which is slightly larger than that from the kinematic model.

Discussion

We model the dynamic rupture of the 2008 Wenchuan earthquake with different assumed prestress fields inferred from the results of inverse kinematic modeling. Even with the same stress drop distribution and very similar slip patterns and surface displacements, model-HETERO and model-COMP display very different rupture behavior and ground motion. Figure 4 shows the peak ground acceleration (PGA) and peak ground velocity (PGV) distributions of model-HETERO and model-COMP. The 2008 Wenchuan earthquake showed thrust faulting in the south and strike-slip toward the north end of the fault rupture. This pattern led to near-source horizontal PGA observed in the fault-normal component being larger than in fault-parallel, while the amplitudes of the two components became nearly equal as the distance to the fault increases (Wang and Xie, 2009). The high horizontal and vertical PGA are both concentrated between epicenter and Qingping (Wen et al., 2010), which is the location of the main asperity. In addition, the high PGV
area also corresponds to the main asperity and decays rapidly with distance from the fault. These observed characteristics are qualitatively reproduced in model-HETERO. However, in model-COMP, horizontal PGA in the fault-parallel component is even larger than in fault-normal component (near Qingping; circles in Fig. 4), and high horizontal and vertical PGAs extend farther to the north along strike from the main asperity. The most obvious difference between model-COMP and model-HETERO is the amplified fault-parallel PGV farther to the north along strike (i.e., comparing the top panels of Fig. 4b). The fault-parallel motion of model-COMP is much higher than that of model-HETERO, while the fault-normal motion is only a little higher. This different partitioning of the peak ground motion may be due to the supershear rupture propagation over a large portion of the fault after passing Qingping in model-COMP (e.g., the shallow part in 100–175 km along strike), and then the speed remains high on the strike-slip portion. The average rupture velocity between 200–300 km is about 3.3 km/s for model-COMP, but the speed is about 2.5 km/s along the same portion of model-HETERO, which is similar to the result of the inverted model. The wide zone of high PGV along the strike-slip faulting segment in model-COMP is not consistent with the observations. These results imply that, for this earthquake, a constant $S$ parameter does not reproduce the observed rupture and ground-motion pattern very well. In other words, variability in slip and rupture propagation speed appears to be controlled largely by the variation of relative fault strength and initial shear stress. A constant relative fault strength ($S$) with variations in the frictional coefficients may well be responsible for some of the variability in stress drop for some events (Ma et al., 2008), but exploring such additional sources of variability would require additional constraints on the material properties around the fault and is beyond the scope of this paper.

Our preferred model (model-HETERO) also shows a better match to the inverted slip than does the model of Duan (2010), which only includes large-scale stress rotations along the strike. Thus, our model indicates that while the regional stress field may strongly affect the large-scale rupture propagation on a complex fault system, to capture more complex variability in rupture velocity and slip it is necessary to include smaller-scale variations in stress than are seen in regional stress fields.

**Conclusions**

Our models show that (1) the rupture behavior and slip pattern of the 2008 Wenchuan earthquake can be explained by the heterogeneity in initial stress and (2) both stress drop and relative fault strength (the seismic $S$ parameter) affect the variation of rupture velocity and the ground-motion pattern. Interestingly, given the same stress drop distribution in model-HETERO and model-COMP, these models produce similar slip distributions (Fig. 2) and coseismic surface deformation (Fig. 3), while they display significantly different distributions of PGA and PGV (Fig. 4). This suggests that near-field seismograms are needed in future work to constrain details of rupture propagation of this event. In addition, we should emphasize that the goal of this study was to construct dynamic models with heterogeneous initial stress to reproduce the kinematic inversion result (Wen et al., 2012), and many assumptions are made for simplicity. In particular, Aochi and Fukuyama (2002) have noted that the local tectonic setting and the nonplanar fault geometry had a significant influence on the rupture propagation and slip of the 1992 Landers earthquake. In this study, it is possible that we mapped some of the effects of complex fault geometry into complex initial stress. For a better understanding of this...
event, we will consider more realistic fault geometry in future work.

An important point to note with our results is that our stress field in the preferred model-HETERO was motivated entirely to fit the final slip pattern as inferred from the kinematic inverse model; no attempt was made to fit the rupture velocity. The fact that our preferred model fits the inferred complex variable rupture velocity of the 2008 Wenchuan event serves as an additional test for the validity of this model. Thus it may be reasonable to choose constant yield strength and variable initial shear stress level to produce dynamic models for other events in the future.

Data and Resources

All data used in this paper came from published sources listed in the references, and all figures were generated using MATLAB (http://www.mathworks.com/products/matlab; last accessed November 2011), Adobe Illustrator, and Generic Mapping Tools version 4.3.1 (www.soest.hawaii.edu/gmt/, last accessed November 2011; Wessel and Smith, 1998).

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Figure 4. (a) Peak ground acceleration (PGA) and (b) peak ground velocity (PGV) distributions of model-HETERO and model-COMP. Panels from top to bottom represent fault-parallel (paral), fault-normal (nor), vertical components (vert), and magnitude (total). Stars show the epicenter of the 2008 Wenchuan earthquake, and circles indicate the location of Qingping city.

References


