Dynamic rupture process of the 1999 Chi-Chi, Taiwan, earthquake

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[1] The dynamic rupture process of the Chi-Chi earthquake has been investigated based on a 3-D spontaneous shear crack model, using a thick fault zone model and a slip-weakening friction law. Our results show that the dynamic rupture process of this event is very complex. The distribution of the rupture starting time is much more inhomogeneous than that of the kinematic model. We find that the zones with a large strength excess on the fault surface delay the rupture propagation. The rupture front jumps from the zones with high strength excess to the near zones with low strength excess when encounters the zones with high strength excess, leaving the unbroken zones behind which subsequently rupture. We also found that the motion on the hanging-wall side is larger than that on the foot-wall side. *INDEX TERMS:* 7209 Seismology: Earthquake dynamics and mechanics; 7215 Seismology: Earthquake parameters; 7260 Seismology: Theory and modeling. **Citation:** Zhang, W., T. Iwata, K. Irikura, A. Pitarka, and H. Sekiguchi (2004), Dynamic rupture process of the 1999 Chi-Chi, Taiwan, earthquake, *Geophys. Res. Lett.*, *31*, L10605, doi:10.1029/2004GL019827.

1. Introduction

[2] Compared with kinematic models, dynamic rupture models better represent the physics of the rupture process of earthquakes and frictional conditions on the fault surface. Consequently their use in constraining a rupture model can improve the accuracy of the modeling of near-source ground motion.

[3] Recently, with greater development of computer capabilities, more sophisticated dynamic models are investigated and applied to analyzing the real earthquakes. *Day* [1982] was the first to study in detail the full three-dimensional problem of spontaneous fault rupture, using a slip-weakening friction law and inhomogeneous prestress. He found that for nonuniform prestress, spatial variations of peak slip velocity are strongly coupled to spatial variations of rupture velocity, and rupture models with significant segments of supershear propagation velocities may be consistent with seismic data for some large earthquakes, even where average rupture velocity can be reliably determined to be subshear. *Madariaga et al.* [1998] formulated appropriate boundary conditions for a 3D finite-difference method to study dynamic failure on planar faults and demonstrated that the method can be used very effectively to study spontaneous rupture propagation in a realistic fault model embedded in a 3D elastic medium. In applications of dynamic models to real earthquakes, *Olsen et al.* [1997] used a finite-difference method and a slip-weakening friction law to model the dynamic source process of the 1992 Landers earthquake. Their dynamic model reproduced the main features of the low-frequency ground motion. *Oglesby and Day* [2001] applied a 3D finite-element method with a slip-weakening law to analyze the dynamics of the 1999 Chi-Chi earthquake. They showed that for dipping faults intersected with the free surface, many important features of earthquake are controlled by the fault geometry. This earthquake was also studied by *Zhang et al.* [2003]. They analyzed the dynamic source parameters of the Chi-Chi earthquake and found that the rupture followed a slip-weakening friction law for this earthquake. In this paper, we focus on rebuilding the dynamic source process of this large event based on the results of *Zhang et al.* [2003]. Due to the limited length of the paper, we do not show the synthetic records. We will present the results of simulation on the near source ground motions based on this dynamic source model in another paper.

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2. Fault Model of the Chi-Chi Earthquake

[4] *Iwata et al.* [2000] used a non-planar fault model and the data recorded at 31 stations to invert the kinematic source model of the 1999 Chi-Chi earthquake. We use the same fault model but with a thickness of 0.33 km. As shown in Figure 1, the fault surface is non-planar. When it is projected onto the free surface, the total length of the fault is 78 km and width is 39 km. The fault is divided into 26 $\times$ 13 subfaults. Each subfault has a different strike and dip angle. However most of the subfaults have a strike direction of N3°E and a dip angle of 29°.

3. Numerical Method and Boundary Conditions for the Modeling

[5] For analyzing the dynamic rupture process of the Chi-Chi earthquake, we apply the 3D finite difference method (FDM) of *Pitarka* [1999] modified for the inclined fault model. Table 1 shows the flat layered model used in our modeling. The maximum calculated frequency is 0.5 Hz. In order to satisfy the stability conditions for FDM, and also to represent the fault geometry adequately, the element grid size of FDM is 0.6 km $\times$ 0.6 km $\times$ 0.33 km. Furthermore, we assume that: (1) The rupture propagates only along the surface of the pre-existing fault rather than other surfaces; (2) The thickness of the fault zone is one element thickness of FDM, 0.33 km; (3) For a point on the fault surface, rupture occurs when the shear stress reaches the local strength excess; (4) During the rupture process, the shear stress and slip on the fault surface are collinear but anti-parallel. The rupture behavior follows the local slip-weakening law which was parameterized using *Zhang et al.*

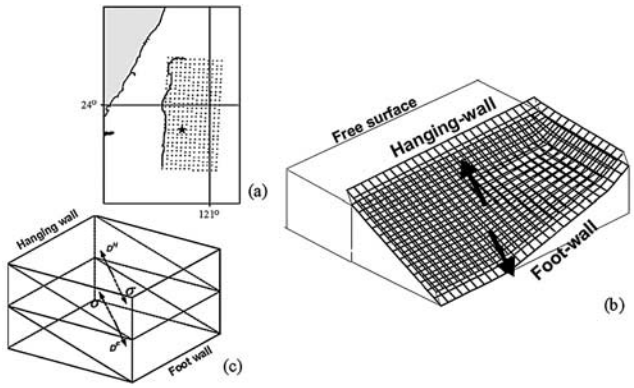

Figure 1. (a) Map showing the surface breaks of the Chi-Chi earthquake (thick line) with our fault model (dot is the center of subfault). (b) A thick fault zone model and (c) one element of the fault model.

[2003] model and the slip-weakening friction law varies over the fault surface; (5) The normal component of the motion is continuous across the fault surface.

[6] Figure 1c shows an element of the thick fault zone model. D is the total slip, and D_c is the critical slip-weakening distance. σ is the shear stress on the two sides of the fault, σ_s is the static stress level and σ_y is the strength excess. The slip-weakening law we used can be described as:

$$D = 0 \qquad for\ \sigma < \sigma_y$$

$$\sigma = \begin{cases} \sigma_y + (\sigma_s - \sigma_y)\dfrac{D}{D_c} & for\ 0 < D \le D_c \\ \sigma_s & for\ D > D_c \end{cases} \qquad (1)$$

The slip-rate on the fault surface is

$$\dot{D} = \dot{D}^H - \dot{D}^F \qquad (2)$$

Here, $\dot{D}^H$, $\dot{D}^F$ is the particle velocity on the hanging-wall side and the foot-wall side, respectively. The shear stress σ is calculated following *Zhang et al.* [2003].

[7] For a non-vertical fault, several researchers found that because of the geometrical asymmetry with respect to the free surface, the normal stress on the non-vertical fault surface is time-dependent [*Nielsen*, 1998; *Oglesby et al.*, 1998, 2000]. As described by the equations (A2), (A3), and (A4) in the paper of *Zhang et al.* [2003], in our case, we must use all stress components (τ_{xx}, τ_{yy}, τ_{zz}, τ_{xy}, τ_{xz}, τ_{yz}) to calculate the shear stress and the normal stress on the fault plane. This means that on the fault plane the normal stress is coupled to the shear stress, and consequently is time-dependent. In our scheme, we apply the slip-weakening friction law on the shear stress only.

Table 1. Structure Parameters Used in This Calculation

Depth (km)	V_p (km/s)	V_s (km/s)	Density (kg/m^3)	Q_s
0.00	2.88	1.55	2000.	100.
0.91	3.15	1.70	2050.	200.
1.91	4.37	2.50	2300.	250.
3.70	5.13	2.85	2400.	250.
8.00	5.90	3.30	2600.	270.
13.0	6.21	3.61	2700.	300.
17.0	6.41	3.71	2750.	350.
25.0	6.83	3.95	2800.	400.
30.0	7.29	4.21	3000.	500.

4. Results and Discussion

[8] For modeling the dynamic rupture process of the earthquake, we use the slip time histories of the kinematic inversion result [*Iwata et al.*, 2000] as the initial crack that starts in an area of 9 × 9 km^2 around the hypocenter. And then the shear crack propagates spontaneously along the fault surface.

4.1. Dynamic Rupture Process

[9] The resultant dynamic rupture process is represented in snapshots of slip distribution on the fault surface (Figure 2) and the distribution of the rupture starting time (Figure 3). In these figures, the corresponding results of the kinematic model are also plotted for comparison. These results indicate that the dynamic rupture initiated at a small area with low strength excess, then spontaneously propagated, circularly around the areas with low and moderate strength excess. The results reveal that the dynamic rupture process is more complex than that of the kinematic model. The rupture velocity of the dynamic model is highly variable. So, the distribution of the rupture starting time of the dynamic model is much more heterogeneous than that of the kinematic model. The dynamic source model reveals that when the propagation front encountered a high strength excess the rupture would decelerate or pause to accumulate more energy to break it. In case there were zones with low strength excess

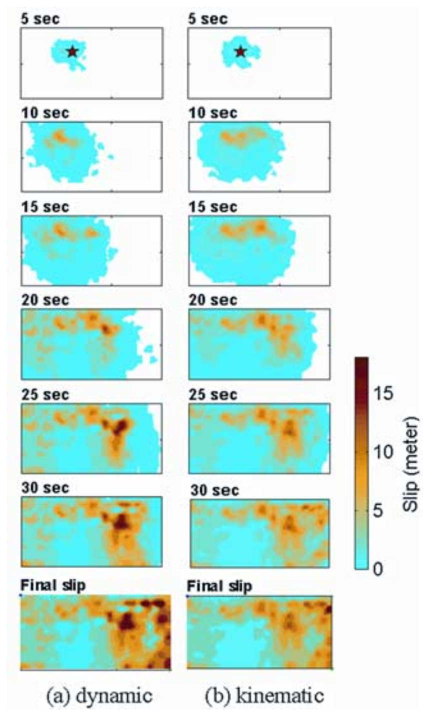

Figure 2. Snapshots of slip distribution: (a) dynamic, (b) kinematic.

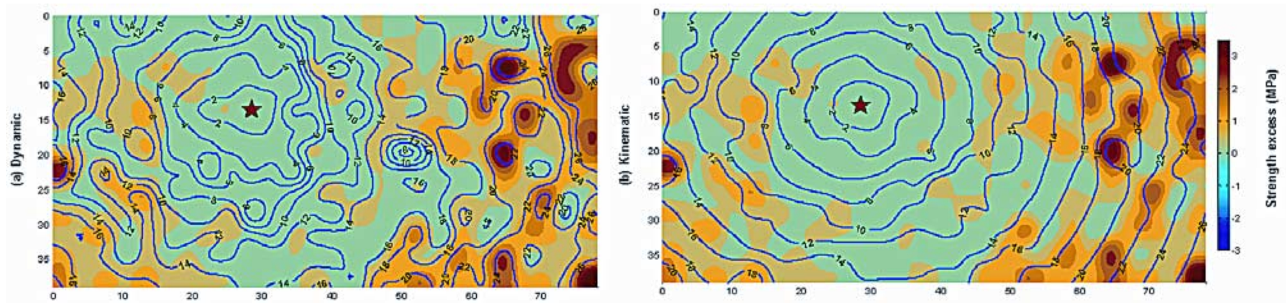

Figure 3. Distribution of rupture starting time (blue lines) with the distribution of strength excess.

around the barrier, the propagating rupture front would jump over the zone with high strength excess to the zones with low strength excess, leaving the unbroken zone behind, which would break later. For the Chi-Chi earthquake, the jumping rupture happened in the northern part of the fault at around 10 second and 20 second (Figures 2 and 3). For the kinematic model, it is difficult to reveal this jumping phenomenon although sometimes the kinematic model can reveal the phenomenon of the rupture propagation delay. From Figure 3b, we can see that the kinematic model revealed the delay phenomenon in the middle of the northern part, but failed to the other zones. This is because *Iwata et al.* [2000] used the multi-time window linear waveform inversion procedure to infer the kinematic model. Usually this method constrains the rupture front to propagate with a certain range of speed, so the rupture fronts are simply connected.

[10] Our discontinuous rupture propagation model is similar to numerical simulations of shear rupture on a heterogeneous fault plane. *Das and Aki* [1977] modeled rupture on a fault plane with high strength barriers and found that rupture could occur discontinuously beyond the strong regions that may subsequently rupture or remain unbroken. *Day* [1982] modeled the dynamic rupture of a fault with constant strength but nonuniform prestress. He found that rupture was very complex and that at some points on the fault the rupture jumped, leaving unbroken areas behind, which subsequently rupture. *Beroza and Spudich* [1988] applied a linearized inversion with a variable rupture velocity model to infer the kinematic model of the Morgan Hill earthquake. They also found a rupture jumping phenomenon for the event, in which the region of high slip ruptured after the surrounding fault had ruptured. *Shin and Teng* [2001] checked the space-time relationship of the major energy releases of the Chi-Chi earthquake. They found that there was no particular order, in time or space, with which the energy releases took place and that this phenomenon could be explained by a discontinuous rupture model. They called this type of rupture as *jumping dislocations*. They concluded that for some very large earthquakes such as the Chi-Chi event, an orderly propagation of rupture might not always happen. Our dynamic source model of the Chi-Chi earthquake provides more evidence for this hypothesis. We believe that the jumping rupture model is reasonable. Because faulting blocks are parts of the crust that in general is highly inhomogeneous, under the regional tectonic stress, the local stress field may be highly irregular and complex. Thus, the rupture may occur whenever and wherever the local stress concentration exceeds the local rock strength. In the views of dynamics, one point on a fault will break when the concentrated stress at this point exceeds its strength. Thus, the phenomenon of jumping rupture may occur for large earthquakes, such as the Chi-Chi earthquake.

4.2. Slip Distribution

[11] Figure 4 shows the particle displacement on each sub-fault. It can be seen that, in general, the displacements on the hanging-wall side are larger than the displacements on the foot-wall side, and the difference between the two sides is larger at shallower parts than that at deeper parts. The larger motion on the hanging wall is because of the asymmetry of the fault with respect to the free surface. *Oglesby et al.* [2000] used a 2D finite element method to

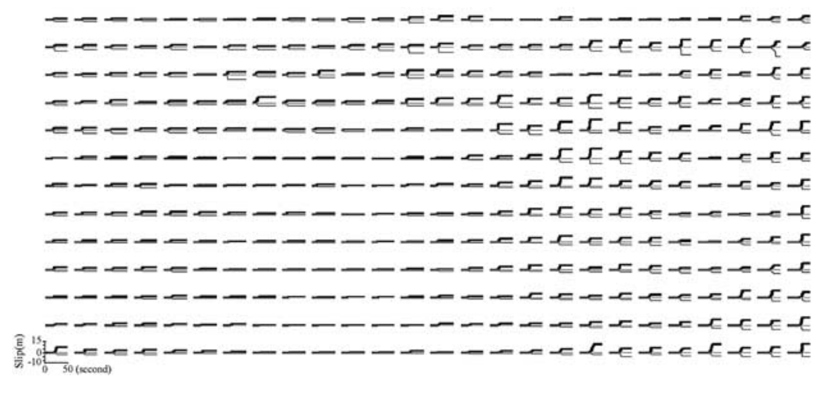

Figure 4. The time histories of the particle displacement on each subfault (thick curves are on the hanging-wall side and thin curves are on the foot-wall side).

analyze the dynamics of dip-slip faulting. They found that for non-vertical dip-slip faults the breakdown of symmetry with respect to the free surface allows radiated seismic waves to reflect off the free surface and to hit the fault again, altering the stress field on the fault. This process can lead to a feedback between the friction/rupture processes and seismic radiation. This asymmetric geometry directly leads to higher motion on the hanging walls of non-vertical dip-slip faults than on the footwalls. The result also can be understood that because of the asymmetry of the fault with respect to the free surface the hanging wall has less volume and mass near the free surface than the footwall, the hanging wall will move more under the same stress.

[12] We should point out that our dynamic model may be just one of a series of possible dynamic rupture solutions. Some researchers found that the dynamic model obtained from the inversion approach is non-unique. Considering, so far, our discontinuous rupture model is not quite common in earthquakes, in the next study, we should check whether a continuous rather than a discontinuous dynamic rupture model could equivalently fit the data as well for this earthquake. How to reduce the non-uniqueness is a great challenge to us. Maybe an improved inversion scheme needs to get source parameters with higher resolution. Such a high resolution source parameters will resolve the details of the dynamic source parameters and give us well-constrained conditions to the dynamic model to reduce the non-uniqueness.

5. Conclusion

[13] Based on the previously obtained dynamic source parameters from the kinematic model, we reconstruct the dynamic source rupture process of the Chi-Chi earthquake. We find that the rupture process of the Chi-Chi earthquake is more complex than that described in the classical propagation rupture model. Our dynamic model revealed that for a large earthquake such as the Chi-Chi earthquake the rupture propagation can be discontinuous, as suggested by many numerical simulations [*Das and Aki*, 1977; *Day*, 1982]. When the propagating rupture front encounters a zone with high strength excess, it will be decelerated or paused to accumulate more energy to break the zone. In case there are zones with low strength excess around the barrier, the propagating rupture front can jump over the barrier to the weak zones, leaving the unbroken zone behind. We also found that the motion on the hanging-wall side is larger than that on the foot-wall side which is a consequence of the asymmetry of the fault with respect to the free surface.

[14] In this paper we focus on constructing the dynamic rupture process based on the dynamic source parameters to reveal the dynamic characteristics of the Chi-Chi earthquake. Based on the understanding on the rupture processes of this earthquake demonstrated in this paper, we shall simulate the observed records to check the validation of our dynamic source model in another paper.

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