Direct Measurement of Slip-Weakening Friction from Near-Fault Strong Motion Data

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Abstract

We show using recent advances in numerical computation of spontaneous rupture propagation and the resultant radiated waves that one of the most important frictional parameters controlling earthquake rupture behavior, the slip-weakening distance D_c, may be estimated directly from near-fault strong motion records for steeply-dipping shear faults. Our results suggest that D_c in a slip-weakening model can be estimated within an error of about 50% as the ground displacement at the time of the peak slip-velocity T_{pv} from the near-field fault-parallel component of ground motion. The method is validated by accelerograms recorded in close vicinity of the causative fault for the 2000 M_w 6.6 western Tottori, Japan, and the 1992 M_w 7.3 Landers, California, earthquakes. This technique may provide the only estimate of D_c independently of the fracture energy.

Introduction

It has been demonstrated from theoretical studies and laboratory experiments (Dieterich, 1979, 1981 [1] [2], Ohnaka and Yamashita, 1989 [10], Rice and Ruina, 1983 [13], Ruina, 1983 [14]) that the constitutive friction relations play a critical role in dynamic fault rupture processes. In particular, for the popular slip-weakening models (Ida, 1977 [4], Ohnaka et al., 1987 [9], Matsu'ura, 1992 [7]) the most important parameter is the so-called slip-weakening distance D_c, which allows the decrease of friction with increasing slip. Until now, D_c has remained poorly constrained, although recent numerical studies of the 1995 Kobe earthquake in Japan (Ide and Takeo, 1995 [5]) and the 1992 Landers earthquake in California (Olsen et al., 1997 [11], Peyrat et al., 2001 [12]) have suggested values for D_c on the order of 0.5-1 m, considerably larger than earlier estimates from laboratory experiments (Dieterich, 1979, 1981 [1] [2], Ohnaka and Yamashita, 1989 [10], Rice and Ruina, 1983 [13], Ruina, 1983 [14]). However, these modeling results are limited by data resolution and may be biased by computational constraints. Moreover, both kinematic (Guatteri and Spudich, 2000 [3]) and dynamic (Olsen et al., 1997 [11], Peyrat et al., 2001 [12]) modeling studies indicate that it may not be possible to separate D_c from the fracture energy, which is the product of the critical strength drop and D_c.

Estimation of D_c

A relation between the breakdown time of shear stress, T_b, and the time of peak slip-velocity, T_{pv}, was recently established using numerical simulations in a slip-weakening model (Mikumo et al., 2002 [8]). In particular, the study suggested that the slip displacement at time T_{pv} on the fault provides a reasonably accurate value of D_c for dynamic rupture simulations. For homogeneous faults, D_c could be retrieved from T_{pv} within an error of 20% except at points near the edges of the fault. For heterogeneous faults D_c could also be estimated with an error of about 20% in the zones of high stress drop, but near the fault edges the error was found to be up to 50%.

Here, we take this idea a step further and attempt to estimate an apparent value of the slip-weakening distance (D'_c) from near-fault strike-parallel strong motion records. The main idea is that, close to the fault trace, the strike-parallel component of the particle velocity is an approximation of the slip velocity on the fault,

$$D'_C = 2u_{\|}(T_{pv}) \quad (1)$$

where $u_{\|}$ is the fault-parallel displacement, and the factor 2 is due to an equal amount of slip on both sides of the fault. To test this idea we simulate spontaneous rupture in a planar shear fault model (Olsen et al., 1997 [11], Peyrat et al., 2001 [12]) discretized with a spacing of 200 m in all dimensions using a fourth-order staggered-grid finite-difference method (Madariaga et al., 1998 [6]). Rupture is forced to initiate by lowering the yield stress in a small patch of radius 1 km inside a high-stress region near the hypocenter. For a vertical fault with homogeneous initial stress generating surface rupture in a halfspace model, we find values of D'_c with an error of less than about 20% at distances up to approximately 1/2 the fault length in the direction perpendicular to the fault trace. Figures 1A and 1B illustrate this result for simulations using D_c of 70 cm and 20 cm, respectively. If rupture terminates 1 km below the surface, D'_c decreases to values less than 75% of D_c (Figure 1C). This decrease is particularly striking within about 2 km of the surface projection of the fault due to the widening of the nodal region for the fault-parallel component of the S-wave. If the fault dips steeply, but is non-vertical, this decrease in D'_c occurs mainly in the up-dip direction of the fault (Figure 1D).

It is possible that the strong correlation between D_c and D'_c shown in Fig. 1 is in part caused by unrealistically small variations in slip duration and geometry of the rupture front in the homogeneous models. A more appropriate test of our method is obtained through the model of a historical earthquake with a realistic variation of the rupture propagation. We have selected the 2000 M_w 6.6 Western-Tottori, Japan, earthquake, in part due to two high-quality strong motion records measured immediately above the fault plane. Figure 2 shows the strike-parallel components of displacement and particle velocity recorded at stations GSH and TTRH02, the latter located at a downhole site 100 m below the surface, within a few hundred meters of the fault. The displacement and velocity records are obtained after correction for instrument response and integration of the recorded accelerations. From Figure 2 we estimate D_c^0 of 25 cm (TTRH02) and 40 cm (GSH) for the Tottori earthquake.

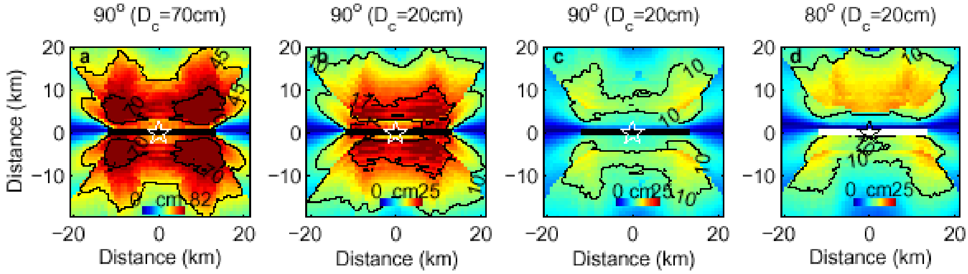

Figure 1: D_c^0 computed from fault-parallel seismograms for spontaneous ruptures with homogeneous initial stress, yield stress, for a vertical fault generating surface rupture with (a) D_c =70 cm and (b) D_c =20 cm, (c) for a vertical fault where rupture is terminated 1 km below the surface (D_c =20 cm), and (d) for a 80° dipping fault where rupture is terminated 1 km below the surface D_c =20 cm). The contours depict selected values of D_c^0 (cm). The star is the epicenter, located 11.8 km from the left side of fault, and the hypocentral depth is 10.6 km.

We used the estimate of D_c^0 at TTRH02 to simulate dynamic rupture propagation for the event. The simulation uses a heterogeneous initial stress distribution (Olsen et al., 1997 [11], Peyrat et al., 2001 [12]) computed from kinematic slip inversion with a yield stress of 50 bars. We use the hypocentral location shown in Figure 1, and the fault dips 84° toward the SW, as inferred from slip inversion. We force rupture to terminate 1 km below the surface, in agreement with the lack of surface rupture and slip inversion. The simulation generates a moment of $1{:}1e^{19}$ Nm and a distribution of D_c^0 that varies between about 50 (just outside the nodal zone near the fault) and 120% of D_c (Figure 3). The result suggests that D_c for the Tottori earthquake lies between about 15 cm and 50 cm. Although such uncertainty may seem large, we believe that this is the first constraint of D_c obtained directly from strong motion records.

The only other high-quality strong motion recording from a station located in close vicinity of the trace of a large, steeply-dipping shear fault that we are aware of is Lucerne Valley for the 1992 M_w 7.3 Landers earthquake. The station was located about 2 km SW of the Camprock/Emersonfault segment of the fault. The recorded ground motion from the Landers event at Lucerne Valley was heavily contaminated by instrument response but corrections allow the record to be used in the analysis. Despite the fault segmentation we rotate the horizontal seismograms into an average longitudinal component which, considering the predominantly long wavelengths from the rupture propagation, is reasonable for our application. We estimate from the Lucerne Valley records that D_c was on the order of 40cm for the Landers earthquake. This value is only half of that obtained from dynamic modeling (Olsen et al., 1997 [11], Peyrat et al., 2001[12]), which however poorly resolves D_c.

Discussion and Conclusions

In addition to the influence of rupture heterogeneity discussed above, the resolution of our proposed method for estimating D_c may be degraded by several factors. Tests show that near-surface low-velocity layers tend to increase D'_c to values larger than D_c, suggesting that the most accurate estimates may be obtained for faults located on rock or for strong motion records obtained at downhole sites. In fact, the slightly larger D'_c obtained at the surface site GSH compared to that for the borehole record at TTRH02 likely illustrates exactly this point. In addition, D'_c is decreased if rupture terminates below the surface. However, the influence of the near-surface layers and depth of rupture termination on D'_c can generally be estimated through dynamic modeling using site-specific information. Another source of uncertainty is soil non-linearity, which is often encountered in the typically large ground motions recorded at sites located close to the fault. Fortunately, such bias is generally stronger after T_{pv}, leaving the critical part of the motion for our analysis relatively unaffected. Moreover, records from boreholes, such as TTRH02, are less likely to be affected by non-linearity. As was the case at Lucerne Valley for the Landers earthquake, contamination of the signal by instrument response may require careful corrections of the seismic motion before estimation of D_c is possible. Finally, the uncertainty of D'_c may increase in the presence of strong heterogeneity in fault geometry and stress distribution or lack of surface rupture. However, it is usually possible to estimate the depth to the top of the fault rupture from field observations and kinematic inversion methods, as well as complexity in the rupture propagation (Olsen et al., 1997 [11], Peyrat et al., 2001 [12]) to obtain an idea of how accurately D_c may be estimated. Moreover, the nodal zone for D'_c near the fault is likely significantly reduced or absent by realistic fault heterogeneity, as for the records of the Tottori earthquake at TTRH02 and GSH. Although results may deviate by up to 50% from the actual value of D_c, we believe that our proposed method can help constrain the slip weakening distance for large, steeply-dipping shear faults. This may be the only way to estimate D_c separately from the fracture energy. If the fracture energy is calculated by dynamic modeling the estimated D_c may furthermore be used to constrain the strength drop of the earthquake. The method should be further calibrated using future, near-fault strong motion recordings.

Before this method should be applied to estimate D_c for real earthquakes, additional tests must be carried out. First, it is possible that the modeling results presented here are limited by the bandwidth of the data involved, and therefore that the estimated D_c are upper bounds for the true values. Slip inversion results for historical earthquakes, including those for the Tottori and Landers events included here, are generally limited to frequencies less than 0.5-1 Hz. Note, however, the estimate of D_c from observed unfiltered strong motion data for the Landers and Tottori earthquakes are in agreement with those for the band-limited synthetics. In any case, future modeling should test the method when higher frequencies are included. Finally, the results presented here were obtained for a simple, linear slip-weakening friction law. It is possible that the correlation between T_b and T_{pv} is degraded for a different shape of the slip-weakening relation, which should also be tested in the future.

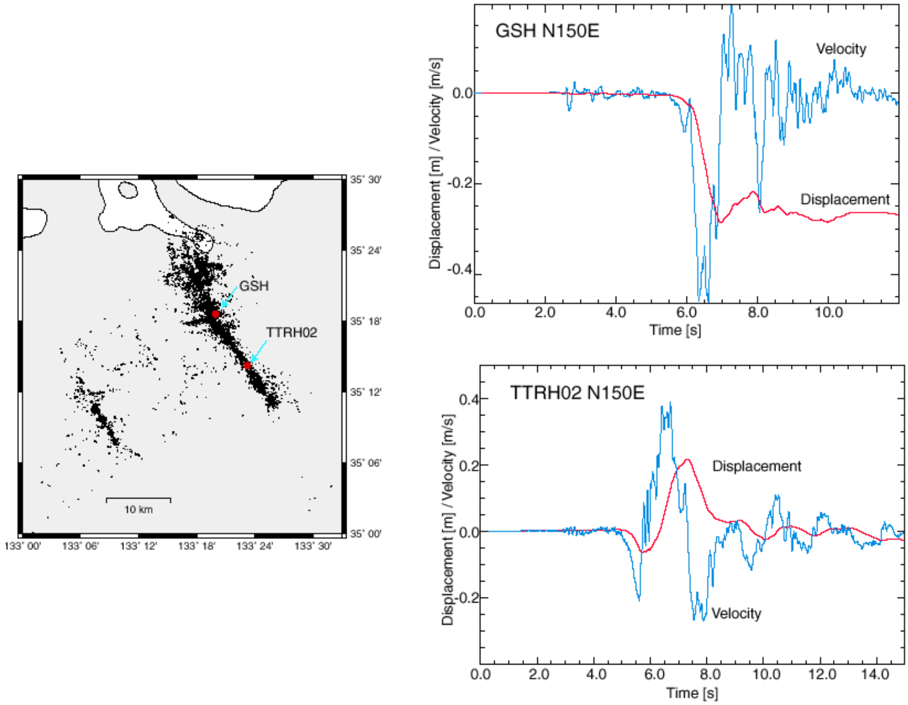

Figure 2: Strike-parallel displacement and particle velocity records for TTRH02 and GSH (see Figure 3 for location). The records suggest values of D_c^0 of 2・12.5 cm or 25 cm (TTRH02) and 2・20 cm or 40 cm (GSH).

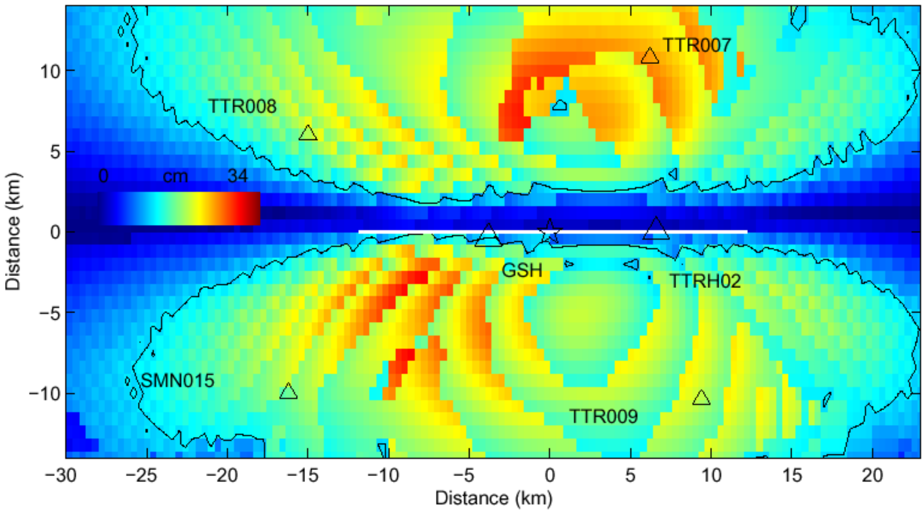

Figure 3: The distribution of D'_c for the dynamic rupture using D_c=25 cm. The contour depicts a D'_c of 14 cm. The triangles depict the locations of the stations used for comparison, and the star is the epicenter.

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