

# Direct Measurement of the Breakdown Slip From Near-Fault Strong Motion Data

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## 1. Introduction

Mikumo et al. (BSSA, 2003) have introduced a method to estimate the breakdown slip on the fault plane,  $D_c$ , as the slip at the time of the peak slip-rate ( $D_c'$ ). Recently, Fukuyama and Mikumo (GRL, Slip-weakening distance estimated at near-fault stations, 2007, hereafter F&M) extended this method beyond the fault plane. They proposed to estimate  $D_c$  directly from off-fault ground motions, up to a distance of five kilometers from the fault, as twice the rake-parallel particle displacement at the time of peak particle velocity. Using this technique they estimated  $D_c$  for the 2000 M6.6 Tottori and the 2002 M7.9 Denali earthquakes.

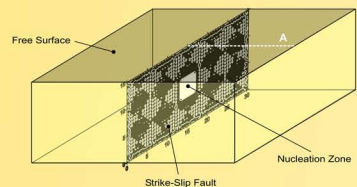
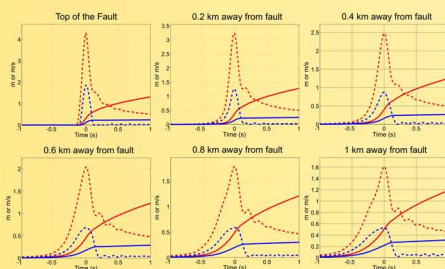


Figure 1 Model geometry for 3D simulations.

Here, we re-examine the method proposed by M&F and show that it is only valid within a very narrow zone (i.e.  $\sim 300$  m), adjacent to the fault plane, if rupture reaches the free surface. We concluded this by integrating both 2D kinematic Green's functions and 3D spontaneous rupture analysis. Our 3D simulations were performed with a recently developed and highly accurate approach, namely the staggered-grid split-node (SGSN) dynamic rupture model, in a fourth-order finite-difference method (Dalguer and Day, JGR, 2007). We assume in the 3D simulations a vertical strike-slip fault governed by a linear slip-weakening friction law.

## 2. Free Surface Amplification Factor

The free surface (FS) generates roughly an amplification factor of 2 on the ground motion (Figures 2, 3 and 4). This means that the observable used by F&M, defined as the FS displacement field at the time of peak velocity, is amplified as well. As a consequence, the procedure introduced by F&M (using full-space Green's functions) overestimates  $D_c$  roughly by a factor of two, even within the close vicinity of the fault.



	With Free Surface	Without Free Surface
Displacement	(Red dashed line)	(Blue solid line)
Velocity	(Red solid line)	(Blue dashed line)

Figure 2 (left) Rake-parallel seismograms along profile A (Figure 1) for a vertical strike-slip spontaneous rupture with breakdown slip  $D_c = 40$  cm (see legend below).

## 3. Rupture and Wave Propagation Effects

Seismograms for a 2D sub-shear anti-plane kinematic rupture were computed every 200 m from the fault assuming a regularized Yoffe slip-rate function (Tinti et al., BSSA, 2005) (Figure 5a).  $D_c'$  values for different  $T_{acc}$  periods (i.e. rise-times up to the maximum slip-rate) were computed as a function of distance from the fault (Figure 5b) finding relatively small variations, as shown by F&M. The  $T_{acc}$  parameter is closely related to the breakdown period (Tinti et al., 2005), which represents the minimum frequency to be resolved to contain information about  $D_c$ . The relative amplitude of those frequencies is plotted in Figure 5c as a function of distance from the fault and exhibits a very fast decay, as predicted by Dunham and Archuleta (GRL, 2004). Seismograms computed using the non-cohesive Kostrov slip-rate solution (i.e.  $D_c = 0$ ) (Figure 5d) clearly show that  $D_c'$  may simply correspond to the rupture and wave propagation effects implicit within the corresponding Green's functions (Figure 5e), which do not retain any information about the breakdown zone.

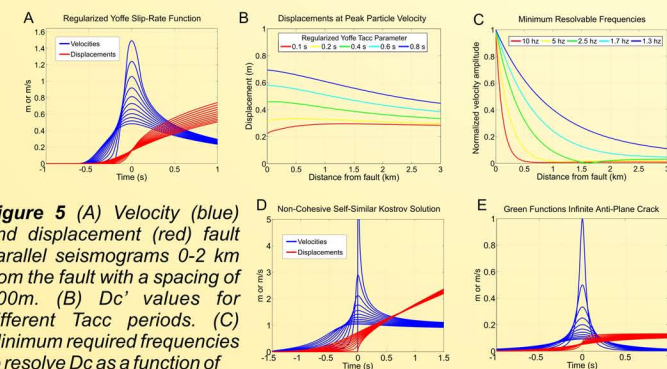


Figure 5 (A) Velocity (blue) and displacement (red) fault parallel seismograms 0-2 km from the fault with a spacing of 200m. (B)  $D_c'$  values for different  $T_{acc}$  periods. (C) Minimum required frequencies to resolve  $D_c$  as a function of distance from the fault. (D) Seismograms computed with the non-cohesive singular slip-rate Kostrov solution as a function of distance from the fault every 200 m. (E) Velocity and displacement Green's functions (same positions) considering a rupture velocity equal to 0.8 times the shear wave velocity.

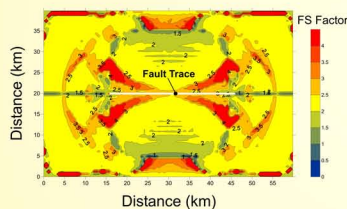


Figure 4 Free surface amplification factors on  $D_c'$  (see Figures 2 and 3). These factors correspond to the ratio of  $D_c$  estimates on the same plane (Gray plane on Figure 1) with and without the free surface boundary conditions.

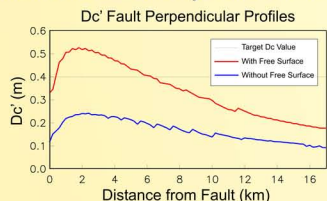


Figure 3  $D_c'$  values along profile A (Figure 1) with and without FS.

## 4. Dependence on Stress Drop and Fracture Energy

$D_c'$  is sensitive to  $D_c$  only within the close vicinity of the fault ( $\sim 300$  m). The extent of this vicinity is case dependent since the minimum required frequencies directly depend on the specific fault constitutive properties.  $D_c'$  seems to change with  $D_c$  when varying it along with other parameters, like the stress drop ( $\Delta\tau$ ) and fracture energy ( $G_c$ ) (Figure 6).

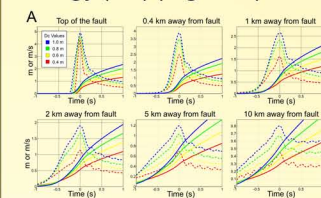


Figure 6 (Left) (A) Velocity (dashed) and displacement (solid) seismograms varying  $D_c$ ,  $\Delta\tau$  and  $G_c$ . (B)  $D_c'$  average profiles and  $D_c$  target values (dotted lines).

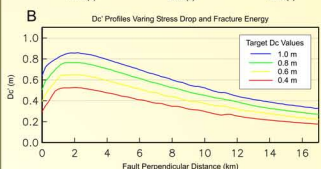


Figure 7 (Right) (A) Same as Figure 6a but keeping  $\Delta\tau$  and  $G_c$  constant. (B) Analogue to Figure 6b.  $D_c'$  is no longer sensitive to  $D_c$  except within the fault vicinity.

## 5. Strike-Slip Buried Faults and the 2004 Parkfield Earthquake

A strike-slip buried rupture was simulated twice with  $D_c = 60$  cm and different depths of 250 m and 500 m to the fault top. We have computed average  $D_c'$  values at the free surface along lines parallel to profile A (Figure 1) running from the fault trace (Figure 9). Our results show that  $D_c$  may not be estimated through  $D_c'$  when rupture is buried since the fault parallel displacement field within the fault trace vicinity is zero (i.e. nodal region). At distances from the fault trace where  $D_c'$  becomes significant (around 2 km) such an observable is already dominated by other source parameters (i.e. stress drop, see section 4).

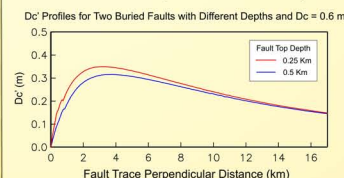


Figure 9  $D_c'$  values along the profile A (Figure 1), running from the fault trace, for two buried faults with different depths to the top and the same  $D_c = 60$  cm.

The ground motion induced by the 2004 (Mw=6.0) Parkfield earthquake has been recorded by 6 broad-band stations a few hundred meters from the fault (Figure 10). There is abundant evidence indicating that co-seismic rupture did not reach the free surface. As a result,  $D_c'$  values estimated at the 6 near-fault stations are negligible ( $< 2$  cm, Figure 10c), as predicted by our numerical simulations (Figure 9).

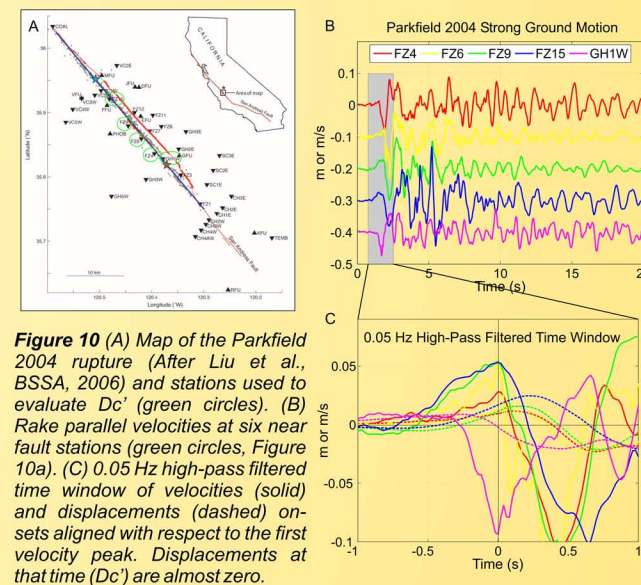


Figure 10 (A) Map of the Parkfield 2004 rupture (After Liu et al., BSSA, 2006) and stations used to evaluate  $D_c'$  (green circles). (B) Rake parallel velocities at six near fault stations (green circles, Figure 10a). (C) 0.05 Hz high-pass filtered time window of velocities (solid) and displacements (dashed) onsets aligned with respect to the first velocity peak. Displacements at that time ( $D_c'$ ) are almost zero.

## 6. Conclusions

- 1) The breakdown slip ( $D_c$ ) of sub-shear ruptures can be estimated by applying Fukuyama and Mikumo's technique (GRL, 2007) only at sites within about 300 m from the fault, if rupture reaches the free surface.
- 2) Under these restrictive conditions, F&M technique overestimates  $D_c'$  roughly by a factor of 2 by neglecting the effect of the free surface.
- 3) Since  $D_c$  may not be estimated for buried strike-slip faults, the F&M technique does not apply neither for the 2004 Parkfield (Mw=6.0) nor for the 2000 Tottori (Mw=6.6) earthquakes.