Critical Slip-Weakening Distance Inferred From Slip-Velocity Functions on Earthquake Faults

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Abstract

We estimate the critical slip-weakening distance on earthquake faults by using a new approach based on a relation between the breakdown time of shear stress, the time of peak slip-velocity, and the prescribed slip-weakening distance, which is independent of the fracture energy or radiated seismic energy. This method has been applied to the 2000 Tottori earthquakes in western Japan. We integrated the slip-velocity functions on the vertical fault obtained from kinematic waveform inversion of strong-motion and teleseismic records, from the arrival time of rupture T_r to the time of the peak-slip velocity T_{pv}, and then corrected the slip obtained at T_{pv} for the errors expected from dynamic calculations. It was found that the slip-weakening distance Dc estimated in the frequency window between 0.05 and 0.5 Hz ranges between 40 and 90 cm. These estimates are not necessarily depth-dependent, but rather spatially heterogeneous, which appears to be dependent on the local maximum slip.

Introduction

It has been demonstrated by both theoretical studies (e.g. Ida, 1972; Andrews, 1976; Day, 1982; Ohnaka and Yamashita, 1989; Matsu'ura et al., 1992; Fukuyama and Madariaga, 1998; Madariaga et al., 1998; Shibazaki and Matsu'ura, 1998), and laboratory experiments (e.g. Dieterich, 1981; Okubo and Dieterich, 1984, Ohnaka and Kuwahara, 1990; Ohnaka and Shen, 1999) that the constitutive frictional relations, particularly the slip-weakening behavior of shear stress, play a critical role in the dynamic part of the rupture process and hence on strong ground motions during large earthquakes.

For actual earthquakes, several attempts have been made to date to infer the slip weakening distance D_c by various methods (Papageorgiou and Aki, 1983; Ide and Takeo, 1997; Olsen et al, 1997; Guatteri and Spudich, 2000; Pulido and Irikutra, 2000; Ohnaka, 2000; Peyrat et al., 2001). It seems, however, that some of the D_c values may be overestimated due to limited data resolution and furthermore biased by computational constraints, although there is no doubt that D_c must be a fraction of the maximum slip on the fault. Our approach in the present study is to estimate the slip-weakening distance D_c

from strong-motion records, independently from the estimate of the fracture energy or radiated seismic energy. We apply this method to estimate D_c in the frequency range between 0.05 and 0.5 Hz for the 2000 Tottori earthquake in western Japan.

Dynamic Rupture Modeling

In order to estimate the slip-weakening slip D_c on actual earthquake faults, we perform, as a first step, numerical experiments for dynamic shear cracks propagating either spontaneously or at a fixed rupture velocity on a vertical fault located in a 3D half-space or a more realistic horizontally-layered structure. From these calculations under various conditions, we find a physically-based relation between the breakdown time of shear stress T_b, the time of peak slip-velocity T_{pv}, and the prescribed slip-weakening distance D_c, at each point on the 2D fault. T_b is the time when the shear stress drops to the level of the residual frictional stress, at which the ongoing slip reaches D_c, but cannot be directly inferred from seismic observations. Instead, T_{pv} should, in principle, be slightly different from T_b, but it is an observable parameter. The slip at T_{pv} is denoted here as D_c'. Based on such relation it is possible to use T_{pv} observed from kinematic waveform inversion of strong motion records from an earthquake, in order to estimate D_c after correcting T_{pv} for T_b. For this purpose, we solve the 3D elastodynamic equations using appropriate boundary conditions, with the second-order and fourth-order staggered grid finite difference schemes. The validity of our method may be justified from theoretical considerations using boundary integral equations given by Fukuyama and Madariaga (1998).

Numerical tests for T_b-T_{pv}-D_c' relations

First, we tested our method for a uniformly loaded vertical fault in a homogeneous half-space using a second-order finite difference scheme (Mikumo et al., 1987), for the case of a prescribed slip weakening distance of 20 cm and a uniform stress drop of 20 bars. The calculations show that the slip-weakening distance in this case can be recovered with an error of less than 30% from the measurement of the time of the peak slip-velocity T_{pv}. The rather large deviations arise mainly from the points closer to the edges of the fault.

For comparison, we also estimated the T_b – T_{pv} – D_c' relation for a preliminary version of Fukuyama-Dreger's slip model (2001) for the 2000 Tottori earthquake, which includes a vertical fault with a dimension of 25 km x 15 km located in a horizontally layered velocity structure. For a prescribed slip-weakening distance of 70 cm, we calculated this relation for 49 points nearly evenly distributed on the fault, by a fourth-order accurate finite difference method (Madariaga et al., 1998). We see that T_{pv} in this case is very well correlated with T_b. D_c' estimated from T_{pv} ranges between 63 and 85 cm, indicating that the slip-weakening distance D_c can be retrieved within an error of 17%. The deviation of D_c exceeding 10% comes from several points near the upper fault edge and near the bottom corner of the fault.

Application to the 2000 Tottori Earthquakes

Now, we apply our method to the Tottori earthquake (M_w=6.6) that occurred in the western Tottori region, western Honshu, Japan on October 6, 2000. The hypocenter of the mainshock was located at 35.27˚ N and 133.35˚ E at a depth of 11 km (Japan

Meteorological Agency, JMA). The CMT solutions from regional data and the focal mechanism solution from local data consistently provided a purely strike-slip mechanism for this earthquake (Fukuyama and Dreger, 2001; Shibutani et al., 2001). Observations from local high-resolution stations revealed that many aftershocks were distributed over a length of about 25 – 30 km in the N27˚-30˚W direction at depths between 1 and 15 km (Shibutani et al., 2001). The mainshock has been well recorded at a number of near-source strong motion stations, the K-Net and KiK-net operated by the National Institute for Earth Sciences and Disaster Prevention (NIED), regional broadband stations, and at teleseismic stations. In this study, we refer to Yagi's slip model (2001), which has been obtained from near-source strong-motion data and from teleseismic waveforms, in order to estimate the dynamic parameters.

Slip distribution from kinematic waveform inversion

Yagi (2001) performed kinematic waveform inversion of 17 strong-motion records from the 6 K-NET stations [operated by NIED] and 10 P-wave records from 10 teleseismic stations. The strong-motion data were band-passed between 0.05 and 0.5 Hz and numerically integrated to ground velocity with a sampling time of 0.25 sec. The teleseismic data were band-passed between 0.01 and 0.8 Hz and converted to ground displacement with a sampling time of 0.25 sec. For this inversion, the entire fault was divided into 3 segments, with 21 subfaults for FD1, 70 subfaults for FD2 and 14 subfaults for FD3, with dimensions of each subfault of 2 km x 2 km. The Green's functions for all subfault to strong-motion station pairs were calculated by the discrete wave-number method. The source time function on each subfault is expanded in 39 overlapping triangles, each with a duration of 0.25 sec at a time interval of 0.05 sec. The observed records and the corresponding synthetic waveforms obtained from the final inversion generally show a very good fit. It was found that large slip exceeding 1.5 m are confined mainly in the upper fault section at depths between 3 and 9 km along the strike distance between 6 and 21 km.

Spatial distribution of stress changes

Next, we calculate the spatial distribution of static stress change from the slip distribution obtained above, following the procedure of Miyatake (1992). For practical reasons, we interpolate the kinematic slip calculated at every 2 km x 2 km subfaults into 0.5 km x 0.5 km subfaults. The maximum dynamic stress drop corresponding to the maximum slip reaches 90 bars, and the stress drop in the zones of slip larger than 1.5 m is about 30 bars. At mid-depths near the WNW fault section and around the ESE fault edge and the shallowest section, there are zones of negative stress drop (stress increase).

Estimate of D_c from the slip-velocity functions

In order to estimate the slip-weakening distance through the procedure described in the foregoing sections, we numerically integrate the slip-velocity time functions from the time of the rupture arrival T_r to the time of the peak slip-velocity T_{pv} on each subfault. The calculations are made only for selected slip-velocity functions that arrive at the time T_r expected from rupture propagation and not contaminated by minor spurious oscillations. The integration procedure provides D_c' at time T_{pv}. The estimated values of D_c' range between 30 and 90 cm. To correct T_{pv} for the breakdown time T_b and estimate the actual slip-weakening distance D_c from D_c', we made dynamic calculations with the fourth-order accurate finite-difference scheme for the heterogeneous fault, using the final slip and the stress change as the observational constraints. For practical reasons, we interpolated the spatial distributions into a grid spacing of 0.25 km. The calculations were made for several selected points, for D_c = 30 cm and 70 cm. From these results we find correction factors D_c/D_c' to be applied to the observed D_c'-values are less than 10% except for one point. For some of the peripheral subfaults, the estimated values may be less reliable due to small peak slip-velocities or shapes of the slip-velocity functions contaminated by spurious oscillations. Also in some subfaults closer to the ESE fault edge, our technique does not apply because of a negative stress drop (stress increase). Excluding these subfaults, we see that estimated D_c-values larger than 80 cm are distributed on the subfaults in the strike direction between 8 and 12 km at depths between 4 and 10 km, and in the distance between 18 and 20 km at a depth around 4 km. The zones of smaller D_c-values between 40 and 60 cm are located not only near the hypocenter but also around the zones with larger values of D_c. This pattern does not necessarily indicate larger D_c at shallow fault sections nor smaller D_c at deeper fault, but rather a spatially heterogeneous distribution. We notice that D_c-values fall in the range $0.27 < D_c / D_{max} < 0.56$, suggesting that the slip-weakening distance appears correlated in some sense with the local maximum slip D_{max}.

Some Remarks

Since we have based our observations on the slip-velocity functions derived mainly from strong-motion records, possible errors in estimating D_c depend also on how accurately T_{pv} can be resolved. The resolution for T_{pv} is restricted by the frequency bandwidth of the records and by the sampling time interval of the slip-velocity functions used in the kinematic calculations. Accordingly, the Dc-values estimated here should be understood as those viewed from the limited frequency range between 0.05 – 0.5 Hz, and hence it is possible that these might be close in some way to the upper bound of their real values. Our dynamic calculations are entirely based on the simple slip-weakening model given by Andrews (1976), in which the shear stress decreases *linearly* with ongoing slip up to the critical weakening slip D_c. However, it is possible that there could be somewhat different slip-weakening behaviors such as those suggested by Ida (1972), Ohnaka and Yamashita (1989) and Campillo et al. (2001). The time of peak slip-velocity T_{pv} in thise cases would correspond to the time of rapid change of the stress and could deviate from the breakdown time T_b to some extent. It would be necessary to test these cases in the future.

The approach described in Dynamic Rupture Modeling could also be applied to near-fault strong-motion records. In our companion paper, Olsen et al. (2002) estimated D_c' directly from the strike-parallel slip-velocity and displacement waveforms recorded at the two sites.

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