A comparison between $D_c'$-values obtained from a dynamic rupture model and waveform inversion

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Received 4 April 2005; revised 10 June 2005; accepted 30 June 2005; published 29 July 2005.

[1] We investigate the validity of a method for estimating the critical slip-weakening distance ($D_c$), which was proposed by Mikumo and Yagi [2003], for a dynamic rupture model of a recent earthquake. Assuming a uniform distribution of $D_c$ on the fault, we simulated spontaneous dynamic rupture process and generated the synthetic waveforms that would be observed at actual recording stations. Then, we carried out kinematic inversion of the synthetic waveforms and obtained the slip-rate time functions on each subfault. We estimate $D_c$ from these functions and discuss whether the assumed $D_c$ could be recovered correctly. We also investigated the rupture propagation effect over each subfault with a finite dimension and the effects from the waveform inversion and band-pass filtering processes on the estimate of $D_c$. We found that the propagation effect could cause an apparent correlation between the recovered $D_c'$-values and the final slip. Citation: Yasuda, T., Y. Yagi, T. Mikumo, and T. Miyatake (2005), A comparison between $D_c'$-values obtained from a dynamic rupture model and waveform inversion, Geophys. Res. Lett., 32, L14316, doi:10.1029/2005GL023114.

1. Introduction

[2] Slip-weakening behavior of shear stress on earthquake faults plays a critical role in the dynamic part of the rupture process and hence on strong ground motions during large earthquakes. Accordingly, it is important in rupture dynamics to study the critical slip-weakening distance at which the shear stress drops to the frictional stress level. A number of seismologists have investigated the critical slip-weakening distance $D_c$ by theoretical studies [e.g., Ida, 1972; Andrews, 1976a, 1976b; Matsu'ura et al., 1992], from laboratory experiments [e.g., Okubo and Dieterich, 1984; Ohnaka, 2000] and based on seismic waveform observations [e.g., Ide and Takeo, 1997; Olsen et al., 1997; Guatteri and Spudich, 2000].

[3] Recently, Mikumo et al. [2003] estimated the critical slip-weakening distance on earthquake faults, by applying a new approach. This approach is based on the finding that the breakdown time of shear stress $T_0$ is well correlated with the time of peak slip-velocity $T_p$ at each point on the fault except at points near fault edges and strong barriers, and that $D_c$ at time $T_0$ may be approximately estimated from slip $D_c'$ at time $T_p$. The validity of this approximation has been justified by Fukuyama et al. [2003] from theoretical considerations and numerical experiments. The above method has later been applied to several large earthquakes [Mikumo and Yagi, 2003; Zhang et al., 2003; Miyatake et al., 2004]. The estimated $D_c$ values appear to be spatially variable and also proportional to the final slip. There is a possibility, however, that such proportionality might be an artifact due to low-pass filtering and/or smoothing effects of recorded waveforms during the inversion procedure [Spudich and Guatteri, 2004], and also due to the assumed shape of the source time function [Piatanesi et al., 2004].

[4] The main purpose of the present study is to investigate the validity of the method proposed by Mikumo et al. [2003]. Firstly, we construct a hypothetical dynamic rupture model for an earthquake, with a uniform $D_c$ distribution. As a second step, we generate the synthetic waveforms from this model for a number of recording stations. Then, we carry out kinematic inversion of the waveforms to obtain the mean slip rate time function on each subfault. Following Mikumo et al. [2003], we try to calculate $D_c'$ from the mean slip rate time functions to see if the assigned $D_c$-value could be correctly recovered. We also investigate the effect from rupture propagation on subfaults, which has not been taken into consideration in the previous studies [e.g., Mikumo et al., 2003], and the effects from waveform inversion and band-pass filtering on the estimate of $D_c$.

2. Dynamic Rupture Model

[5] In order to make an input data for waveform inversion in our simulation, we constructed a hypothetical dynamic rupture model for the 2001 Geiyo, Japan, earthquake ($M_w = 6.7$), with an assumption of uniform $D_c$ distribution, by referring to the previous model proposed by Miyatake et al. [2004]. In the manuscript we use “dynamic model” for dynamic rupture computation in which elastodynamic equations of motion are solved with the dynamic (stress) boundary condition [Kostrov and Das, 1988, p. 49]. Following Miyatake et al. [2004], we assumed the fault dimension of 40km long and 25km wide. We also referred to the rupture time distribution estimated from the delay time of kinematic “mean slip rate” time function on the subfault, the final slip distribution and the static shear stress change distribution that have been obtained in the kinematic model of Miyatake et al. [2004]. Assuming that the dynamic behavior of shear stress change follows a simplified slip-weakening law [Andrews, 1976a, 1976b], we assumed a critical slip-weakening distance of 25 cm distributed uniformly over the fault instead of heterogeneous distribution of $D_c$ [Miyatake et al., 2004], because one of the purpose of
our study is to study whether the correlation between obtained $D_c$ and the final slip is artificial or not. Firstly, we solve the 3D elastodynamic equations imposing the fault boundary condition of slip-weakening law with fixed rupture times on the fault, by using the 4th-order finite difference method (FD) with 3D staggered grids, where the grid interval and the time increment are taken as 0.25 km and 0.005 s, respectively. This case is not exactly a spontaneous rupture model and may be called a “quasidynamic model”. At each time step in FD computations, the calculated stress just before the arrival of rupture front is considered to be the strength excess at each point on the fault. Given the distribution of strength excess, the uniform $D_c$ distribution, heterogeneous stress drop and uniform initial stress, we performed spontaneous rupture simulations again by solving the elastodynamic equations, and then we calculated the slip $D_c$ (denoted by $D_c^0$) at the time of peak of the ‘dynamically-generated’ slip rate time function on each of the grid points.

3. Waveform Inversion Analysis

[6] We generated the synthetic waveforms from point source summation of 160 × 100 dynamic slip rate time functions described before, for teleseismic P-waves at 15 stations and for 12 components of near-field P- and S-waves at 4 strong-motion stations, which have been used by Miyatake et al. [2004]. The Green’s functions for teleseismic P-waves were calculated by using Kikuchi and Kanamori’s [1991] method and those for near-field ground motions were calculated by the discrete wave number method developed by Kohketsu [1985]. The structure model used to compute both the teleseismic body waves and near-source ground motions are shown by Miyatake et al. [2004, Table 1].

[7] In order to set the same situation as in the actual kinematic waveform inversion, the teleseismic synthetic waveforms and the near-source synthetic waveforms were bandpassed between 0.01 to 1.0 Hz and 0.1 to 0.5 Hz, respectively. We used a causal 4th-order Butterworth filter passed forward and backward to the time series.

[8] We then carried out inversion of the synthetic waveforms obtained from the above procedure. This waveform inversion was performed by the same method as described by Yagi et al. [2004]. In this case, the fault was divided into 16 × 10 subfaults (as indicated in Figure 1), each having an area of 2.5 km × 2.5 km. Applying a multi-time window analysis [e.g., Yoshida, 1992], the slip rate time function on each subfault was expanded in a series of 32 overlapped triangle functions with a rise time of 0.15 s. To stabilize the solution, we imposed here a smoothness constraint on the time and space distribution of slip, using an optimized Akaike’s Bayesian information criterion (ABIC) [e.g., Yagi et al., 2004]. From these procedures, we determined the slip distribution on the fault (Figure 2a). It should be noted that a single point source is used as the subfault Green’s function, and that rupture propagation is not included in the subfault Green’s function.

[9] In Figure 2b, the ‘inverted mean’ slip rate time functions indicated by red curves are compared with the ‘dynamically-generated mean’ slip rate time functions indicated by black curves that are the sum of the dynamic slip rate time functions within each subfault, summed at constant absolute time, which causes them to be broadened by the propagation of rupture within each subfault. It can be seen that the two time functions fit quite well each other. We calculate $D_c^{02}$ distribution at the time of peak of the ‘dynamically generated mean’ slip rate time functions.

4. Result and Discussions

[10] We compare three different types of the slip rate time functions to calculate the slip amount $D_c^0$, following the method proposed by Mikumo et al. [2003]. We calculated the slip $D_c^{01}$ at the time of peak of the ‘dynamically-
generated slip rate time function on each grid point, the slip \( D_c^{\alpha} \) at the time of peak of the ‘dynamically-generated mean’ slip rate time function on each subfault, and the slip \( D_c^{\beta} \) at the time of peak of the ‘inverted mean’ slip rate time function on the corresponding subfault. It should be noted that the inverted slip rate time functions obtained by this waveform inversion are elongated to include the effect of rupture propagation inside the subfaults because our subfault is modeled as a point source.

[11] Following Mikumo’s criterion, we exclude the data of the following locations; a) faults edges, b) barriers and its vicinity, c) final slip values smaller than 30 cm, d) the rupture starting area and its vicinity.

[12] \( D_c^{\alpha} \) does not correspond exactly to \( D_c \) because of the time difference between \( T_b \) and \( T_{pf} \) \cite{Mikumo et al., 2003}. \( D_c^{\beta} \)-values differ slightly from \( D_c^{\alpha} \) because of blurring effects of rupture propagation inside each larger subfault. \( D_c^{\alpha} \) additionally includes the effect of the inversion. Using the above three \( D_c \)’s, we can discuss the following sources of contamination in estimating \( D_c \); (1) the difference between the break down time of stress drop and the time of peak of the slip rate (2) the effect of omission of rupture propagation inside the larger-size subfaults in parameterization of the inversion process and (3) the inversion process (except the source modeling) with band-pass filtering and a smoothness constraint. In order to study the above effects (1), (2) and (3), we calculate \( D_c^{\alpha}/D_c \), \( D_c^{\beta}/D_c^{\alpha} \) and \( D_c^{\alpha}/D_c^{\beta} \) as shown in Figure 3 for selected subfaults after applying the above criterion. We also calculate the mean value and standard deviations of \( D_c^{\alpha}/D_c \), \( D_c^{\beta}/D_c^{\alpha} \), \( D_c^{\alpha}/D_c^{\beta} \) (Table 1 and Figure 4) where we omitted the data for slip tentatively less than 30 cm or 60 cm.

Figure 3. \( D_c^{\alpha}/D_c \), \( D_c^{\beta}/D_c^{\alpha} \) and \( D_c^{\alpha}/D_c^{\beta} \) for selected subfaults.

[13] In Figures 3 and 4, \( D_c^{\alpha}/D_c \)-values are somewhat smaller than 1, indicating that \( D_c^{\alpha} \)-values are partly consistent with the prescribed \( D_c \) or underestimated. \( D_c^{\beta} \)-values are almost consistent with \( D_c^{\alpha} \)-values or overestimated on subfaults from No. 55 to No. 70. This comes from ignoring the effects of rupture propagation inside each subfault, which may correspond to a weighted average of the 10 \times 10 slip rate time functions over each large-size subfault. This process is similar to the low-pass filtering effect which causes the elongation of \( D_c \) \cite{Spudich and Guatteri, 2004}. \( D_c^{\alpha} \)-values seem to be scattered around \( D_c^{\beta} \)-values.

[14] All the \( D_c^{\alpha} \), \( D_c^{\beta} \) and \( D_c^{\beta} \) values are plotted versus final slip in Figure 5. It seems that for slips less than 60 cm, \( D_c^{\alpha} \)-values are scattered between 7 and 27 cm, (and might increase with slip), but almost constant for slips larger than 60 cm. \( D_c^{\beta} \) and \( D_c^{\beta} \) have an apparent proportionality with the final slip. It seems that \( D_c^{\beta} \) is about half the total slip, which agrees with the prediction of Spudich and Guatteri [2004] based on the central limit theorem. Considering that short slip causes poor resolution of \( D_c \) and that \( D_c^{\beta} \) includes

| Table 1. The Mean Value and Standard Deviations of \( D_c^{\alpha}/D_c \), \( D_c^{\beta}/D_c^{\alpha} \) and \( D_c^{\alpha}/D_c^{\beta} \) |
|-----------------|-----------------|-----------------|
| \( D_c^{\alpha}/D_c \) | \( D_c^{\beta}/D_c^{\alpha} \) | \( D_c^{\alpha}/D_c^{\beta} \) |
| \( D > 30 \text{ cm} \) | 32 | 32 | 32 |
| Mean | 0.76 | 1.17 | 1.13 |
| Standard deviation | 0.26 | 0.25 | 0.40 |
| \( D > 60 \text{ cm} \) | | | |
| Data | 11 | 11 | 11 |
| Mean | 1.02 | 1.27 | 1.03 |
| Standard deviation | 0.09 | 0.24 | 0.30 |

Figure 4. We also estimate the mean value and standard deviations of (a) \( D_c^{\alpha}/D_c \), (b) \( D_c^{\beta}/D_c^{\alpha} \), (c) \( D_c^{\beta}/D_c^{\beta} \) where we omitted the data of short slip less than 30 cm or tentatively 60 cm.
the above three effects, we conclude that the effects of rupture propagation inside the larger-size subfaults causes such an apparent correlation. Spudich and Guatteri [2004] mentioned that low-pass filtering causes an artificial correlation between $D_c$ and the final slip. Our calculations in this study show similar effects to their results. In our simulation, the effect of inversion with band-pass filter and smoothness constraint did not give a bias of $D_c$ estimates, because the filtering effect is already included in $D_c^{\omega}$. The averaged or low-pass-filtered slip rate time functions were not much changed by additional low-pass filtering during the inversion process.

5. Conclusions

[15] We have investigated the validity of the $D_c$ estimation method, using a dynamic rupture model of the 2001 Geiyo earthquake. Following Mikumo et al. [2003], we estimated the critical slip-weakening distance and investigated whether the assumed value could be recovered correctly. We investigated the effect of rupture propagation on the larger-size subfaults adopted in the inversion process, which has not been taken into consideration in the previous studies [e.g., Mikumo et al., 2003], and also studied the effects of the waveform inversion and band-pass filtering. We found that $D_c^{\omega}$ calculated from the ‘dynamically generated mean’ slip rate functions deviates, to some extent, from the assumed value of $25$ cm, and that the rupture propagation effects inside the subfaults causes an apparent correlation between $D_c$ and final slip. $D_c^{\omega}$ obtained from the waveform inversion are relatively consistent with $D_c^{\omega}$. As mentioned by Spudich and Guatteri [2004] and Guatteri and Spudich [2000], the effect of $D_c$ on the waveforms in high frequency range seems to be quite large. If this information were retained in the inversion process, and if we could refine our method of estimation, it would not be impossible to correct the obtained $D_c^{\omega}$-values for the estimate of $D_c$ distribution on the fault.

[16] Acknowledgment. We wish to thank Prof. Raul Madariaga and Dr. Paul Spudich for helpful comments.

References


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Figure 5. The estimated $D_c^{\omega}$-values plotted versus the final slip on subfaults.