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HIGH-FREQUENCY SEISMIC WAVE RADIATION FROM ANTIPLANE COHESIVE ZONE MODEL AND f_{max} AS SOURCE EFFECT

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Abstract

While a high-frequency cutoff, f_{max}, is widely observed in strong-motion seismic data, there is no consensus on whether it is due to source processes or to attenuation and scattering of high-frequency radiation in the crust or near the surface. To investigate the ability of source processes to control f_{max}, we use a standard antiplane crack propagation formalism to numerically model the effect of rupture nucleation and arrest on high-frequency radiation based on a simple physical hypothesis, a slip-weakening model. We model rupture arrest due to three types of inhomogeneity: (1) a strong portion of rupture medium (barrier); (2) a drop in the pre-existing stress distribution of rupture medium; and (3) a finite length of unruptured medium (asperity) lying between previous ruptures. For cases (2) and (3) high frequencies fall off more steeply than ω^{-2}, and f_{max} cannot be properly defined. For case (1), we find that $f_{max} = V_f L_f / L_i^2$, where V_f is the final crack velocity, L_f is the final rupture length, and L_i is the initial crack size. We extrapolate this result to the rupture for a three-dimensional model and try to explain observed f_{max}. If we assume that an earthquake is a single crack, L_i is large for a large earthquake. However, if we assume that an earthquake is made up of set of cracks and asperities, f_{max} will be determined by the interaction of small cracks and barriers. If the distribution of these cracks and asperities is independent of source size, then f_{max} will be nearly constant for all earthquakes.

Introduction

Using observations of strong ground motions near seismic faults, Hanks (1982), Gusev (1983), Papageorgiou and Aki (1983), Faccioli (1986), and Papageorgiou (1988) observed an upper limit on the frequency of acceleration spectra, f_{max}. It is controversial whether f_{max} is due to source processes (Papageorgiou and Aki, 1983) or to attenuation and scattering in the crust or near the surface (Hanks, 1982). Observed seismic waves are affected by attenuation and scattering and have f_{max}^{path} due to such effects (e.g., Hanks, 1982). However, Fujiwara *et al.* (1989), Faccioli (1986), Umeda *et al.* (1984), and Aki and Papageorgiou (1988) reported that f_{max}^{source} due to source processes exists by eliminating the local-site and path effects from observed data. According to their studies, f_{max}^{source} is nearly constant or slightly depends on earthquake size. In this article, f_{max} refers to f_{max}^{source}.

In order to explain f_{max}, it is assumed that near the crack tip there is a cohesive zone that weakens stress concentration at the crack tip. The cohesive zone is introduced by considering a slip-weakening model. Based on the experiments of rock rupture, Ohnaka *et al.* (1986) and Okubo and Dieterich (1984) reported that the critical displacement D_c, which is one of the parameters in the slip-weakening model and relates to the size of the cohesive zone, depends on the geometrical shape and the roughness of the fault plane. The greater the roughness is, the larger D_c is. Using a rupture velocity V and a cohesive zone size L, Papageorgiou and Aki (1983) and Aki (1985) showed that V, L, and f_{max} have the following relation:

$$f_{max} = V/L.$$

They obtained this relation, however, under static conditions and did not consider the dynamic properties of V and L. In this study, f_{max} is simulated under dynamic conditions.

Another important point is that seismic waves from earthquakes have been observed to follow the scaling law predicted by the ω^{-2} model. It is necessary to investigate whether or not the seismic radiation from each simulation follows the scaling law of the ω^{-2} model. As the f_{max} discussed in this article means the cut-off frequency in the ω^{-2}-model, if the radiated seismic waves do not follow the ω^{-2}-model, we can not discuss the f_{max} for such models.

The rupture propagation is simulated, using an antiplane shear crack. Numerical simulations of rupture propagation have been carried out by many researchers. In 2-D crack studies, Das and Aki (1977a) used Hamano's criterion, and Yoshida (1985) used Irwin's criterion. In 3-D crack studies, Day (1982) simulated the rupture process with a slip-weakening criterion, while Miyatake (1980a, b). Virieux and Madariaga (1982), and Das (1981) used a maximum stress criterion. Furthermore, Das and Aki (1977b) simulated rupture propagation for a 2-D inplane barrier model and Das and Kostrov (1983) for a 3-D single asperity model. The method of simulation used in this article is equivalent to that of Andrews (1985). Andrews (1976a, b, 1985) emphasized rupture propagation, neglecting the effects of rupture arrest on seismic radiation. Here we account for both the growth and the arrest of the rupture.

Inhomogeneities of fault planes affect the radiation of high-frequency seismic waves. In this article, crack propagation and arrest are simulated for three cases of inhomogeneities: case 1: a strong portion of rupture medium (barrier); case 2: a drop in the pre-existing stress distribution of rupture medium; and case 3: a finite length of unruptured medium (asperity) lying between previous ruptures. The properties of high-frequency seismic waves radiated from each inhomogeneity model are studied from the simulated results.

The main purpose of this article is to demonstrate a source model that explains both the ω^{-2} scaling law and the cutoff frequency f_{max}.

Slip-Weakening Model and Quasi-Static Crack

A crack in a perfectly elastic body creates a $1/\sqrt{x}$ stress singularity with x being the distance from the crack tip. Barenblatt (1959) and Ida (1972) showed that the singularity can be eliminated by assuming the stress to be a function of the displacement in the region of the crack tip. Ohnaka and Yamashita (1988) gave the following relation, based on laboratory experiments:

$$\tau = (\tau_0 - \tau_f)[1 + \alpha \log(1 + \beta \Delta u)]\exp(-\eta \Delta u) + \tau_f, \tag{1}$$

where τ_0 is initial stress, τ_f is dynamic frictional stress, Δu is displacement, and α, β, and η are constants. This equation eliminates not only the stress singularity in the vicinity of a crack tip but also the singularity in acceleration.

We have approximated (1) with the following equation, which is equivalent to the slip-weakening model of Andrews (1976a, b) (Fig. 1).

$$\begin{aligned} \tau &= \tau_0 \sim \tau_f, && \Delta u = 0 \\ &= \tau_u - (\tau_u - \tau_f) \cdot \Delta u / D_c, && 0 < \Delta u \le D_c, \\ &= \tau_f, && \Delta u > D_c \end{aligned} \tag{2}$$

where τ_u is yield stress, τ_0 is initial stress, τ_f is frictional stress, D_c is critical displacement, and Δu is displacement. Ohnaka *et al.* (1987a, b) confirmed from analysis of experimental data that τ_u, τ_f and D_c can be regarded constants during rupture propagation.

If the slip-weakening model is assumed, a crack whose size is less than $2L_c$ is stable. L_c is determined from the parameters in the slip-weakening model. The quantity $G_0 = D_c(\tau_u - \tau_f)/2$ is defined from equation (2) and provides a rupture criterion. G_0 is the maximum value of the energy stored per unit area of the cohesive zone. If the crack is small and the energy stored per unit area of the cohesive zone is less than G_0, rupture does not nucleate. In this article, such a crack is called quasi-static. An upper bound on the quasi-static crack length $2L_c$ exists and L_c is regarded as the maximum length of the static cohesive zone size.

Solving the following equation, we can obtain L_c for the antiplane shear crack.

$$\frac{\partial^2 \Delta u}{\partial x^2} + \frac{\partial^2 \Delta u}{\partial y^2} = 0$$

$$\begin{cases} \mu \dfrac{\partial \Delta u}{\partial y} = \tau_u - \tau_0 - (\tau_u - \tau_f) \cdot \Delta u / D_c, & |x| \le L \\ \Delta u = 0, & |x| > L \\ \lim\limits_{\epsilon \to 0} \mu \left.\dfrac{\partial \Delta u}{\partial y}\right|_{L+\epsilon} = \tau_u - \tau_0 \end{cases} \tag{3}$$

Method of Computation

We consider a two-dimensional antiplane shear crack (Fig. 2). The fault plane is taken on the $x - z$ plane. The crack is infinite along the z axis and symmetric about the z axis.

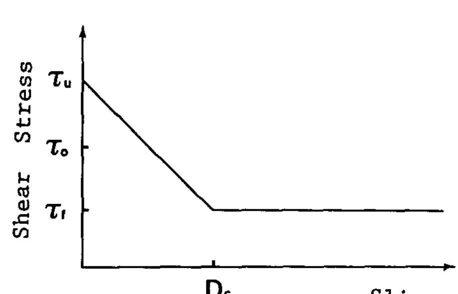

FIG. 1. Relations between stress and slip in our calculation. τ_u, τ_0, and τ_f are yield stress, initial stress, and frictional stress, respectively. D_c is critical displacement.

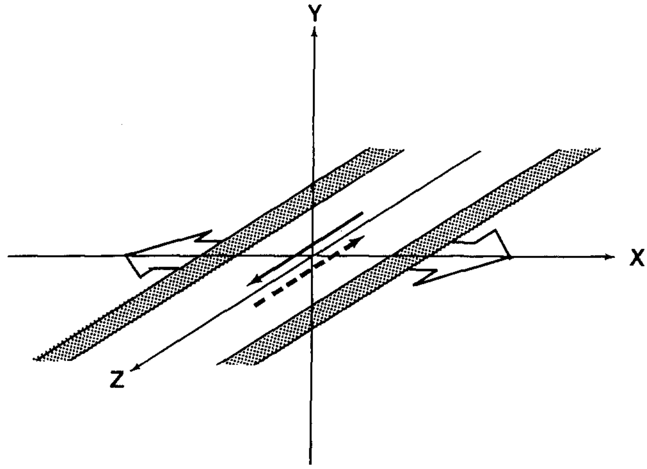

FIG. 2. Antiplane shear crack with cohesive zones. The shaded areas are cohesive zones. The crack is infinite along the z axis and symmetric about the z axis.

The displacement Δu satisfies

$$\frac{1}{\beta^2}\frac{\partial^2 \Delta u}{\partial t^2} = \frac{\partial^2 \Delta u}{\partial x^2} + \frac{\partial^2 \Delta u}{\partial y^2}. \tag{4}$$

The boundary conditions for (4) are

$$\begin{aligned} &\Delta\tau = \mu\frac{\partial \Delta u}{\partial y} = \tau_f - \tau_0, && \text{inside the crack} \\ &\Delta\tau = \tau_u - \tau_0 - (\tau_u - \tau_f)\Delta u/D_c, && \text{inside the cohesive zone} \\ &\Delta u = 0, && \text{outside the crack} \end{aligned} \tag{5}$$

and the initial conditions are

$$\begin{aligned} \Delta u(x,0,0) &= \Delta u_0(x) \\ \Delta\tau(x,0,0) &= \Delta\tau_0(x) \end{aligned} \tag{6}$$

where Δu is displacement, $\Delta\tau$ is stress drop, β is shear-wave velocity, τ_f is frictional stress, τ_u is yield stress, τ_0 is initial stress, and $\Delta u_0(x)$ and $\Delta\tau_0(x)$ are the displacement and the stress drop of the initial crack, respectively.

The boundary conditions (5) and initial conditions (6) are not enough to solve differential equation (4), as they do not include information about the location of the crack tip. A rupture criterion gives this information. The criterion we use is given by $G > G_0$, based on the slip-weakening model. This criterion is based on an energy balance and is equivalent to the Griffith criterion.

From the differential equation (4), we obtain

$$\Delta u(x,y,t) = \frac{2}{\mu}\iint_S g(x,y,t;x',0,t')\Delta\tau(x',0,t')\,dx'\,dt', \tag{7}$$

where

$$g(x, y, t; x', 0, t') = \frac{H\left\{(t - t') - \left[(x - x')^2 + y^2\right]^{1/2}/\beta\right\}}{2\pi\sqrt{(t - t')^2 - \left\{(x - x')^2 + y^2\right\}/\beta^2}}, \tag{8}$$

and S is the region such that $t - t' < |x - x'|/\beta$.

Discretizing (7) we obtain

$$\Delta u(x_M, 0, t_N) = \frac{1}{\pi\mu} \sum_{i=1}^{L} \sum_{j=1}^{N} \Delta\tau(x_i, 0, t_j)\bar{g}(x_M, t_N; x_i, t_j), \tag{9}$$

where

$$\bar{g}(x_M, t_N; x_i, t_j) = \int_{x_i - \frac{\Delta x}{2}}^{x_i + \frac{\Delta x}{2}} \int_{t_j - \frac{\Delta t}{2}}^{t_j + \frac{\Delta t}{2}} g(x_M, 0, t_N; x', 0, t')\, dx\, dt'. \tag{10}$$

When we take Δx and Δt such that $\Delta x = \beta \Delta t$, then

$$\Delta u(x_M, 0, t_N) = \frac{1}{\pi\mu} \sum_{i=1}^{L} \sum_{j=1}^{N} \Delta\tau(x_i, 0, t_j)\bar{g}(x_M, t_N; x_i, t_j) + \frac{1}{\pi\mu} \Delta\tau(x_M, 0, t_N)\bar{g}(x_M, t_N; x_M, t_N). \tag{11}$$

If we know Δu and $\Delta\tau$ for all time $t < t_{N-1}$, the first term of the right side of (11) is known, and (11) gives the relation between $\Delta u(x_M, 0, t_N)$ and $\Delta\tau(x_M, 0, t_N)$. Adding this equation to equation (5), which is obtained from the slip-weakening model, we can solve for Δu and $\Delta\tau$ at time t_N. Then we have to determine whether the point $(x_M, 0, t_N)$ is inside the crack, in the cohesive zone, or out of the crack. The slip-weakening criterion gives the information for this judgment.

Theoretically, we should take the quasi-static crack whose size is $2L_c$ as the initial conditions. However, if we use this critical crack, too much time is consumed before the rupture starts. We therefore use a crack size slightly larger than L_c in the initial conditions.

Models for Computation

Strength and initial stress are inhomogeneous on fault planes. High-frequency seismic waves are radiated when the rupture velocity changes rapidly due to these inhomogeneities (Madariaga, 1977; Yamashita, 1983). In this article, these inhomogeneities are classified into three cases. For each case, the rupture propagation and arrest of a crack with a cohesive zone is simulated and the change of the rupture velocity, the size of cohesive zone, and the seismic wave radiation are investigated. We can regard each case as a single earthquake or as components of an earthquake.

In case 1, there are regions where the strength is very high and where the strength is relatively low. The regions of high strength are called barriers. When a crack nucleate in a region of low strength and the crack tip reaches a barrier, the rupture propagation temporarily or permanently stops. We assume here that the strength of the barrier is infinite.

In case 2, the strength is uniform, however the prestress is inhomogeneous. We assume there is a region of high initial stress surrounded by regions in which the initial stress τ_0 is equal to the frictional stress τ_f. The rupture starts at the high prestress region and the rupture propagates into the low prestress region.

In case 3, a region where strength and prestress are high exists surrounded by regions where strength and prestress are very small. This means that an unbroken region is left within a broken region. This unbroken region is an asperity. In our calculation, $\tau_0 = \tau_f$ and strength $G = 0$ are assumed out of the asperity. This model is proposed by Rudnicki and Kanamori (1981).

RESULTS

Initiation of Rupture

The rupture starts spontaneously in all cases. the rupture process is shown in Figures 3, 4, and 5. The rupture velocity is slow at first and gradually

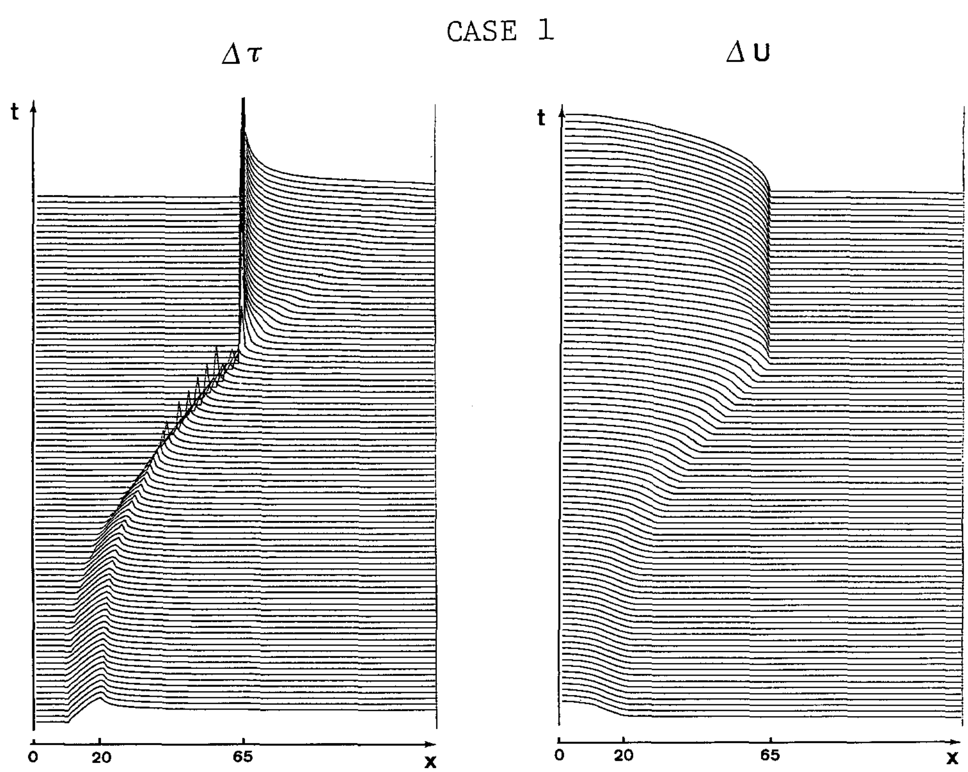

FIG. 3. Plots of $\Delta\tau(x, t)$ and $\Delta u(x, t)$ for the barrier model (case 1). The region for $X > 65$ is a barrier.

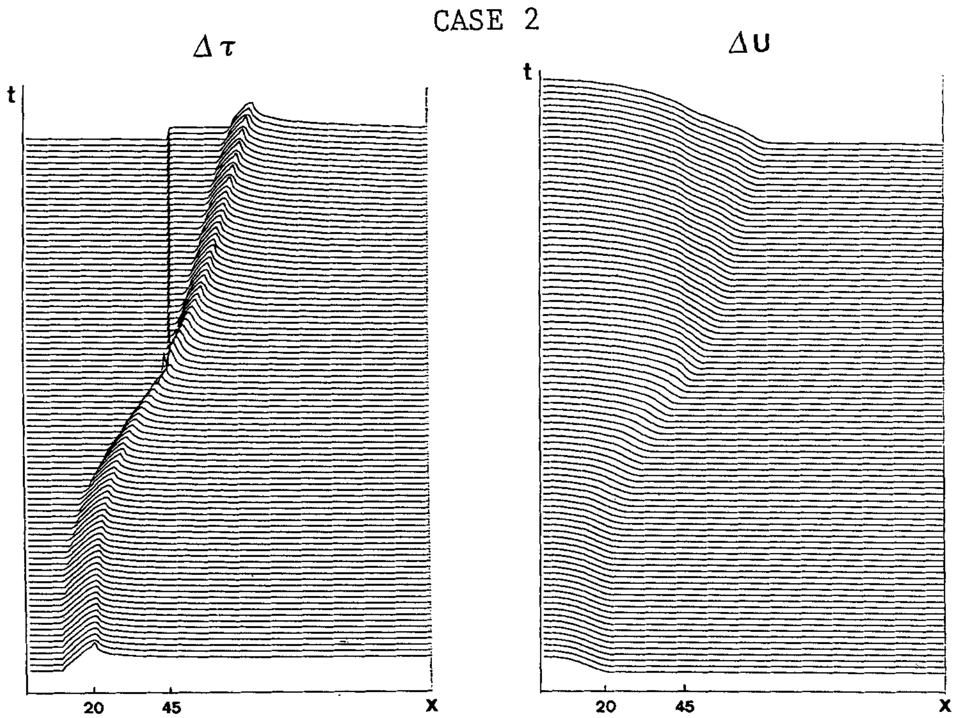

FIG. 4. Plots of $\Delta\tau(x, t)$ and $\Delta u(x, t)$ for the prestress discontinuity model (case 2). $\tau_0 = \tau_f$ in the region for $X > 45$.

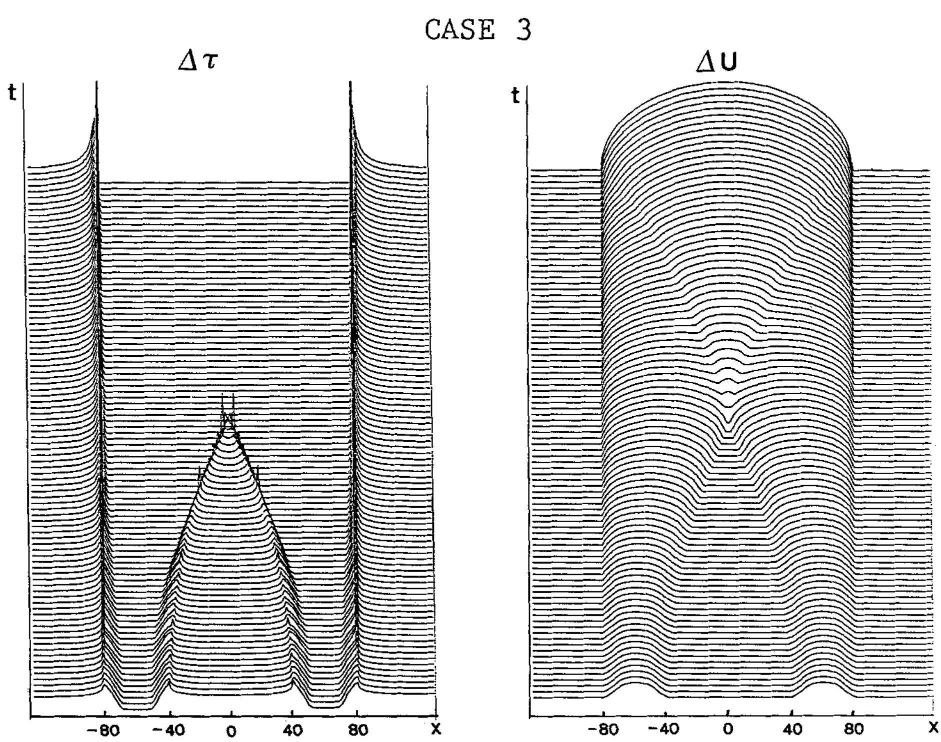

FIG. 5. Plots of $\Delta\tau(x, t)$ and $\Delta u(x, t)$ for the asperity model (case 3). The region for $-20 < x < 20$ is asperity. The regions for $x < -40$ or $x > 40$ are unbroken regions.

accelerates to the shear-wave velocity. The cohesive zone size is largest at the beginning of rupture propagation. As the crack grows, the cohesive zone size is smaller in inverse proportion to the crack size (Fig. 6).

Stopping of Rupture

Case 1 (Barrier Model). When the crack tip reaches a barrier, the rupture stops. In the calculated example used here, the rupture propagates at nearly the shear-wave velocity just before the crack tip reaches the barrier and suddenly stops, as shown in Figure 3. Therefore, the rupture velocity has a discontinuity at this point. The size of the cohesive zone becomes one third of the initial cohesive zone size just before the crack tip reaches the barrier. From this calculation we find that the size of cohesive zone is inversely proportional to the crack size.

Case 2 (Prestress Discontinuity Model). The results for this case are shown in Figure 4. The rupture velocity is nearly the shear-wave velocity just before the crack tip reaches the region where $\tau_0 = \tau_f$. After the crack tip crosses into that region, the rupture velocity in the calculated example decelerates to one third of the shear-wave velocity. We did not continue the calculation for the complete arrest of rupture to save computational time; however, by calculating rupture stability for the static model, we can estimate that the crack will be stable when the crack tip is at $x = 85$ and the cohesive zone size is 7 for this example. We guess that the rupture stops when the crack tip reaches around the point $x = 85$. The cohesive zone spreads after the crack tip crosses into the region where $\tau_0 = \tau_f$. Inside the region of $\tau_0 = \tau_f$, the size of the cohesive zone remains constant as the crack grows.

Case 3 (Asperity Model). As shown in Figure 5, the asperity is the region between two cracks. The strength in the region $|x| > 80$ is infinite. In this example, the rupture starts at both sides of the asperity. When the rupture fronts from both sides reach to the center of the asperity, the asperity is completely broken. However, the slip on the fault plane continues until the region made up of two initial cracks and the asperity is completely broken.

Displacement and Slip Velocity on the Fault Plane

If a cohesive zone does not exist, the displacement on the fault plane is proportional to $H(t)\sqrt{t}$ at the rupture front, and the slip velocity has a

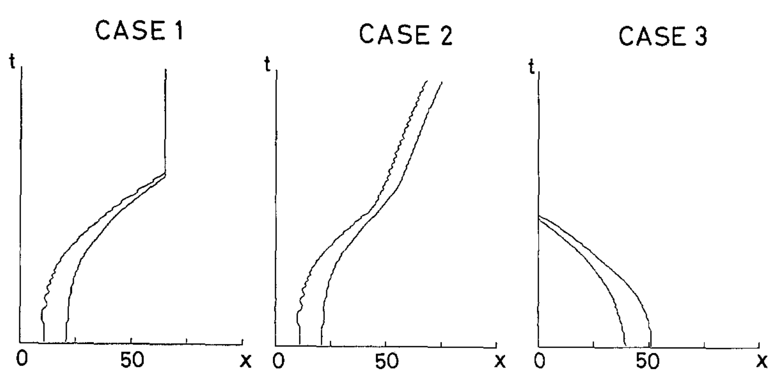

FIG. 6. Locations of cohesive zones.

singularity of $H(t)/\sqrt{t}$. If a cohesive zone does exist, such a singularity is weakened in proportion to the cohesive zone size. For case 1 (Fig. 7), the slip velocity has a discontinuity of $H(t)$ form due to the stopping phase if cohesive zone does not exist. Such a discontinuity is weakened by the cohesive zone effect. The cohesive zone effect used here means the effect of the cohesive zone on seismic waves radiated as a so-called stopping phase. For case 2 (Fig. 8), since the rupture velocity changes continuously, there do not appear to be phases corresponding to the stopping phase in case 1. The slip velocity in case 2 changes more smoothly than in case 1. For case 3 (Fig. 9), the slip velocity has peaks due to phases radiated when the asperity is completely broken. However, the slip velocity does not include a step-function form.

Near-Field Displacement and Velocity

Madariaga (1983) obtained an analytic solution for the semi-infinite antiplane shear crack without a cohesive zone. He also discussed the high-frequency radiation due to discontinuities in strength and that due to variations in stress intensity. He considered a semi-infinite crack, while our calculations are for a finite crack. We cannot, therefore, compare all seismic phases but only individual phases radiated by the discontinuities in rupture velocity and dynamic stress drop.

According to the analytic solution obtained by Madariaga (1983), the velocity waveform for case 1 has a discontinuity proportional to $H(t)$ due to the stopping phase if a cohesive zone does not exist. Because of this discontinuity, the spectral shape of the seismic wave follows the ω^{-2}-model. As the model we used here has a cohesive zone, this discontinuity is weakened (Fig. 10). The size of

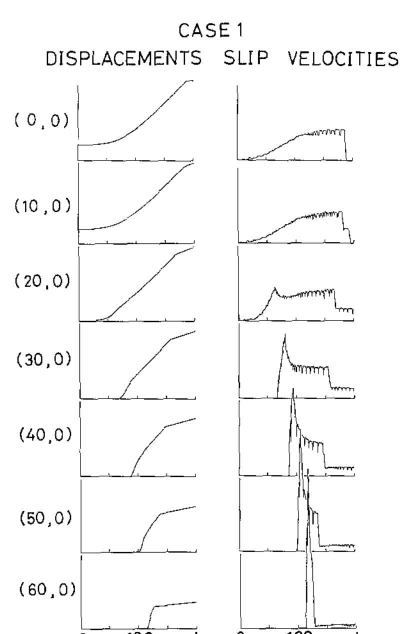

FIG. 7. Displacements and slip velocities on the fault plane for case 1. The slip velocities are obtained from finite differences of the displacements. Small negative-spikes seen in the velocity waveforms are caused numerical noise.

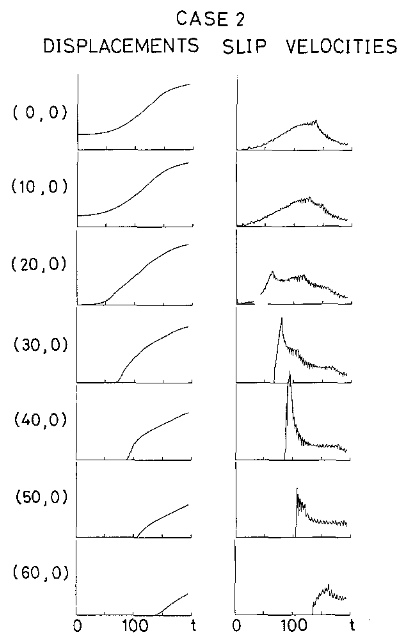

FIG. 8. Displacements and slip velocities on the fault plane for case 2.

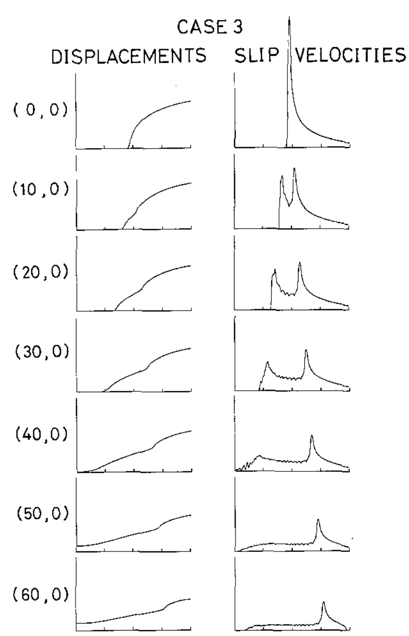

FIG. 9. Displacements and slip velocities on the fault plane for case 3.

the cohesive zone becomes smaller than L_c when the rupture arrests. Therefore, the effect of the cohesive zone is restricted to a higher frequency than that expected from the static condition. For cases 2 and 3 (Figs. 11 and 12), the velocity waveforms have no step-function discontinuities. This means that the seismic waves radiated in cases 2 and 3 do not follow the scaling law of the

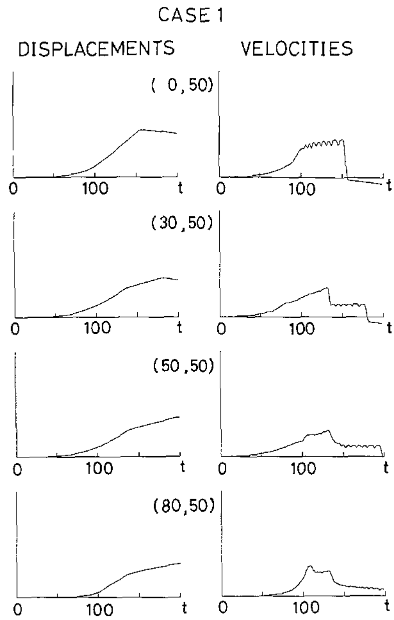

FIG. 10. Near-field displacements and velocities for case 1. The velocity wave has discontinuities due to the stopping phase. However, these discontinuities are weakened by the existence of cohesive zones.

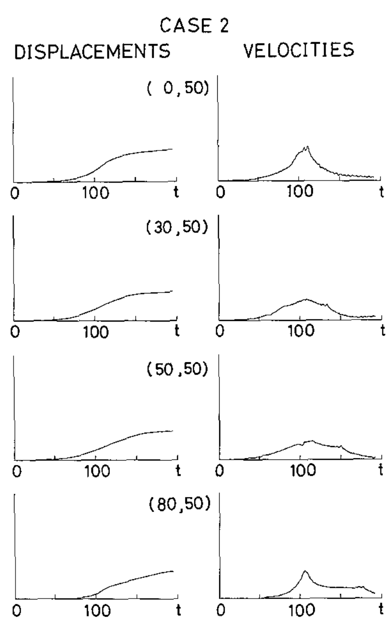

FIG. 11. Near-field displacements and velocities for case 2.

ω^{-2}-model. Therefore, in order to discuss $f_{\max}$ under the condition that the seismic radiation should follow the ω^{-2}-model, we have to consider case 1. The seismic waves radiated in cases 2 and 3 are less important than those in case 1, if we restrict our interest to $f_{\max}$. However, when a lower frequency than $f_{\max}$ is studied, it is important to consider cases 2 and 3.

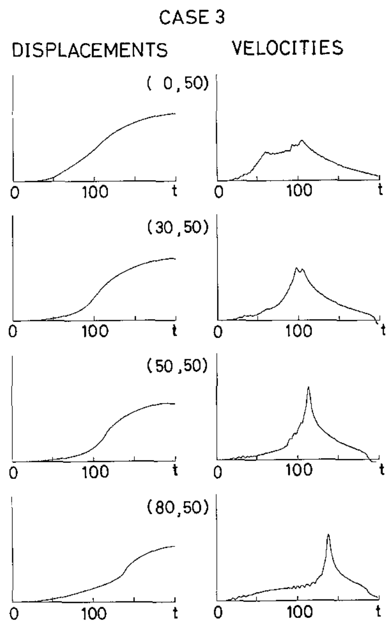

FIG. 12. Near-field displacements and velocities for case 3.

Discussion and Conclusions

In our simulation, we showed that the seismic waves that have f_{max} and follow the scaling law of the ω^{-2}-model are only radiated in case 1. Following Papageorgiou and Aki (1983) and Aki (1985), the relation between rupture velocity $V(t)$, cohesive zone size $D(t)$, and f_{max} is obtained for case 1:

$$f_{max} = V(t_0)/D(t_0), \tag{12}$$

where t_0 is the time that the stopping phase is radiated.

According to our results, $D(t)$ is inversely proportional to the crack size. Therefore

$$D(t) = L_c^2/L(t). \tag{13}$$

L_c is the maximum cohesive zone size and $L(t)$ is the crack size at time t. From (12) and (13), we obtain

$$f_{max} = V(t_0)L(t_0)/L_c^2. \tag{14}$$

This relation is obtained from a restricted model for a two-dimensions antiplane. However, it is expected that a similar relation holds for three-dimensional models. Using (14), we attempt to explain the observed f_{max}.

At first, we assume that both large earthquakes and small earthquakes consist of a single crack. If the initial crack sizes are the same, then the f_{max} of the large earthquake will be high. However, observed f_{max} only slightly depends on earthquake size (e.g., Faccioli, 1986; Fujiwara *et al.*, 1989). The f_{max}'s of large earthquakes are a little lower than those of small earthquakes. Therefore, in order to explain observed f_{max} by the single crack model, it must be assumed that L_c's are different between large earthquakes and small earthquakes. We need to consider that large earthquakes have large initial cracks and small earthquakes have small initial cracks.

Another model is obtained if we assume that an earthquake consists of a set of inhomogeneities. These inhomogeneities include cases 1, 2, and 3. In the rupture process, cases 1, 2, and 3 locally appear many times. In this model, the high-frequency seismic waves related to f_{max} are locally radiated when small cracks temporally stop at barriers. Lower-frequency contents than f_{max} are radiated when asperities are broken. The asperities behave as barriers until they are eventually broken. In this model, f_{max} only relates to cohesive zone sizes of small cracks. Therefore, if the distribution of these cracks and asperities is independent of source size, then f_{max} will be nearly constant for all earthquakes.

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