Simulation of earthquake rupture process and strong ground motion

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Abstract

Computer simulation of the strong ground motion generated from the earthquake rupture process on a shallow strike-slip fault are carried out by using a 3-D finite difference method. The faulting process is modeled using a dynamic crack model with fixed rupture velocity or with finite-stress-fracture criterion. The near-source ground motion is sensitive to the details of slip-rate or slip-acceleration function. So we do not choose the kinematic modelling in which slip-rate time need to be assumed. In dynamic modelling, the slip-rate time function at each fault point is calculated by solving 3D wave equation of motion.
The variability of peak ground velocity patterns, correlated with fault location and source parameters such as stress drop or rupture velocity is investigated. Our findings suggest that these patterns are strongly affected by rupture directivity and the uppermost depth of the fault, or that of the asperity. These results help better predict the strong ground motion generated from a potential fault.

Introduction

Near-field ground motion depends on various factors, including surface topography, soil conditions, and earthquake source parameters. The multiple effects due to topography and the subsurface structures of a site have long been a focus of interest, particularly in the engineering community.

On the other hand, theoretical studies of relationships between strong motion and earthquake source parameters were carried out by several authors[Aki, 1968; Haskell, 1969; Anderson, 1974; Boore and Zoback, 1974; Levy and Mal, 1976; Israel and Kovach, 1977; Hartzell, 1978; Bouchon, 1979, 1980; Olsen and Archuleta, 1996]. Through these studies, the effects of the rise time of particle displacement, rupture velocity and its directivity, as well as the effect of sedimentary layers, have been elucidated. Most studies, however, presented the source as propagating dislocation. As Boore et al. [1974] noted, kinematic models are limited by the need to specify the source as a function of space and time.

In kinematic models, forces or stresses are not considered fundamental quantities; solutions therefore depend on predetermined source functions. These functions have usually been assumed to be uniform over the fault plane, although the results of more physical and dynamic calculations suggest that this is not realistic [e.g. Cochard and Madariaga, 1996; Day, 1982a,b; Virieux and Madariaga, 1982]. Hence, it is more desirable in dynamic source modeling to calculate strong ground motion in the near-field based on realistic faulting motion.

The stress-relaxation model has been formed to describe the rupture process in terms of a dynamic propagating stress relaxation. This model has been the subject of many articles (see Archuleta and Frazier [1978]). Archuleta and Day [1980] developed a scheme for computing ground motion from a propagating stress relaxation in a vertically heterogeneous medium. In their method, propagating stress relaxation is used only for computing fault slip functions; wave propagation is calculated by the elastodynamic representation theorem in 2-D modeling, reducing the overall computation. They also referred to the distribution of maximum near-field ground motion, but the dependence of this distribution on various model parameters has not been discussed in detail. This is the very subject of our present study.

In this present paper, we discuss a frequency range up to 2 Hz. Such low-frequency strong motion is important because large structures, which are most sensitive to stress periods lasting longer than 1 sec., are increasing in urban areas [Kanamori (1974); Graves(1995)].

Method and model construction

Our models have been constructed as simply as possible to clarify the fundamental relationships between strong motion and various model parameters. We consider a rectangular-shaped strike-slip fault. A rupture is assumed to initiate at the middle point of the left margin of the fault and propagate circularly outward at a given velocity v_r. When the rupture front arrives at a point on the fault plane, shear stress drops at that same point to a prescribed frictional stress. The rupture suddenly stops when it reaches the boundaries of the fault.

Studies of rock friction and earthquake source process suggest slip and/or rate dependent friction [e.g., Dieterich (1979), Heaton (1990), Ida (1972), Ohnaka et al.(1987), Ruina (1983)]. The slip weakening friction may cause the f_{max} of the acceleration spectrum [Papageorgiou and Aki, 1983a, b]. Because the observed f_{max} is about 5Hz, seismic waves with frequencies lower than 5Hz are not affected by slip-dependent friction. Rate-dependent friction affects the decelerating part of the slip rate time function, which is smaller than the large initial onset of the function [Cochard and Madariaga, 1994, Beeler and Tullis, 1996], so little effect is expected on peak ground motion, although the rise time of the slip rate time function decreases.

Although we choose the slip weakening frictional model with Dc of 5 or 20cm, the resultant 2Hz-low-pass-filtered ground waveforms are the same as the case for a classical frictional model (sudden stress drop).

The 4th order 3-D finite difference method with staggered grids [Graves, 1996] is employed for our simulation. Absorbing boundary conditions [Clayton and Engquist, 1977] are adopted on all sides of the calculating space, except on the free surface. In numerical computation, we calculate only a quarterspace using a symmetry condition.

Synthetics and the spatial pattern of strong motion

We used velocity-stress formulations [Viriuex and Madariaga, 1982] in our basic equations; velocities at each grid points are therefore calculated directly. Fig.3 shows the time history of slip velocity at each point on the fault plane calculated from the standard model. These time histories are very similar in form to the analytical slip velocity function presented by Kostrov [1964] in his study of a self-similar shear-crack propagation. In addition, we should note that the shape of the time history is not uniform over the fault plane. The peak slip velocity is remarkably amplified near the surface and in the direction of the rupture propagation. These features clearly indicate that the general assumption of the same source function on the whole fault plane, which has often been adopted in the past kinematic models, is unrealistic, especially in shallow earthquakes.

The velocity waves, acceleration waves, and the particle motions on the surface, derived from standard model A1(see Table), are calculated. Two remarkable features can be seen in case A1: First, an impulsive S wave, which propagates with the rupture front at the surface, appears in both the components. From this impulsive motion derives peak velocity and acceleration**.** Second, Velocity component perpendicular to the fault exceeds fault-normal component at peak amplitude. The particle motion at each point exhibits a characteristic trace. Each point moves rapidly in a direction perpendicular to the fault trace on the arrival of the direct S wave, and then moves parallel to the fault as the fault plane ruptures and slides. A strong impulsive motion normal to the fault has been pointed out in previous theoretical studies [e.g., Aki, 1968; Boore and Zoback, 1974; Bouchon, 1979]. This strong impulsive normal motion also agrees with observational studies [Cloud, 1967; Hudson and Cloud, 1967; Housner and Trifunac, 1967]. This is thought to be a feature common to shallow strike-slip earthquakes and accurate prediction of this motion is an important subject in assessing damages caused by shallow earthquakes. The main focus of this present study is the spatial pattern of strong motion.

Source effects on spatial pattern of strong motion

We first consider how the burial depth of a fault, which we hereafter refer to as fault-depth, affects the spatial pattern of strong motion. Patterns of peak ground velocities are greatly different when the fault is buried beneath the ground surface. First, the location of maximum V_x (fault-parellel component) moves away from the fault nearly in proportion to the fault-depth. The location of maximum V_y (fault-normal) also moves from the end to the center of the fault. The near-source ground motion are dominated by the rupture in the direction of the receiver (Archuleta and Hartzel, 1981).

Second, peak ground velocity amplitude decays drastically, by a factor of more than 4, near the fault trace. Consequently, we can summarize the effects of fault-depth on the ground velocities using two factors that strongly control the spatial pattern of strong motion: the first is the positional change of the large ground velocity regions and the second is the amplitude decay of ground velocities. Generally, a rupture process on a real fault is heterogeneous and there are some regions referred to as “asperities”, where large stresses are released. Each asperity can be related to its own respective localized large slip velocity area; the depth of the asperity is a dominant factor controlling the resultant pattern of strong motion. We also assess the effect of the fault area, the heterogeneity of the rupture velocity and stress drop on strong motion.

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