

# NEAR-FAULT GROUND MOTION AND ITS RELATION TO THE FAULT RUPTURE PROCESS

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# ABSTRACT

The effect of fault rupture characteristics on near-fault strong ground motions is investigated using a kinematic modeling approach in an attempt to identify physical processes that lead to specific ground motion patterns. The shear-stress distribution on the causative fault plane of well-documented seismic events (i.e., 1979 Imperial Valley, 1985 Michoacan, 1989 Loma Prieta, and 1999 Izmit) is calculated based on fault slip models available in the literature using the methodology proposed by Bouchon (1997) for stress field computations. In order to associate the fault rupture characteristics (i.e., slip, rupture velocity, state of stress) of the investigated earthquakes with near-fault ground motions generated by the events, forward ground motion simulations are performed using the discrete wavenumber representation method and the concept of the S-wave isochrones is exploited. The results indicate that the seismic energy radiated from the high-isochrone-velocity region of the fault arrives at the receiver within a time interval that coincides with the time window of the long-period ground motion pulse recorded at the site. Furthermore, the near-fault ground motion pulses are strongly correlated with large slip on the fault plane locally driven by high stress drop. In addition, the local rupture velocity seems to be inversely correlated to the spatial distribution of the strength excess over the fault plane confirming findings of previous studies. For various events the area of the fault that contributes to the formation of the near-fault pulse encompasses more than one "patch" of significant moment release (subevent) (e.g., 1979 Imperial Valley). This observation explains why a dislocation model with average properties (i.e., slip, rise time, etc) reproduces successfully near-fault ground motions for strike-slip faults and for dip-slip faults with intermediate-to-large earthquake magnitudes (Aki, 1979). However, for very large earthquakes, such as megathrust events on subduction zones (e.g., 1985 Michoacan), the fault region that contributes to the pulse formation encompasses individual subevents and, consequently, crack-like slip functions (rather than dislocation models) may be more appropriate for the simulation of the near-fault ground motions.

KEYWORDS: near fault, state of stress, slip distribution, rupture velocity, rise time, isochrones

# **1. INTRODUCTION**

Results obtained from kinematic and dynamic ground motion simulations may provide valuable insight into the understanding of the qualitative and quantitative effects of basic parameters of the fault rupture process on near-fault strong ground motions. The variation of fundamental source parameters such as slip, rise time or rupture velocity on extended faults is nowadays routinely computed using strong motion and teleseimic waveforms, frequently combined with geological mapping of surface offsets, geodetic observations of static deformation or even tsunami waveforms. On the other hand, stress drop is linked to energy release and seismic radiation, and therefore it is associated with the dynamics of the earthquake rupture.

In this article, the effect of fault rupture characteristics such as slip, rupture velocity and state of stress on near-fault strong ground motions is investigated using a kinematic modeling approach in an attempt to identify physical processes that lead to specific ground motion patterns. The shear-stress distribution on the causative fault plane of well-documented seismic events is calculated based on fault slip models available in the literature using the methodology proposed by Bouchon (1997) for stress field computations. In order to associate the fault rupture characteristics of the investigated earthquakes with near-fault ground motions generated by the events, forward ground motion simulations are performed using the discrete wavenumber representation method and the concept of the *S*-wave isochrones is exploited. Preliminary results pertaining to this study have previously been reported by Mavroeidis (2004).



## **2. FAULT MODELS**

Four well-documented seismic events are considered in this study; namely, the 1979 Imperial Valley, the 1985 Michoacan, the 1989 Loma Prieta, and the 1999 Izmit earthquakes. Several researchers have extensively studied the fault rupture process of the aforementioned earthquakes, and inferred the spatial and temporal slip distribution on the causative fault planes by performing inversion analyses or trial-and-error forward simulations of strong motion data. Tables 1 and 2 summarize basic parameters pertaining to the source mechanism of the selected earthquakes with reference to the preferred fault models; these idealized models of the earthquake source will be used next for the computation of the shear-stress distribution on the fault plane and for the generation of synthetic ground motions on selected locations in the immediate vicinity of the tectonic fault. Figure 1 illustrates tomographic images of the fault rupture for the 1999 Izmit earthquake obtained from Bouchon et al (2002). Due to space limitations, only indicative results will be presented in this article.



Figure 1. Tomographic images of the rupture front (top), strike-slip final offset (middle), and rise time (bottom) on the causative fault of the 1999 Izmit earthquake obtained from Bouchon et al. (2002).



## **3. STRESS IMAGES**

Many researchers have contributed to the reconstruction of the state of stress on fault planes by proposing and implementing alternative methodologies for fault stress simulations of actual or hypothetical seismic events. In the present study, the methodology for shear-stress computations proposed by Bouchon (1997) is used for the calculation of the state of stress on the causative fault planes of the earthquakes listed in Tables 1 and 2. The proposed technique facilitates the derivation of the time and space distribution of stress over the fault plane directly from the kinematic model of the fault rupture, while most of the other techniques in the literature infer the fault stress indirectly by finding a dynamic crack model that best fits the kinematic model obtained for the rupture.

Time series of the shear-stress components are computed on a quadrilateral grid of receiver points on the fault plane over a specific time window. Each shear-stress time history is characterized by three physical parameters: the strength excess, the dynamic stress drop, and the static stress drop. According to Bouchon (1997) (see also Quin, 1990; Miyatake, 1992), "the stress increase at the onset of the rupture denotes the strength excess that when added to the initial stress gives the yield stress of the rock to fracture or the static friction on a preexisting fault. This stress increase begins with the arrival of seismic waves from the hypocentral area and reaches its peak value just before rupture occurs. This peak stress may be viewed as an implicit rupture criterion. Once the vield stress of the rock or the static friction is reached, rupture occurs and the stress drops. The dynamic stress drop corresponds to the largest drop from the initial shear stress level during the rupture process, while the static stress drop measures the change in stress produced by the earthquake". A negative value of the static stress drop implies that the level of shear stress is higher after the earthquake. The resolution of the shear-stress images is of the order of few kilometers comparable to the resolution of the kinematic slip models exploited in the computation of stresses. This implies that short scale-length features of the slip variation remain unresolved and thus not considered in the computations (Bouchon, 1997). Therefore, it is possible that the high degree of heterogeneity that characterizes the stress distributions over the fault plane may exist at finer scales as well. Moreover, this observation suggests that the stress drops inferred using the methodology of Bouchon (1997) may be regarded as a lower bound to the actual stress drop values.



Figure 2. Spatial distribution of static stress drop (top), dynamic stress drop (middle), and strength excess (bottom) on the causative fault of the 1999 Izmit earthquake based on the fault model inferred by Bouchon et al. (2002).



Images of the spatial distribution of the strength excess, dynamic stress drop and static stress drop on the fault plane of the 1999 Izmit earthquake obtained from the shear-stress time histories along the strike direction are illustrated in Figure 2. For these computations, the fault slip model proposed by Bouchon et al. (2002) was used as an input.

#### 4. GROUND MOTION SIMULATIONS

In order to associate the fault rupture characteristics of the investigated earthquakes with near-fault seismic excitations, forward ground motion simulations are performed and the concept of the *S*-wave isochrones is exploited. The computation of the low-to-intermediate frequency synthetic motion is carried out using the discrete wavenumber representation method (Bouchon and Aki, 1977; Bouchon, 1979). The generalized transmission and reflection coefficient technique (Luco and Apsel, 1983) is utilized for the propagation of the wavefield through the layered half-space.

For the simulation of the low-to-intermediate frequency ground motion due to the 1999 Izmit earthquake, the fault fracture is modeled as an ensemble of extended dislocation sources with rupture properties (e.g., slip, rise time, rupture velocity) consistent with the faulting model proposed by Bouchon et al. (2002) (Figure 1). Figure 3 illustrates the horizontal components of the synthetic ground velocity and displacement time histories at selected locations coinciding with sites of strong motion instruments that recorded the ground excitation during the earthquake. For comparison purposes, the low-passed recorded ground velocities and displacements are also illustrated. The horizontal ground motion components are oriented along the NS and EW directions, roughly coinciding with the fault-normal and fault-parallel directions, respectively. The overall agreement between synthetic and recorded ground motions is very good both in terms of amplitude and waveform characteristics. It should be pointed out that the synthetic time series are presented with respect to an absolute time scale whose origin coincides with the nucleation of rupture at the hypocenter. On the other hand, the recorded time histories have been shifted to achieve best fit since the absolute time is not available for most stations.



Figure 3. Synthetic (gray trace) and recorded (black trace) velocity and displacement time histories low-pass filtered at 2 Hz. All components are plotted to the same amplitude scale. Since the absolute time is not available for most stations, the recorded time series have been shifted to achieve best fit.



# 5. DISCUSSION

## 5.1. Stress Images

A brief description of the most significant features of the state of stress on a fault plane is presented in view of the shear-stress images produced in this study confirming findings of previous investigations (e.g., Day, 1982; Quin, 1990; Bouchon, 1997):

- The distributions of strength excess, dynamic stress drop, and static stress drop over the earthquake fault are characterized by large heterogeneity (Figure 2). This is an indication that both the pre-earthquake shear stress and the fault strength vary significantly over the fault plane.
- The slip and stress drop distributions on the fault are strongly correlated; that is, regions where high stress drop occurs coincide with regions where large slip takes place (Figures 1 and 2). This observation indicates that large slip is locally driven by high stress drop.
- Comparison of the dynamic and static stress drop images indicates that both spatial distributions follow the same variation pattern (Figure 2). As anticipated, the dynamic stress drop is higher than the static stress drop by a percentage that varies over the fault plane.
- A negative static stress drop value implies a higher level of shear stress after the earthquake. The white area in the top image of Figure 2 indicates regions of the earthquake fault that exhibited a shear-stress increase. These areas coincide with low slip regions of the fault plane.
- The spatial distribution of the strength excess over the fault plane appears to be inversely correlated to the local rupture velocity; that is, low rupture velocity implies high strength excess, while high rupture velocity implies low strength excess. This feature was particularly noticeable in the 1979 Imperial Valley and the 1999 Izmit earthquakes characterized by large variability in rupture velocity ranging from subshear to supershear (Figures 1 and 2).

## 5.2. Isochrones

Isochrone is the locus of all those points on the fault plane the radiation of which arrives at a certain observer at a specified time. The concept of isochrones is frequently exploited in seismology to provide intuitive insight into factors that strongly influence the generation of strong ground motions. As pointed out by O'Connell and Ake (2009), a simple and accurate way to employ the isochrone method for sites located in the near-fault region is to assume that all significant seismic radiation from the fault consists of direct shear-wave arrivals. By plotting the *S*-wave isochrones on the fault planes of the investigated seismic events, the long-period velocity pulses of the near-fault ground motion time histories can be directly associated with specific regions and characteristics of the fault rupture (see also Bernard and Madariaga, 1984; Spudich and Frazier, 1984).

#### 5.3. Fault Rupture Characteristics and Near-Fault Ground Motions

Figures 4 and 5 illustrate near-fault ground motion time histories and *S*-wave isochrones for characteristic stations of the 1999 Izmit, the 1979 Imperial Valley, and the 1985 Michoacan earthquakes. The spatial distributions of the static slip offset, static stress drop, strength excess and rupture time on the causative fault planes of the investigated earthquakes are also displayed. These figures aim at illustrating the results in a visually informative manner in an attempt to relate the long-period ground motion pulses with specific regions and characteristics of the fault rupture. The following observations can be made:

• Isochrone velocities attain large values on a substantial area of the fault plane. This area extends from the hypocenter to the top of the fault for strike-slip faults (e.g., 1979 Imperial Valley, 1999 Izmit; see Figure 4) and for dip-slip faults with intermediate-to-large earthquake magnitudes (e.g., 1989 Loma Prieta). However, for very large dip-slip earthquakes, such as megathrust events on subduction zones (e.g., 1985 Michoacan; see Figure 5), the high-isochrone-velocity region does not necessarily reach the top of the fault.



- High-isochrone-velocity region implies that all seismic radiation from that portion of the fault arrives at the receiver at approximately the same time. This feature is a strong indication of ground motion amplification associated with rupture directivity. As a matter of fact, this short time interval, within which the seismic energy radiated from the high-isochrone-velocity region of the fault arrives at the site, coincides with the time window of the long-period ground motion pulse. The effect of isochrone velocity on strong ground motions has been addressed in several studies including Bernard and Madariaga (1984), Spudich and Frazier (1984), Sato (1994), Dong and Papageorgiou (2003), O'Connell and Ake (2009).
- The correlation between a high-isochrone-velocity region (i.e., directly associated with long-period ground motion) and the spatial distributions of slip and stress drop over the fault plane indicates that the impulsive near-source ground motion is strongly linked to large slip on the fault plane locally driven by high stress drop. As a result, the correlation between near-fault strong motion pulses and slip patches may be interpreted as correlation between near-fault strong motion pulses and regions of high stress drop instead.
- For various events the area of the fault that contributes to the formation of the near-fault pulse encompasses more than one "patch" of significant moment release (subevent) (e.g., 1979 Imperial Valley, 1989 Loma Prieta). This observation explains why a dislocation model with average properties (i.e., slip, rise time, etc) reproduces successfully near-fault ground motions for strike-slip faults and for dip-slip faults with intermediate-to-large earthquake magnitudes (Aki, 1979). However, for very large earthquakes, such as megathrust events on subduction zones (e.g., 1985 Michoacan), the fault region that contributes to the pulse formation encompasses individual subevents and, consequently, crack-like slip functions (rather than dislocation models) may be more appropriate for the simulation of the near-fault ground motions (Campillio et al., 1989).





Figure 4. Recorded (black trace) and synthetic (gray trace) near-fault ground motion time histories and *S*-wave isochrones for selected stations of the 1999 Izmit (left) and the 1979 Imperial Valley (top) earthquakes. Tomographic images of the static slip offset, rupture time, static stress drop, and strength excess are also illustrated.

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Figure 5. Recorded (black trace) and synthetic (gray trace) near-fault ground motion time histories and *S*-wave isochrones for selected stations of the 1985 Michoacan earthquake. Tomographic images of the static slip offset, static stress drop, and strength excess are also illustrated.

#### 6. SUMMARY

The effect of fault rupture characteristics on near-fault ground motions was investigated using a kinematic modeling approach in an attempt to identify physical processes that lead to specific ground motion patterns. The results indicated that the seismic energy radiated from the high-isochrone-velocity region of the fault arrives at the receiver within a time interval that coincides with the time window of the long-period ground motion pulse recorded at the site. Furthermore, the near-fault strong motion pulses are strongly correlated with large slip on the fault plane locally driven by high stress drop. In addition, the local rupture velocity seems to be inversely correlated to the spatial distribution of the strength excess over the fault plane confirming findings of previous studies. For various events the area of the fault that contributes to the formation of the near-fault ground motions for strike-slip faults and for dip-slip faults with intermediate-to-large earthquake magnitudes. However, for very large earthquakes, such as megathrust events on subduction zones, the fault region that contributes to the pulse formation encompasses individual subevents and, consequently, crack-like slip functions (rather than dislocation models) may be more appropriate for the simulation of the near-fault ground motions.

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#### REFERENCES

- Aki, K. (1979). Evolution of quantitative models of earthquakes, in *Fracture Mechanics*, R. Burridge (Editor), SIAM-AMS Proceedings 12, 43-58.
- Archuleta, R. J. (1984). A faulting model for the 1979 Imperial Valley earthquake, J. Geophys. Res. 89, 4559-4585.
- Bernard, P., and R. Madariaga (1984). A new asymptotic method for the modeling of near-field accelerograms, *Bull. Seism. Soc. Am.* **74**, 539-557.
- Bouchon, M. (1979). Discrete wave number representation of elastic wave fields in three-space dimensions, J. *Geophys. Res.* 84, 3609-3614.
- Bouchon, M. (1997). The state of stress on some faults of the San Andreas system as inferred from near-field strong motion data, *J. Geophys. Res.* **102**, 11731-11744.
- Bouchon, M., and K. Aki (1977). Discrete wave-number representation of seismic-source wave fields, *Bull. Seism. Soc. Am.* 67, 259-277.
- Bouchon, M., M. N. Töksoz, H. Karabulut, M.-P. Bouin, M. Dietrich, M. Aktar, and M. Edie (2002). Space and time evolution of rupture and faulting during the 1999 Izmit (Turkey) earthquake, *Bull. Seism. Soc. Am.* 92, 256-266.
- Campillo, M., J.-C. Gariel, K. Aki, and F. J. Sanchez-Sesma (1989). Destructive strong ground motion in Mexico City: Source, path and site effects during the Great 1985 Michoacan earthquake, *Bull. Seism. Soc. Am.* 79, 1718-1735.
- Day, S. M. (1982). Three-dimensional simulation of spontaneous rupture: The effect of nonuniform prestress, Bull. Seism. Soc. Am. 72, 1881-1902.
- Dong, G., and A. S. Papageorgiou (2003). On a new class of kinematic models: Symmetrical and asymmetrical circular and elliptical cracks, *Phys. Earth Planet. Interiors* **137**, 129-151.
- Luco, J. E, and R. J. Apsel (1983). On the Green's functions for a layered half-space, Part I, *Bull. Seism. Soc. Am.* **73**, 909-929.
- Mavroeidis, G. P. (2004). Modeling and simulation of near-fault strong ground motions for earthquake engineering applications, *Ph.D. Dissertation*, Department of Civil, Structural and Environmental Engineering, State University of New York at Buffalo, Buffalo, NY.
- Mendoza, C., and S. H. Hartzell (1989). Slip distribution of the 19 September 1985 Michoacan, Mexico, earthquake: Near-source and teleseismic constraints, *Bull. Seism. Soc. Am.* **79**, 655-669.
- Miyatake, T. (1992). Reconstruction of dynamic rupture process of an earthquake with constraints of kinematic parameters, *Geophys. Res. Lett.* **19**, 349-352.
- O'Connell, D. R. H., and J. P. Ake (2009). Earthquake ground motion estimation, in *Earthquakes (Hazards and Disasters)*, C. M. Rodrigue and E. Rovai (Editors), Routledge, New York (in press).
- Quin, H. (1990). Dynamic stress drop and rupture dynamics of the October 15, 1979 Imperial Valley, California, earthquake, *Tectonophysics* 175, 93-117.
- Sato, T. (1994). Seismic radiation from circular cracks growing at variable rupture velocity, *Bull. Seism. Soc. Am.* 84, 1199-1215.
- Spudich, P., and L. N. Frazier (1984). Use of ray theory to calculate high-frequency radiation from earthquake sources having spatially-variable rupture velocity and stress drop, *Bull. Seism. Soc. Am.* 74, 2061-2082.
- Zeng, Y., K. Aki, and T.-L. Teng (1993). Mapping of the high-frequency source radiation for the Loma Prieta earthquake, California, J. Geophys. Res. 98, 11981-11993.