

## Near-fault site effects: Some theoretical results

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**ABSTRACT.** Site effects in the near field are studied using a complex source model composed of an aggregate of circular shear cracks. To accomplish this, complete synthetic seismograms at the bedrock and atop a soil column at selected sites around the fault were calculated, together with corresponding spectral ratios. A comparison between the transfer functions obtained for an SH wave, vertically incident under the soil column, and the spectral ratios indicates that caution should be exercised when seeking to apply this method in the near vicinity of a fault. It is likewise demonstrated that different rupture velocity values or hypocentral locations can bring about wide variations in the level of amplification and its predominating frequencies. Lastly, site effect prediction in the near field through the use of weak motions is seen to be liable to cause amplification peaks to be underestimated both level- and frequency-wise.

### 1. INTRODUCTION

Observations made on the occasion of major earthquakes that have taken place during the past ten years (Mexico, Armenia, Loma Prieta, the Philippines) have highlighted the rôle played by superficial geological formations in amplifying and increasing the duration of ground motion. Meanwhile, the development of efficacious analytic and numerical methods (refer to Bard, 1988, for an overview) has enabled a better understanding to be gained of the physical phenomena at work during seismic wave propagation through heterogeneous media. In particular, the use of two-dimensional computer codes has made it possible to explain actual observations during the Mexico earthquake, for instance (Bard & al., 1988; Kawase & Aki, 1989), where the classical monodimensional approach was incapable of doing so. Despite significant progress in both the experimental and theoretical realms, a number of themes call for further investigation, most important among which are: 1) the experimental and theoretical study of non-linear soil behavior and its impact on attenuation laws; and 2) a study of site effects in the immediate vicinity of the fault (near field).

The present study is devoted to this second point. It is in fact current practice in earthquake engineering to predict ground motion atop a soil column by convolving the column's response with the bedrock accelerogram. This response is most often procured by means of a monodimensional

code (horizontal layers) that may or may not take into account non-linear behavior in that soil (cf. codes SHAKE or FLUSH). The response is computed for a plane SH wave with a vertical incidence. If this approximation can indeed be accepted for sources at distance (far field), it can legitimately be questioned for sites neighboring the rupture zone, as the incident wave field is made up of various types of wave originating in different directions, with amplitudes directly dependent on variations in stress and strength along the fault plane. It is obvious that, due to the scarcity of records in the near field, a sufficient basis for an experimental study of these complex phenomena does not exist. Recourse must therefore be had to numerical simulation techniques in order to analyze, both qualitatively and quantitatively, the influence of rupture characteristics on site effects in the immediate vicinity of the fault. Using a complex source composed of an aggregate of circular cracks, synthetic accelerograms were computed for sites near the fault (< 20 km) as well as spectral ratios between alluvial and rocky sites. In this manner, it has been possible to study the influence of such parameters as rupture velocity or hypocentral location on amplification phenomena. It should be noted that the medium was described in terms of horizontal layers and that the linear viscoelastic hypothesis has been retained, making it easier to isolate the effects due to the rupture. Lastly, the source model adopted (an aggregate of individual sources) has allowed certain conclu-

sions to be drawn about techniques of site effect prediction from the study of weak motions.

## 2. THE FAULT MODEL

It is now widely admitted that the rupture process for strong or moderate earthquakes is highly heterogeneous, bringing about variations in stress and strength over the entire length of the fault plane. It is therefore logical to think that strong ground motion observed in a given station is the product of the superimposition of signals generated by ruptures at specific points along the fault. In order to simulate this complexity, we have represented the fault by an idealized composite model comprising a network of circular shear cracks. This model is generously inspired from the model of source spectrum proposed by Papageorgiou & Aki (1983). The rupture pertaining to each sub-event is manifested by an emission of high-frequency pulses, arising when the rupture is halted sharply on reaching the final radius of the crack (Archuleta & Hartzell, 1981; Campillo, 1983). The motion generated by the rupture of all the sub-events will accordingly be equivalent to the sum of the contributions of each circular crack, thus allowing the expression of a certain degree of the rupture complexity. This model is completely defined using five parameters: 1)  $v_p$ , the elementary rupture velocity of each crack, 2)  $V_R$ , the velocity with which the rupture propagates from one crack to the next, 3)  $N$ , the total number of cracks, 4)  $R$ , the crack radius, and 5)  $D$ , maximum displacement at the center of a crack. A number of studies (Izuani, 1981; Papageorgiou & Aki, 1985) have shown that a similarity condition exists between seismic moment and the size of the elementary crack, this latter increasing with magnitude. The model used in this study contains a  $3 \times 3$  network of 2.5 km diameter cracks arranged on a perfectly vertical plane (Fig-

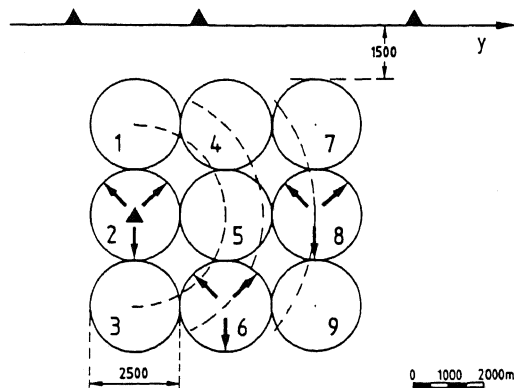


Figure 1. Schematic source model used in this study.

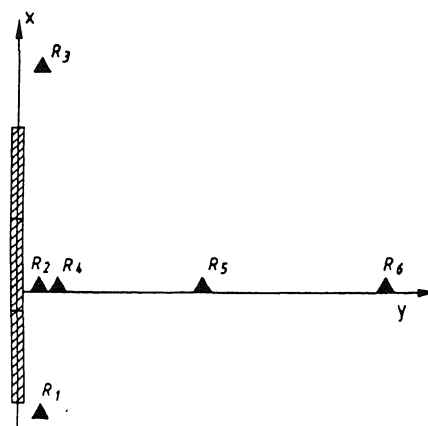


Figure 2. Layout of the source/receiver geometry used (the scale is the same as on Figure 1). The most distant receiver, not shown, is located along the Y axis, 20 km from the fault trace (cross-hatched area).

ure 1). The associated mechanism is purely slip. The top of the fault is situated 1500 m below the free surface. The rupture velocity of each sub-event is set at 2600 m/s, or 0.75 times shear wave velocity. The final displacement at the center of each crack is 30 cm (equalling an average displacement  $\bar{D}$  of about  $2/3 \times 30$ , or 20 cm). The seismic moment,  $M_0$ , inherent to the model can therefore be estimated as being:

$$M_0 = \mu \bar{D} S = 2.6 \times 10^{24} \text{ dyne} \times \text{cm} \quad (1)$$

corresponding to a magnitude  $M_W$  of 5.5 (cf. Kanamori and Anderson, 1975).

Synthetic seismograms were computed for seven receivers placed at between 0.5 and 20 km from the fault trace (Figure 2). To compute them, we called upon the Bouchon method (1981) involving a discretization of the wave field in terms of the horizontal wave number. Following Campillo (1983), a circular shear crack is represented by a network of point sources, and the superimposition of the elastic field radiated by all the elementary sources is effected in the frequency-horizontal wave number realm. The interval between ele-

Table 1. Velocity profile used for soft-soil sites.

$b$ (m)	$V_p$ (m/s)	$V_s$ (m/s)	Density ( $t/m^3$ )	$Q_p$	$Q_s$
50	300	150	1.5	20	20
150	1000	600	1.8	40	40
1000	3400	2000	2.0	300	300
-	5900	3500	2.8	1000	1000

Table 2. Velocity profile used for rocky sites.

$b$ (m)	$V_p$ (m/s)	$V_s$ (m/s)	Density (t/m <sup>3</sup> )	$Q_p$	$Q_s$
1200	3400	2000	2.0	300	300
-	5900	3500	2.8	1000	1000

mentary sources is set smaller than one fifth of the shortest wave length considered. The contribution of each element of the fault was thus estimated separately, and the resulting total motion is obtained by summing (using the phase shift introduced by the velocity of propagation of the the rupture front,  $V_R$ ) all the contributions. Owing to lengthy computational time, only the frequency domain (0-3 Hz) has been addressed.

For each configuration studied, synthetic seismograms were calculated for two different velocity models (Tables 1 and 2), that do or do not take into account the presence of low-velocity layers (corresponding to soft soils) near the free surface. The comparison of the two configurations was performed by calculating spectral ratios between the seismograms obtained with sedimentary layers and those without.

### 3. COMPARISON BETWEEN THE ACTUAL AND THE SH TRANSFER FUNCTIONS

We first compared the transfer function computed by taking into account a vertically incident SH wave beneath the soil column described in Table 1 (SH transfer function) and the one obtained by calculating the spectral ratio between the two configurations (soft-soil/rocky site). The synthetic seismograms were computed supposing a rupture onset at the center of crack #2 (unilateral propagation, cf. Figure 1) that propagated to the other cracks, triggering their rupture, in turn, at a velocity of 2600 m/s ( $V_R$  therefore equals  $v_r$ ). The synthetics were computed for components oriented parallel to the X axis (see Figure 1) and perpendicularly thereto. Because of the spacial extent of the fault with respect to the fault-receiver distance, it was not possible to separate the components into transversal and radial, as the waves arrived from directions spread out over angles ranging from 20° to 160° (for the most distant - 20 km - and the closest-in receivers - 500 m - respectively).

On Figure 3, the SH transfer function is compared with the spectral ratios for two components of the seven receivers. For receivers R1 and R3, situated on either side of the fault tip (Figure 2), it will be noted that, while the spectral ratio for component X fairly closely resembles the SH transfer function, the component Y ratios display a wide

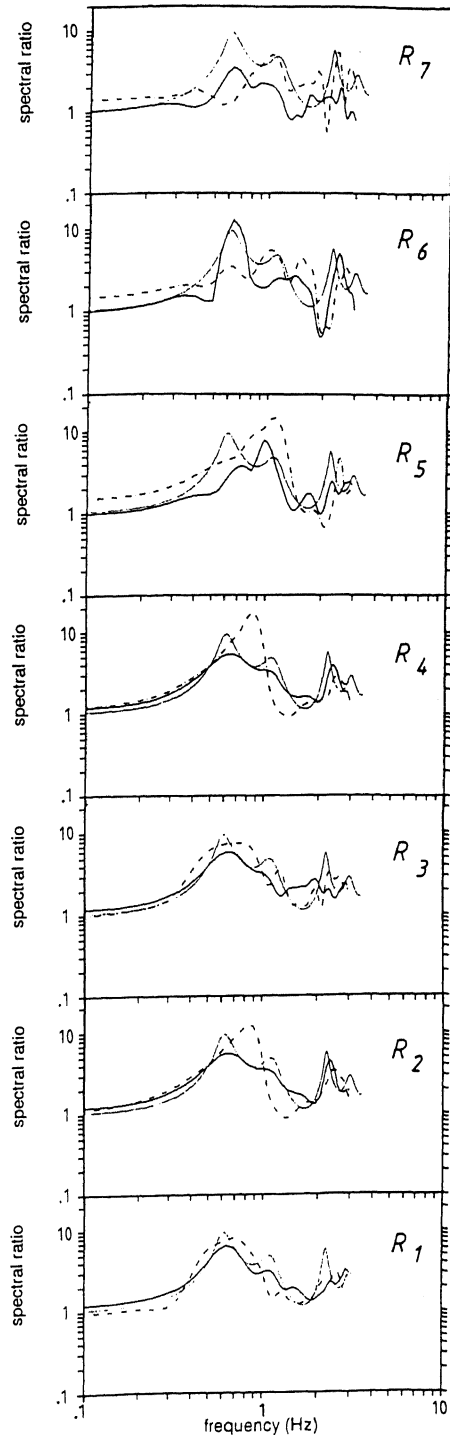


Figure 3. Comparison between the SH transfer function (normal-weight line) and the soft-soil site/rocky site spectral ratios for component X (heavy line) and Y (dotted and dashed line) for the seven receivers, R1 through R7.

amplification over the 0.5–1.0 frequency range as compared with this latter. For receivers R2 and R4, nearest the fault, the spectral ratios for component X are again not unlike the SH transfer function. On component Y, on the other hand, a strong amplification (a factor of around 15 to 20) is observed near 1 Hz, significantly offset, furthermore, with respect to the SH transfer function peak ( $\approx 0.6$  Hz). For receivers R5 and R6, situated respectively at 5 and 10 km from the fault, the spectral ratios on component X differ markedly from the SH transfer function, unlike the preceding case. This can be explained by the fact that ground motion there is dominated by the rupture on the closest portion of the fault (in this instance, crack #4), which, because of the mechanism and of the azimuth between the sub-event and the stations, is characterized by a strong SH-wave radiation. In contrast, receivers R5 and R6, situated farther away (at a distance comparable to the fault length) can be expected to be influenced by all the sub-events, albeit to varying degrees, and the incident field will incorporate the interference of a wide variety of waves from an assortment of azimuths. For both components X and Y, the amplification peaks observed do not coincide in frequency with those on the SH transfer function and may exceed these latter by 50 or 60%. Lastly, for the most distant receiver (20 km), it will be seen that the component X spectral ratio closely resembles the SH transfer function in shape although the amplitude level is smaller. Here the fault-to-station distance is long as compared with the size of the source, so it is not surprising that the far-field SH approximation should begin to be applicable, the lower amplitude level on component X being probably explained by an oblique incidence of the waves beneath the soil column.

#### 4. INFLUENCE OF THE RUPTURE VELOCITY

Near a fault, ground motion is strongly influenced by the rupture velocity. One may accordingly expect the response of a soil column to vary for two contrasting values of this parameter, in function of the differing nature of the incident wave field. In order to test this hypothesis, synthetic seismograms were calculated (on the bedrock and atop a soil column) for two values of rupture velocity  $V_R$ : 2000 and 3400 m/s (or, respectively, 0.4 and 0.9 times the shear wave velocity). A comparison between the spectral ratios for receivers R2 and R5 is depicted on Figure 4a. For the closest-in receptors (R1, R2, and R3), while the component X spectral ratios are hardly affected, if at all, by a variation in this velocity, those for component Y display a noticeable shift in the frequency of the amplification peak, from 0.6 to 1 Hz, and an increase

in amplitude of around 50% when the rupture velocity increases. The stability of component X is linked with the fact that, near the fault, motion in this direction is dominated by the closest sub-event (SH component), for which  $v_r$  is constant (2600 m/s). On the contrary, component Y, influenced by SV waves generated by all the sub-events, is therefore strongly affected by  $V_R$ . For the most distant receivers (R5, for instance), a significant difference is observed between the two rupture velocities on both components, since motion is determined by interferences among the contributions of all sub-events. This results in both a shift in frequency of the amplification peaks and in an increase in level, multiplied by up to 3 for  $V_R = 3400$  m/s.

#### 5. INFLUENCE OF HYPOCENTRAL LOCATION

A factor likely to influence the nature of the incident wave field near the fault is the direction in which the rupture propagates, and hence the position on the fault plane of the starting point. So as to qualify and quantify this effect on the amplification of waves atop a soft soil column, we computed the spectral ratios for three different hypocentral locations: crack #1 (unilateral downwards propagation), crack #5 (bilateral propagation of the rupture front), and crack #9 (unilateral upwards propagation). The spectral ratios for the two components are presented on Figure 4b for a nearby station (R2) and a more distant one (R5). For receiver R2, component X remains invariable with respect to hypocentral location for the same reason as in the preceding section (dominance of the closest sub-event). On component Y, however, when the rupture starting point is displaced, the preponderant frequency shifts and amplitudes may vary by more than 50%. Such variations are also to be observed on both components of the more distant station (R5). The amplification peak shifts from 0.6 Hz, for a crack #1 rupture, to over 1 Hz for a hypocenter on crack #9.

#### 6. COMPARISON OF SPECTRAL RATIOS FOR LARGE AND SMALL EVENTS

A current practice when seeking to predict the amplification caused by superficial geologic formations in the event of a major earthquake is to call upon studies of weak motions (Borcherdt, 1978; Rogers & al., 1984, 1985). Using actual recordings of small events on neighboring sites obtained simultaneously on the bedrock and on soft soil, spectral ratios are computed to procure the amplification factor. For formations that behave linearly even when subjected to high levels of acceleration, it has been demonstrated that these

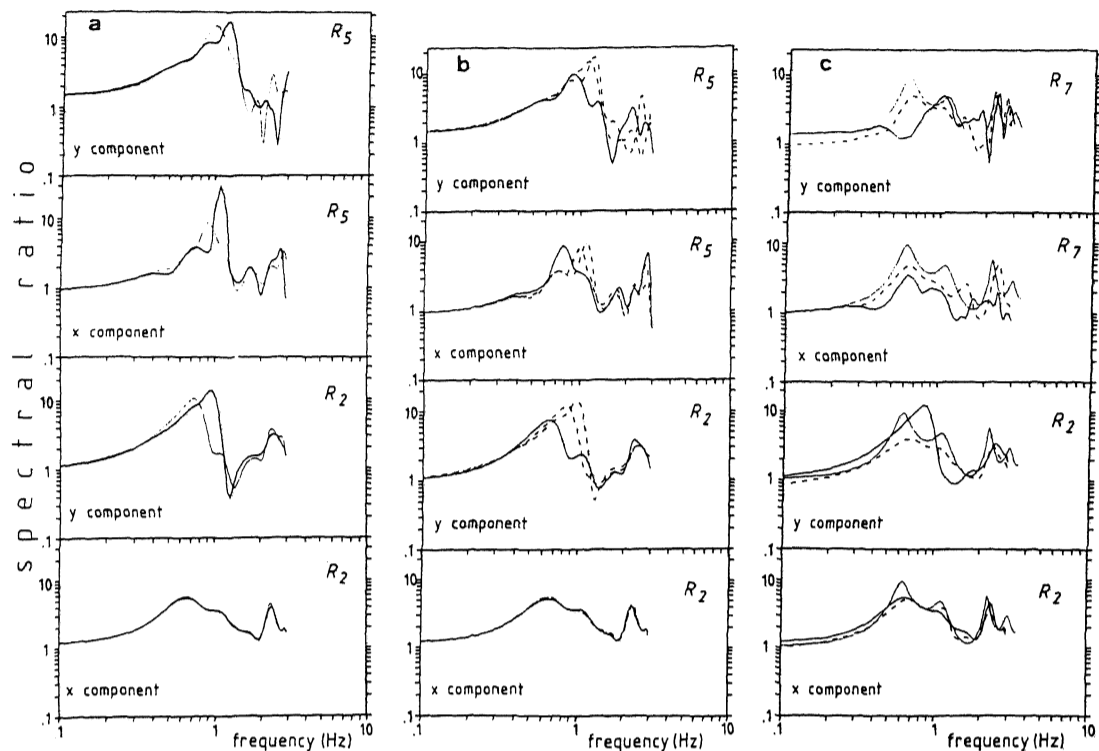


Figure 4. Comparison between soft-soil site/rock site spectral ratios obtained: a) for rupture velocities  $V_R$  of 3400 m/s (heavy line) and 2000 m/s (normal-weight line); and b) with hypocentral locations in the center of crack #1 (solid line), in the center of crack #5 (dashed line), and in the center of crack #9 (dotted and dashed line); c) comparison between the SH transfer function (normal-weight line), the soft-soil site/rock site spectral ratio obtained with the complete model (heavy line), and the same obtained by averaging the spectral ratios computed for each crack separately.

factors were adequate predictors of the amplifications that would occur during a large earthquake (Singh & al., 1988). Where soils behave in a non-linear manner, this type of approach is obviously no longer valid, as was shown by Chin and Aki (1991) in the case of the Loma Prieta earthquake. However this may be, we used our model in order to ascertain whether a linear hypothesis could be reliable in the immediate vicinity of a fault. To accomplish this, we calculated the spectral ratios for the nine cracks taken individually, then averaged them. Figure 4c compares these average ratios with the SH transfer function and the spectral ratios obtained for the complete model employed in section 2. For station R2, component X, a good agreement is procured between the three functions. For component Y, however, the average ratio is similar to the SH transfer function, whereas the complete model ratio differs in both amplitude and frequency. It is thus seen that the interference between the contributions of the various sub-events may result in a complex wave field that will

produce high levels of amplification at frequencies that cannot be identified either on the strength of the SH transfer functions or on that of weak motions. Similar observations are to be made with respect to the other close-in receivers (from R1 to R6). For R7 (20 km from the fault), on component X, agreement between the three approaches is fairly good, at least as far as the dominant frequencies are concerned. This is a consequence of the relatively longer fault-receiver distance (by a factor of about 3) as compared with the fault length: the incident wave field can thus be represented by a simple SH plane wave. Differences in amplitude are doubtless due to the fact that in computing the SH transfer function, a vertical incidence is taken into account, which is not true of the model. Actually, it will be noted that, because of the presence of a velocity gradient, the incidence is practically vertical. On component Y, agreement is less satisfactory, probably due to the presence of obliquely incident SV waves. Nevertheless, the SH transfer function is a better predictor than the spectral ratios

yielded by the other methods.

## 7. CONCLUSION

A complex source model composed of an aggregate of circular cracks has been used to study the influence of various aspects of the rupture process on near-field site effects. Although the symmetries associated with the model geometry make certain results difficult to interpret, some conclusion can be drawn as to site effect prediction near a fault. In the near field, owing to the ratio of the size of the source to the fault/receiver distance, the incident wave field impinging the base of the soil column is excessively complex. Considerable care should be employed when employing the common practice consisting in convolving the response to a vertically incident SH wave with the accelerogram. The results of this study indicate that the spectral amplification may be up to 50% higher and may occur at frequencies entirely other than those obtained by the preceding method. Furthermore, the importance of such rupture parameters as its velocity or the hypocentral location on the fault plane should be underlined. In the near field, the amplifications produced for one event can be quite different from those for another if one of these parameters varies. Lastly, for distances up to twice the source size, amplification prediction by means of the study of weak motions should also be used with caution, for these motions correspond to small-sized sources that do not integrate the complexity related to rupture propagation over large distances.

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