PHYSICAL PHENOMENA CONTROLLING HIGH-FREQUENCY SEISMIC WAVE GENERATION IN EARTHQUAKES

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ABSTRACT

Several physical parameters may contribute to control the amount of high frequency energy in the spectrum of strong ground motions. These phenomena include the total amount of geological slip on the fault causing the earthquake, the slip rate (or repeat time) of earthquakes on the fault, dynamics of fault rupture, lithology of the fault zone, whether the fault is in an extensional or compressional environment, and geometrical factors including whether or not the rupture reaches the surface. In this paper, we review evidence that points towards the significance of these parameters, and present examples where they may play a role. These considerations are particularly relevant when considering the significance of ground motions from the three largest earthquakes that are well-recorded on strong motion accelerographs, and for all of which the peak accelerations were surprisingly low. The first was the Michoacan, Mexico earthquake of Sept. 19, 1985 (Mw=8.0), where peak accelerations at four stations on rock directly above the fault had peak accelerations of 13-17 percent of gravity. The second is the Kocaeli, Turkey, earthquake of August 17, 1999 (Mw=7.6), where stations on rock within ~10 km of the fault recorded peak accelerations of 23-40 percent of gravity, a factor of two below predictions. The third is the Chi-Chi, Taiwan, earthquake of September 21, 1999, where peak accelerations at numerous sites with uncertain conditions were generally a factor of two smaller than regression models. Since many factors affect high frequencies, more data is needed before we will understand the general case. Before we attribute differences in high frequencies to one effect, we need to consider other potential factors.

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Introduction

Three large and well recorded earthquakes have had surprisingly low peak accelerations. Those are the 1985 Michoacan, Mexico earthquake (M8.0), the 1999 Kocaeli, Turkey earthquake (M7.6), and the 1999 Chi-Chi, Taiwan earthquake (M7.6). Although peak acceleration (pga) is a rather poor predictor of damage, the parameter is useful as a measure of the amount of high frequency energy in an accelerogram. Thus, the low values of pga in Turkey and Taiwan point to a fundamental problem for strong motion seismology: what controls the amplitude of the high frequency content of earthquake ground motions? They also point to an important dilemma facing the earthquake engineering community: were these large earthquakes representative of earthquakes in other locations with similar fault geometry and mechanisms? The questions must be answered by physical reasoning and more data.

This paper discusses some physical models for control of high-frequency radiation from earthquakes. We present some evidence that the peak acceleration is a reasonable proxy for the level of the high frequency portion of the Fourier amplitude spectrum, when comparing accelerograms from otherwise similar sized events and distances. If this is accepted, then the analysis of data from a large number of earthquakes is simplified, as ground motion prediction equations for peak acceleration have a long history of development. We compare peak accelerations for similar earthquakes in various environments. The paper will discuss similarities and differences among the earthquakes, and use this primarily annecdotal evidence to support the hypothesis that many different physical factors might be affecting the high frequencies. The implication is that, before the Turkey and Taiwan data are not universally representative, but may be a good analog for some cases.

Phenomena Affecting High Frequencies

In this article, “high frequencies” must meet dual criteria. First, they are greater than about 1 Hz, and thus in the frequency band that controls peak acceleration. Second, they must exceed the corner frequency of the earthquake. For earthquakes above magnitude 6, the corner frequency is usually below 1 Hz, so the corner frequency criterion is not restrictive. Rupture models identify two different ways an earthquake can generate high frequencies. The first is at the rupture front as the fault enlarges in space. The second is through accelerations and decelerations of opposite sides of the fault during slip, as irregularities in the fault surface “chatter” against each other.

Lithology

In laboratory tests, the shear stress sufficient to cause rocks to fail depends on many factors, including confining pressure, temperature, strain rate, and rock type (e.g. Kirby and McCormick, 1984). The strain rate effects were discussed above. For a given rock type, in general as the temperature increases, shear strength of the rock decreases, and also the rock becomes more ductile. As the confining pressure increases, shear strength of the rock increases, and also the rock becomes more ductile. When considering faults with the same geometry and mechanism (i.e. same strike, dip, slip direction, depth of faulting), then to first order the range of temperatures and pressures on the fault may be considered constant. For the tests reported by Kirby and McCormick (1984) at room temperature, 1 kbar pressure, and strain rate of 10^{-4} sec^{-1}, shear strengths range from averages of about 0.02 kbar for shale (the weakest rock reported) and

8 kbar for granite (one of the strongest rocks reported). This suggests that lithology can give over two orders of magnitude in strength differences.

If high frequency radiation is caused by asperities on the fault, then the strength of those asperities would be expected to affect the intensity of high frequency radiation. Under this model, one might expect that faults in weaker rock would emit lower levels of high frequency radiation.

Total Fault Slip

Wesnousky (1988) demonstrated that strike-slip faults with a greater total slip have smoother expressions at the surface. Figure 1 illustrates this point. The physical explanation for this result is that as the total offset increases, irregularities in the fault will be smoothed out. If this is true for the surface trace, then it is reasonable that this would also be true for the fault at depth. It is also plausible that irregularities in the fault are particularly efficient points in generating high frequency seismic energy. If this is the case, then faults with more slip, and thus fewer irregularities, might be expected to generate lower amounts of high-frequency energy than faults with smaller total slip.

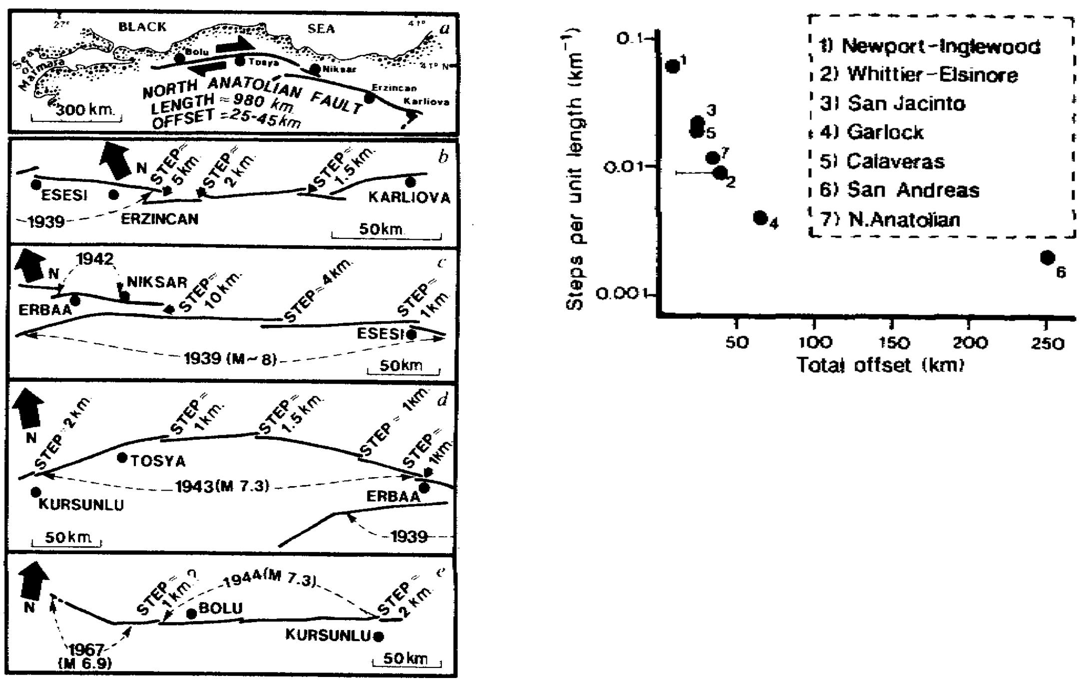

Figure 1. Left: Example of the methodology employed by Wesnousky (1988), in which steps in the surface trace of an active fault are identified and counted. Right: Summary showing that the number of steps per kilometer decreases in a fairly regular manner as the total offset of the fault increases.

Fault Slip Rate

Quantifying earlier observations by Kanamori and Allen (1986) and Wesnousky (1986), Anderson et al (1996) concluded that when normalized by rupture length, faults with a higher slip rate have smaller magnitude events, as shown in Figure 2. Normalized to fault dimension, a smaller magnitude corresponds to a smaller average slip on the fault.

Another way to express this is to use static stress drop, which is proportional to the ratio of average slip to fault dimension. There is more than one way to explain this observation. Anderson et al (1996) lean towards the idea that a fault with a low slip rate has a longer time for the fault to heal between events. Since the healing makes the fault stronger, then a greater amount of stress needs to accumulate to cause the next earthquake, so faults with low slip rates would tend towards higher static stress-drop earthquakes. However one explains the data, it is plausible that earthquakes with higher static stress-drop would also generate more high-frequency energy than earthquakes of the same magnitude with lower static stress drop. This hypothesis implies that faults with a larger slip rate would generate less high-frequency energy than slowly slipping faults.

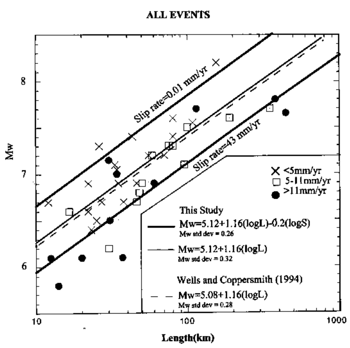

Figure 2. Regression by Anderson et al (1996) for earthquake magnitude as a function of fault rupture length and the fault slip rate.

Rupture Dynamics

Kanamori and Heaton (2000) present evidence that as the magnitude of earthquakes increases, the fraction of the released energy that is radiated, although small, also increases. This gives direct evidence that something about the physics of earthquakes changes as the magnitude gets larger. Kanamori and Brodsky (2001) suggest that one possible explanation is some mechanism of fault lubrication. The idea is that an earthquake with a large total slip will generate substantial amounts of energy which can cause the fault surface to melt or cause fluids on the fault to vaporize causing an increase in fluid pressure. Brune et al (1993) and Anooshehpoor and Brune (1994) offer an alternative explanation, that the dynamic processes in a large earthquake (e.g. interaction of asperities or processes at the rupture tip) cause the two sides of the fault to separate, thus reducing friction. Either of these mechanisms could cause the high frequency radiation to be decreased in a large earthquake.

Trans-Tensional Tectonics

Brune and Anooshehpoor (2000) suggested that ground motions may be low close to the surface trace of faults in extensional or trans-tensional environments. Brune (2000) finds low accelerations on the footwall of normal faults. In addition, he has located precarious rocks in Nevada, at a location just a couple of kilometers from a strike-slip fault with Quaternary activity, and suggests that the low accelerations in the 1999 Turkey earthquakes could also be associated in part by the extensional tectonic environment. In contrast to environments where one of the major stress axes is horizontal, in a trans-tensional environment the only forces on near-surface material arise from gravity, which can result in less energy being available to be released near the surface.

Surface Rupture

Somerville (2000) finds that at short and intermediate periods, the ground motions from earthquakes that produce large surface rupture appear to be systematically weaker than those whose rupture is confined to the subsurface. This abstract does not suggest a physical mechanism. The earthquakes he studied are all crustal earthquakes, and most occurred on high-angle faults. Under these circumstances, processes that stop the upper edge of the fault beneath the surface could be a source of high frequency energy that would be absent when rupture reaches the surface, as Somerville discussed during his oral presentation of this paper.

Data

Continental Thrust Earthquake

Figure 3 shows maps of the faults and locations of strong motion stations for two continental thrust earthquakes, with parameters listed in Table 1. Figure 4 shows peak accelerations for both earthquakes, as a function of distance from the fault, and compared to a ground motion prediction equation. Site conditions are ignored in development of this figure. It is noteworthy that even though the Chi-Chi earthquake is larger, peak accelerations are smaller than in Kern County at the equivalent distances, and also are smaller than predicted.

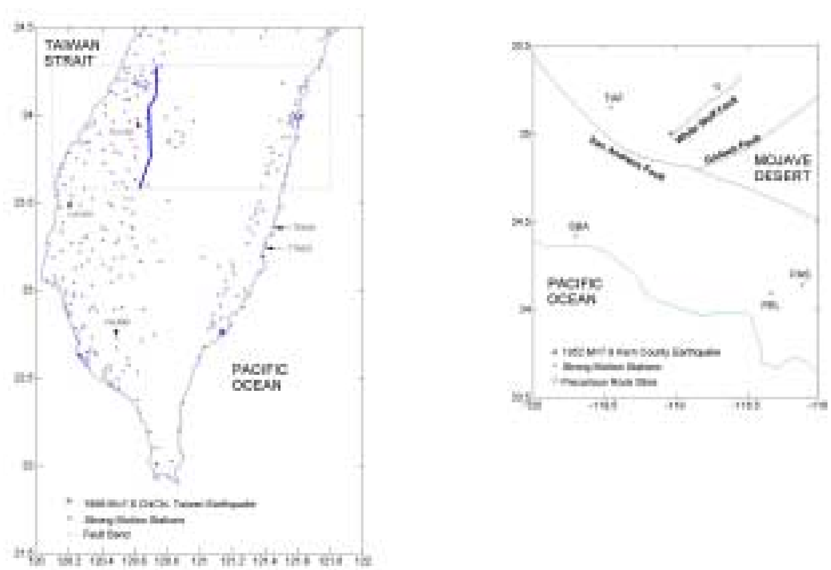

Figure 3. Fault surface ruptures and accelerograph locations for the Chi-Chi earthquake (left) and the Kern County earthquake (right). Circles on the Taiwan map surround stations with a geometry similar to one of the stations that recorded the 1952 earthquake.

A feature that can be seen in Figure 3 is that the Chi-Chi earthquake and the Kern County earthquake have very similar geometries. For both, an observer at the epicenter and looking directly updip towards the fault would have the rupture propagating to his right. Fault dips are similar. The Chi-Chi earthquake is so well instrumented that it is possible to select several instruments with the same geometry as the few that recorded the Kern County earthquake, as indicated by the circles. Figure 5 compares Fourier amplitude spectra of all of the accelerograms with geometry similar to the geometry of the Taft accelerogram from the Kern County earthquake, the nearest of the four stations to record the 1952 earthquake. This figure shows that at the low frequencies, the spectral amplitudes are similar, but at the high frequencies the Taft accelerogram exceeds the spectra of nearly all of the Chi-Chi records. Similar results are obtained for the other stations. Thus in this case, the higher peak accelerations in the Kern County earthquake are reflecting that the high frequencies in that event are almost uniformly greater.

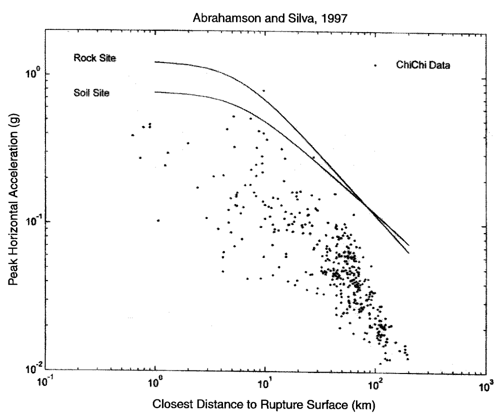

Figure 4. Peak accelerations plotted as a function of the distance from the fault to the station for the 1952 Kern County and 1999 Chi-Chi earthquakes. The ground motion prediction model of Abrahamson and Silva (1997) is shown for comparison, but it should be noted that hanging wall effects in that model are not accounted for here.

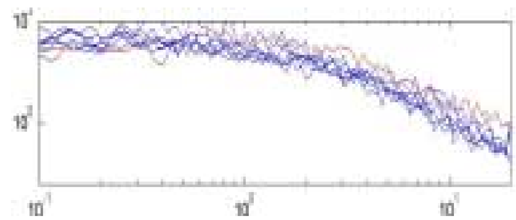

Figure 5. A horizontal component of Fourier amplitude spectra for the Taft accelerogram from the 1952 Kern County earthquake (red), compared with spectra from several stations recording the Chi-Chi earthquake at a similar geometry (blue).

Table 1. Characteristics of two continental thrust earthquakes

Characteristic	Kern County, 1952	Chi-Chi, 1999
Moment (10^{27} dyne-cm)	1.3	2-4
Mw	7.4	7.6
L	57	80
W	19	40
Average slip	60	300
Maximum slip	300	900

Wang et al (2000) point out that the Chi-Chi earthquake took place on a bedding plane fault, in a shale layer. The shale is directly observable on geologic maps and at the surface, and reflection seismology models conclude that this shale persists at depth. In contrast, the Kern County earthquake took place in granite. Shear strength of granite and shale were discussed above. Wang et al (2000) go on to suggest that the low peak accelerations can be attributed to lithological differences. Ma et al (2001) have proposed that fault lubrication occurred in the Chi-Chi earthquake. Also, if it existed, such a phenomenon would be stronger in Chi-Chi since the average slip was greater. Partial evidence that Ma et al cite is that the high frequencies in Chi-Chi were depleted at the north end of the fault, where the slip was greatest. We do not contradict that, but note that we are comparing accelerograms from the southern ends of both ruptures, where in Chi-Chi it is known that the high frequencies were stronger. Thus we believe that this earthquake pair provides anecdotal support for the idea that lithology is an important factor in high frequency generation.

Major Strike-slip Earthquake

Figure 6 shows peak accelerations for “rock” sites for three predominantly strike-slip earthquakes (Table 2), and compares with predictions from four different models for a magnitude 7.6 earthquake. There are several features to notice about this. First, adjusted for distance, ground motions are generally larger than motions for the two Turkish earthquakes, at least if one can use the curves as a guide for the comparison. Second, while the Landers earthquake is reasonably consistent with the models, the Turkish accelerograms come in with lower accelerations than expected. We tentatively interpret these observations that the Landers earthquake has more high frequency energy radiated than either of the Turkish earthquakes.

There are two major differences between the earthquakes in Turkey and California. One is that the offset on the North Anatolian fault in Turkey is about 35 ± 10 km, whereas the total geological slip on the faults involved in Landers is between 1.6-4.0 km. The second is that the slip rate on the North Anatolian fault is about 24 mm/yr, while the slip rates on the faults in the Landers earthquake are only about 1-2 mm/yr. Thus in this case, while the data are consistent with either total slip or slip rate being a factor, there is no capability to discriminate between these two hypotheses. All three earthquakes took place in trans-tensional environments and caused surface rupture.

Table 2 Characteristics of three predominantly strike-slip earthquakes.

Characteristic	Landers 1992	Kocaeli 1999	Duzce 1999
Moment (10^{27} dyne cm)	1.06	2.88	0.665
Mw	7.3	7.6	7.2
L	70	120	40
W	15	18	18
Average slip (cm)	300	400	280
Max surface slip (cm)	600	490	450

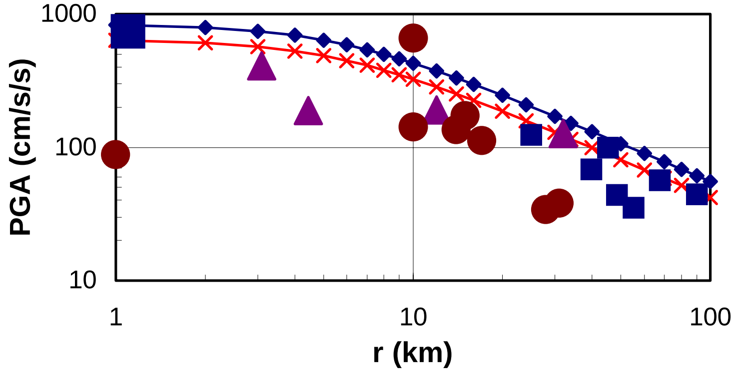

Figure 6. Peak accelerations on rock sites plotted as a function of the distance from the fault to the station for the 1992 Landers [squares] and the 1999 Kocaeli [triangles] and Duzce [octagons] earthquakes, modified from Anderson (2000). The ground motion prediction models are rock motion models for Mw=7.6 from Abrahamson and Silva (1997) [line with diamonds] and from Spudich et al (1997) [line with x's].

Subduction Thrust Earthquake

Figure 7 shows results from Johnson (1999) that model several earthquakes in Guerrero, Mexico. The decreasing subevent stress drop indicates that high frequencies decrease as magnitude increases. Most of these events are on the subduction thrust, so slip, slip rate, and lithology are constants. Consequently, this magnitude dependence, if confirmed by future data, may result from dynamics of the rupture process. Purvance and Anderson (2002) discuss normal faulting events in Guerrero that are enriched in high frequencies compared to thrust faulting. The normal faulting events are presumed to have smaller slip and slip rates than the thrust faulting earthquakes.

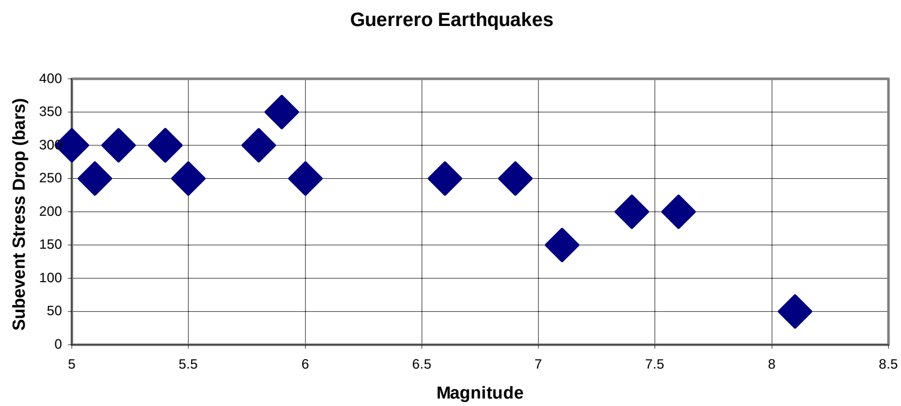

Figure 7. Subevent stress drop parameter in models of Guerrero, Mexico, strong motion records, as a function of magnitude. The subevent stress drop is a parameter in the composite source model of Yu (1994) and Zeng et al (1994), and is correlated with the peak acceleration and high frequency amplitudes. Johnson (1999) found composite source models for these earthquakes based on data gathered by the Guerrero Accelerograph Network (Anderson et al, 1994).

Discussion and Conclusions

We believe that a credible case exists that many factors affect high frequencies, and therefore conclude that more data is needed before we will understand the general case. Applications are anecdotal at this time, and might be seen as identifying potential avenues for research in the future. This paper considered three important cases where ground motions were surprisingly low. Because of the potential that lithology was a major factor in causing the low accelerations in Taiwan, we cannot consider the Taiwan ground motion data to be typical of continental thrust earthquakes that might occur in the United States, particularly in southern California. The data from Turkey has a better chance of being representative of major earthquakes on the San Andreas fault, but not of other important strike slip faults in the western United States, such as the Newport-Inglewood or San Jacinto faults in southern California or the Owens Valley fault in the western Great Basin. The data from Guerrero, Mexico, suggest that major subduction thrust events may be depleted in high frequencies compared to smaller events on the same fault – a hypothesis that will be tested whenever the Guerrero seismic gap generates a major earthquake. Until these hypotheses and others based on the ideas in this paper are tested, we should be very cautious in attributing differences in high frequencies to one effect, but rather we need to consider other potential factors.

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