7 Ground Motion Models

7.1 Introduction

Ground motion equations are often called attenution relations but they describe much more than just the attenutation of the ground motion; they describe the probability density function of the ground motion given the properties of the earthquake source (magnitude, style-of-faulting), the wave propagation (distance), and site response (site class or V_{S30}). In nearly all cases, the ground motion is assumed to follow a lognormal distribution and the ground motion equation gives the median ground motion and the standard deviation in log units.

Since the ground motion models are probabilistic descriptions of the level of ground motion, even the deterministic approach described in chapter 2 has an element of probability associated with it. There is a common misunderstanding of the probabilistic nature of the ground motion models in the earthquake engineering practice.

7.2 Tectonic Regions for Ground Motion Models

Different tectonic regimes give rise to different ground motion models Three broad categories of tectonic regimes are typically used for ground motion equations used in seismic hazard assessments: shallow crustal earthquakes in active tectonic regions (e.g. California, Japan, New Zealand, Italy, Turkey), shallow crustal earthquakes in stable continental regions (e.g. Australia, Eastern North America, northern Europe), and subduction zone earthquakes (e.g. Japan, Chile, Alaska, New Zealand). A summary of ground motion equations commonly used in the US for these tectonic categories are given in a special issue of the Seismological Research Letters in February, 1997. The models for the active regions are being updated as part of the PEER NGA project. These new models will be completed in early 2007. Some of the new results from the NGA project are discussed in this chapter.

Most recent ground motion models distinguish between the ground motion from reverse and strike-slip earthquakes with the ground motion from reverse earthquakes being 20 to

30 percent larger than for strike-slip earthquakes. Due to the small number of normal faulting earthquakes in most strong motion data sets, the difference between ground motions for strike-slip and normal faulting earthquakes is not well resolved and has not been included in most models. The standard practice is to use strike-slip attenuation relations to predict the ground motion from normal faults; however, some recent evaluations of normal faulting earthquakes have found that the ground motions from normal faulting earthquakes are 10-20% smaller than for strike-slip earthquakes.

7.2.1 Regionalization

As the number of recordings of strong ground motion increase, there has been a trend toward developing region-specific ground motion models rather than just using the global average models developed for the broad tectonic categories. In my opinion, often there is a tendency to overemphasize region specific data in developing region specific attenuation. Typically, there are not enough data in a specific region to completely determine the attenuation relation. In particular, usually there are not enough data close to the fault to constrain the behavior of the attenuation relation at short distances.

One way to address regionalization of attenuation relations is to only update parts of the global attenuation relations. For example, the simplest update is to estimate a constant scale factor to use to adjust a global attenuation model to a specific region. (This can reflect differences in the earthquake source or differences in the site categories.) If there are enough data over a range of distances, the slope of the attenuation could be updated while maintaining the magnitude scaling of the global model. An example of this type of regionalization of parts of the attenuation relation is the attenuation relations developed for New Zealand (McVerry and Zhao, 1999). The peak acceleration attenuation relation from this region-specific model is compared to a global model in Figure 1.

7.3 Model Parameters

The primary model parameters used in ground motion models are the magnitude, distance, site condition, and style-of-faulting. As the ground motion data sets increase, the dependence of the ground motion on additonal parameters can be estimated. The recent NGA models have included the following additional model parameters: hanging wall flag, depth to top of rupture, fault dip, and depth of the soil. These parameters are discussed breifly below.

7.3.1 Magnitude

Moment magnitude is the preferred magnitude measure and has been adopted in nearly all recent attenuation relations. Here, we will only consider moment magnitude based models.

7.3.2 Distance

A single consistent definition of the site-to-source distance has not been widely adopted by different authors of attenuation relations. In applications of the attenuation relations, these differences in distance definitions are often ignored, but it is important to use the appropriate distance measure with each attenuation relation, particularly for short distances.

Commonly used distance measures include the following: r_{jb}, the closest horizontal distance to the vertical projection of the rupture (the "Joyner-Boore" distance); r_{rup}, the closest distance to the rupture surface (slant distance); r_{seis}, the closest distance to the seismogenic part of the rupture surface (assumes that near-surface rupture in sediments is non-seismogenic); r_{cent}, the centroid distance; r_{hyp}, the hypocentral distance; and r_{epi}, the epicentral distance. The first three distances measure some sort of closest distance to the rupture plane, whereas, the last three distances are point source measures. For large-magnitude earthquakes, the closest distance measures are generally preferred over the point source distances. Some of these different distance measures are shown graphically in Figure 2 for a vertical fault and for a dipping fault. The main differences are for sites located close to the fault. The appropriate distance measure should be used with each attenuation relation considered.

7.3.3 Site Classifications

There are also several site classification schemes used in different ground motion models, ranging from qualitative descriptions of the near-surface material to very quantitative definitions based on shear-wave velocity. Without consistent site classifications for the attenuation relations, it is often difficult to know how to apply the attenuation relations to a specific site. Site classifications can vary from country to country. The site classifications used in global models of the attenuation may not fit into the site classification system for a particular region. Site classifications based on the shear wave velocity, such as used in the IBC 2000, provide a basis for consistent site classifications around the world, but most existing attenuation relations do not use shear wave velocity for the site classification because the shear wave velocities are not widely available for strong motion station sites. Most of the new NGA models are based on the shear-wave velocity in the top 30 m, consistent with the IBC. This removes a significant source of uncertainty in the application of the ground motion models.

Even for "rock" site classifications, there is a range of what is classified as rock. In California, sites that are classified as "rock" often contain weathered rock and/or thin soil (< 20m thick). In practice, these "rock" ground motions are usually assumed to be outcrop rock (e.g. shear wave velocity of 1300 m/sec) for site response calculations. When used in site response calculations, this outcrop motion should not include the effects of the weathered rock and thin soil. Idriss and Silva (1999) have evaluated suites of the recorded "rock" ground motions with measured shear-wave velocity profiles to determine the effect of the weathered rock and thin soil layers. They found that at high frequencies, the typical "rock" ground motions are 20 to 30 percent larger than true outcrop ground motions. It is common practice to ignore this difference between "rock" ground motions from attenuation relations and outcrop ground motions. As a result, the effects of the weathered rock/thin soil layers are often double counted in site response calculations.

All of the attenuation relations separate soft-soil sites from typical soil sites. Since the response of soft-soil sites is strongly site specific and there are few soft-soil strong motion recordings, response spectral attenuation relations have generally not been developed for soft-soil sites. This site condition is typically addressed with a site-specific site-response analysis.

7.3.5 Style-of-faulting

There are five general styles-of-faulting: reverse, reverse/oblique, strike-slip, normal/oblique, and normal. These are typically defined by the rake of the earthquake as shown in Figure 3. The rake is defined as the relative movement of the hanging wall with respect to the footwall, measured on the plane of the fault. The rake angles that separate different styles of faulting are not the same for all models, but most recent models follow the classfication shown in Figure 3.

7.3.6 Hanging-wall / Footwall wall

Dipping faults have a hanging wall and a footwall as shown in Figure 4. Hanging wall and footwall are mining terms. If you were digging a mine down a fault, you would hang your lantern on the Hanging Wall and walk on the foot wall. Sometimes the terms upthrown block and downthrown block are used interchangeably for hanging wall and footwall. While this works for reverse faults, it is not correct for normal faults. For a normal fault, the hanging wall is downthrown.

For earthquakes that rupture to the surface, the defintion of hanging wall and footwall is clear. For ruptures that do not reach the surface, the separation is less clear. For ground motion models, the separation between hanging wall and footwall for buried ruptures is given by the vertical projection of the top of the fault (Figure 4) and not by the projection updip.

7.3.7 Depth to Top of Rupture

New models have found that there is a dependence with the depth of the faulting. This effect is included in the new NGA models through the depth-to-top of rupture as shown in Figure 4. Note: this parameter is the depth to top of the specific earthquake rupture and not the depth to top of the fault itself.

7.3.8 Dip

The fault dip is the angle from the horizontal to the fault plane (see Figure 4). A vertical fault has a 90 degree dip.

7.3.9 Depth of Soil

The VS30 site parameter is a single parameter that has been used to classify sites. It is intended to be a proxy for the entire velocity profile. It does a reasonable job of distinguishing between different velocity profiles. One limitiation of this parameter is that is does not distingusih between shallow soil sites and deep soil sites. To address this limitation, a second site parameter is being introduced to some ground motion models: the depth to a specified VS isosurface. In the NGA models, two depths are considered in the various models: the depth to VS=1000 m/s and the depth to VS=2500 m/s.

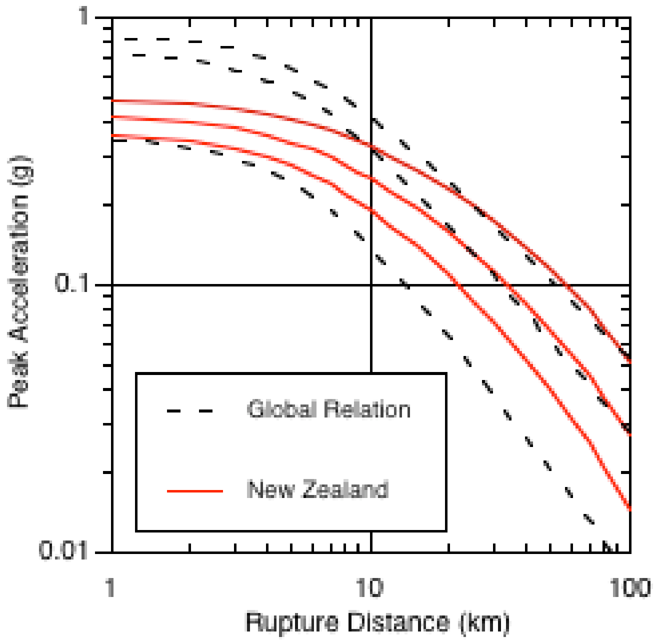

Figure 1. Comparison of regionalized attenuation relation for peak acceleration developed for New Zealand (strike-slip, weak rock) with the global model from Abrahamson and Silva (1997) for rock. THe three curves in each set are for magnitude 5.5, 6.5, and 7.5.

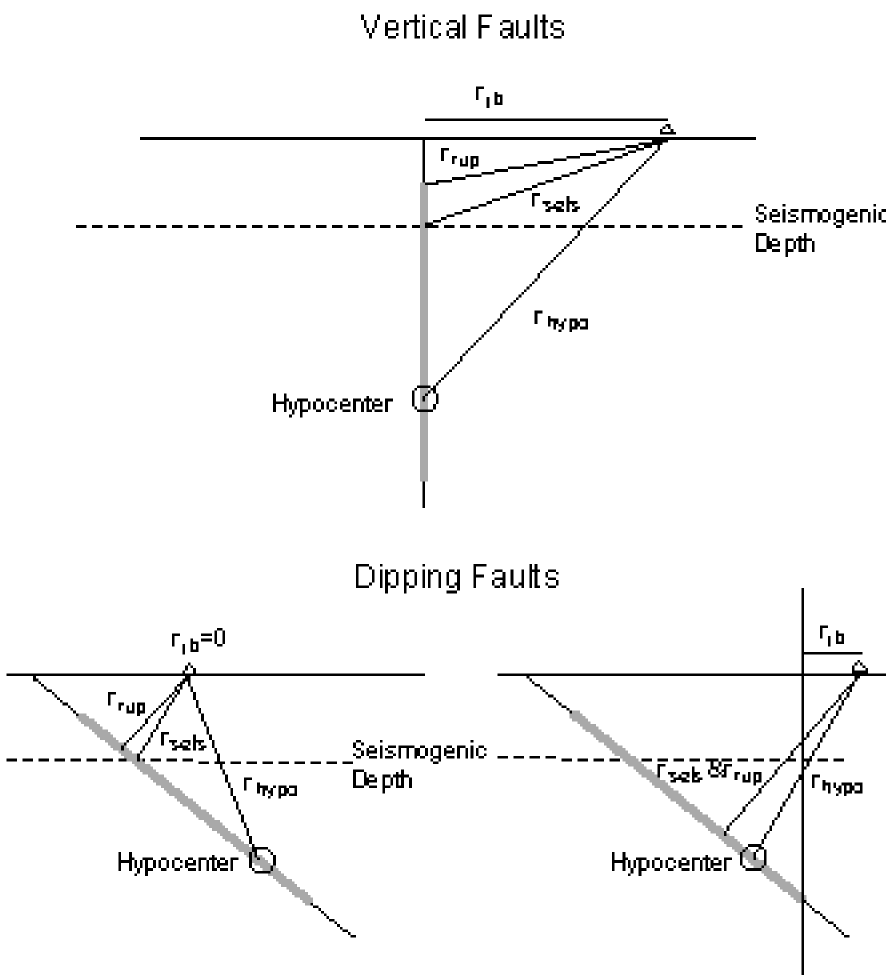

Figure 2. Various source to site distance measures for ground motion attenuation models shown in cross-section. The shaded region indicates the extent of the rupture.

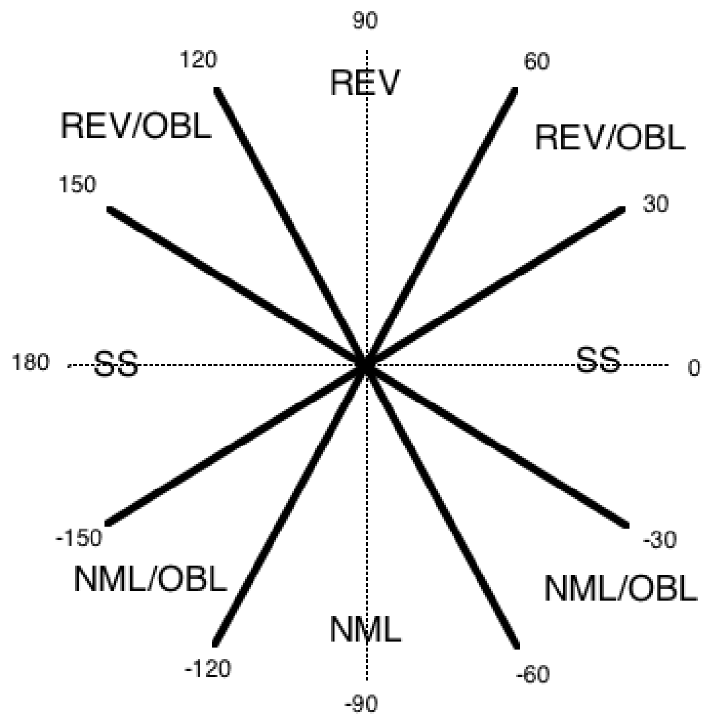

Figure 3. Style-of-Faulting in terms of the rake angle.

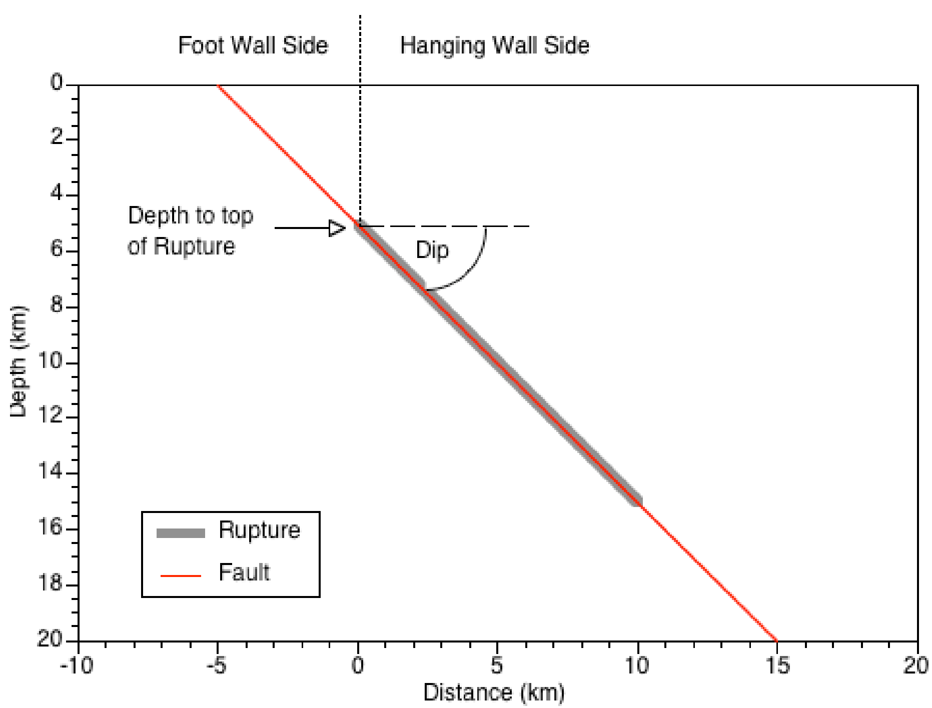

Figure 4. Hanging wall and foot wall definitions for a buried rupture.