REDUCING UNCERTAINTY IN STRONG MOTION PREDICTIONS

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SUMMARY

Current ground motion models based on recorded strong motion data predict ground motion parameters using a simplified model in which the effects of the earthquake source are represented by earthquake magnitude; the effects of wave propagation from the earthquake source to the site region are specified by a distance; and the effects of the site are specified by a site category. Analysis of the partition between inter-event and intra-event variability in recorded data indicates that while the average ground motions from one large earthquake are very similar to those of another, the ground motions vary significantly from one location to another at the same distance from a given earthquake. This indicates that empirical ground motion models have a large degree of uncertainty because other conditions that are known to have an important influence on strong ground motions are not treated as parameters of these simple models. These conditions include source effects such as those due to rupture directivity or the orientation of the fault, and the effects of deep structure such as sedimentary basins, basin edges, and buried folds and faults. In order to reduce the uncertainty in ground motion prediction at a given site, the parameterization of ground motion models can be augmented to include more realistic representations of source, path and site effects. One approach to accounting for these effects is to include them in empirical models by using a larger number of predictive parameters related to source, path and site conditions. Another approach is to use seismologically-based ground motion models derived from strong motion simulations that take account of the specific source, path and site conditions.

INTRODUCTION

Empirical ground motion prediction methods use a simplified approach in which the effects of the earthquake source are represented by earthquake magnitude; the effects of wave propagation from the earthquake source to the site region are specified by a distance; and the effects of the site are specified by a site category. Current models usually specify the median value (μ) of the ground motion parameter and the scatter (σ) about the median value. To be optimally useful for seismic design, the uncertainty in each of these two values (σ_μ and σ_σ) should also be specified.

During the past several decades, large sets of strong motion recordings were obtained from numerous earthquakes, significantly expanding the data base of strong motion recordings available for the derivation of empirical ground motion models. A collection of recent models based on recorded data and in some cases on seismological models, accompanied by an overview (Abrahamson and Shedlock, 1997), was published in Seismological Research Letters. These ground motion models are for distinct tectonic categories of earthquakes: shallow crustal earthquakes in tectonically active regions; shallow crustal earthquakes in tectonically stable regions; subduction earthquakes occurring the shallow plate interface, and earthquakes occurring within the subducting plate.

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VARIABILITY IN RECORDED GROUND MOTIONS

There is a large amount of variability in ground motion characteristics due to effects that are more complex than the simple parameterization described above based on magnitude, distance and site category. New methods for analyzing the origins of this variability have provided important insight into the nature of strong ground motions, and indicate the directions in which further research may be able to reduce the uncertainty in the estimation of ground motions for engineering application. Specifically, the random effects approach (Abrahamson and Youngs, 1992) has been applied to the strong motion data base to separately quantify two sources of variability: the variability in the average ground motions from one earthquake to the next, and the variability in ground motions from one site to another at the same closest distance from a given earthquake. For earthquakes of a given tectonic category larger than about magnitude 6, the event-to-event variability becomes very small and is insignificant compared with the intra-event variability (Youngs et al., 1995). The overall variability thus decreases significantly for the larger magnitudes. The decrease in the variability of ground motion amplitudes with increasing magnitude can have a significant effect on the estimation of ground motions for engineering analysis and design.

This finding indicates that while the average ground motions from one large earthquake are very similar to those of another, there are conditions that cause the ground motions to vary significantly from one location to another at the same distance from a given event. The factors that cause this variability are related to aspects of the earthquake source process, the propagation of seismic waves from the source region to the site region, and the site response that are not contained in the simple magnitude-distance-site category parameterization of standard attenuation relations. In these simple models, these other sources of variability are treated as randomness, whereas they potentially could be treated as resulting from specific effects which may be predictable. While those predictable effects may have uncertainties of their own, in some cases it should be possible to reduce these uncertainties. In order to reduce the uncertainty in predicting the ground motions at a given site, we need to augment these ground motion prediction models to include more realistic representations of source, path and site effects.

ENHANCED GROUND MOTION MODELS

One approach to accounting more realistically for these effects in ground motion models is to include them in empirical models by using a larger number of predictive parameters related to source, path and site conditions. Examples of this approach are the empirical models of hanging wall effects (Abrahamson and Somerville, 1996), which is incorporated in the ground motion model of Abrahamson and Silva (1997), and near-fault rupture directivity effects (Somerville et al., 1997). The former uses a simple geometrical model to distinguish hanging wall sites from other sites, and the latter uses parameters such as the angle between the fault rupture direction and the direction from the earthquake to the site.

Another approach is to use seismologically-based ground motion models that take account of the specific source, path and site conditions. These methods can be used to augment the recorded data used to generate empirical models, or to generate suites of ground motion estimates that can be used to develop independent ground motion models. Ground motion models based on synthetic seismograms can then be used to complement available empirical models. In some regions, the data base of strong motion recordings is too sparse to allow the development of empirical ground motion models, in which case ground motion models are based primarily on seismological models (e.g. Toro et al., 1997). Also, considerable progress has been made in understanding and predicting ground motion variability, especially at periods longer than about 1 second, through the modeling of rupture directivity and the effects of basins, basin edges, and buried folds and faults on ground motions (e.g. Graves et al., 1998; Hartzell et al., 1997; Kawase, 1996; Pitarka et al., 1998). By incorporating these effects into ground motion models, in addition to the standard parameters of magnitude, distance and site category, it should be possible to reduce the uncertainty in the ground motion estimates for a specified site.

NUMERICAL GROUND MOTION MODELS

Broadband Green's function procedures (e.g., Somerville et al., 1996) are available to generate ground motions that include more realistic representations of these source, path and site effects. The broadband Green's function procedure has a rigorous basis in theoretical and computational seismology (Helmberger, 1983). The earthquake source is represented as a shear dislocation on an extended fault plane, whose radiation pattern, and its tendency to become subdued at periods shorter than about 0.5 sec, are accurately represented, and whose spatial and temporal variation of slip of the fault surface is specified. Wave propagation is represented by Green's functions computed for the seismic velocity structure which contains the fault and the site, or by empirical Green’s functions derived from strong motion recordings of small earthquakes. These Green's functions contain both body waves and surface waves. The ground motion time history is calculated in the time domain using the elastodynamic representation theorem. This involves integration over the fault surface of the convolution of the slip time function on the fault with the Green's function for the appropriate depth and distance.

To use the broadband Green’s function method, the spatial distribution of slip on the fault and the time function of slip on the fault need to be characterized. Detailed studies of the spatial distribution of slip on the fault plane for earthquakes in tectonically active regions, derived from strong motion recordings and other data, have shown that the slip distribution is highly variable, characterized by asperities (regions of large slip) surrounded by regions of low slip. These slip models have been used to develop relationships between seismic moment and a set of fault parameters that are needed for predicting strong ground motions (Somerville et al., 1999). These parameters include fault length, fault width, rise time (duration of slip at a point on the fault), and the size, slip contrast and location of asperities.

To illustrate the performance of the broadband simulation procedure, the top part of Figure 1 compares the recorded three component time histories of the Arleta recording of the 1994 Northridge earthquake (top row) with those simulated using empirical source functions derived from the Whittier Narrows aftershock (center row) and the Imperial Valley aftershock (bottom row of each panel). The recorded and simulated displacement waveforms are quite similar, especially on the north component. There is also considerable resemblance between the recorded and simulated velocity waveforms, especially in the lower frequency features. At high frequencies, there is little resemblance in waveform between the recorded and simulated motions, as seen in comparing the recorded and simulated time histories, but there is resemblance in the duration of the strong motion.

UNCERTAINTY IN GROUND MOTIONS PREDICTED BY NUMERICAL MODELS

There are two kinds of uncertainty in the estimation of ground motions using seismological models (Abrahamson et al., 1990). One is the modeling uncertainty associated with the simulation procedure, described further below. This is estimated from comparison between recorded and simulated ground motions of past earthquakes for which estimates of all of the parameters required by the model are available. The other source of uncertainty is parametric uncertainty associated with uncertainty in the parameters of future earthquakes. These parameters include the slip distribution, the location of the hypocenter, the slip velocity and the rupture velocity, described further below. In practice, each of these two sources of uncertainty contributes about equally to the overall uncertainty.

The modeling uncertainty in ground motion amplitudes can be described by two goodness of fit parameters: the bias and the standard error. In this formulation, the bias measures the difference between recorded and simulated motions averaged over all stations, and provides an indication of whether, on average, the simulation procedure is overpredicting, underpredicting, or evenpredicting the recorded motions. The standard error measures the average difference between the simulated and recorded motions for a single observation, and provides an indication of the uncertainty involved in predicting a single value. The average of all these differences, which include both overprediction and underprediction, is the bias.

An example of modeling uncertainty in response spectral amplitudes is shown at the bottom of Figure 1. Averaged over 15 recordings of the 1994 Northridge earthquake in the San Fernando Valley, the simulation procedure has little significant bias (i.e. it neither over predicts nor under predicts the recorded ground motion on average) in the period range of 5.0 to 0.03 seconds, as shown on the lower left of Figure 1. At a given station and for a particular period, the standard error is about a factor of 1.4 on average over the period range of 5.0 to 0.03 seconds, as shown on the lower right of Figure 1. This means that, due to the limitations of the simulation procedure, which at short periods may relate to the inherently stochastic nature of strong ground motion, our simulated motions at a given site for a given period have an uncertainty whose standard error is on average about a factor of 1.4.

Modeling uncertainty can also be measured for other ground motion parameters. For example, in order to characterize the uncertainty in a time domain model of the rupture directivity pulse (Somerville, 1998), it may be appropriate to use a cross correlation function. In the top of Figure 2, we show the recorded and simulated waveforms of the north component of the Newhall recording of the 1994 Northridge earthquake, which contains a strong forward rupture directivity pulse. The waveforms are bandpass filtered in the frequency range of 0.1 to 1.0

Hz. The maximum value of the cross correlation function, which is plotted below the waveforms, can be used to characterize the goodness of fit of the waveform of the simulated time history to that of the recorded time history. To complement this waveform measure of goodness of fit, the amplitude goodness of fit can be represented by the smoothed Fourier amplitude spectrum, shown in the bottom of Figure 2, or by the response spectral amplitude.

The parametric uncertainty is described by a standard error that represents the uncertainty in the ground motion estimate due to uncertainty in the values of the parameters of future earthquakes. It is estimated from ground motion simulations in which the values of these parameters are systematically varied. In Figure 3 we show an example of parametric uncertainty estimates in ground motion simulations for a magnitude 8 subduction earthquake (Ohtsuka et al., 1998). The four source parameters that were varied to estimate the modeling uncertainty were slip distribution, hypocenter location, rupture velocity, and rise time. We calculated the variability in the response spectrum due to each parameter, assuming that the variations in ground motions due to variations in other parameters are uncorrelated, which is equivalent to taking partial derivatives. The combined parametric standard error obtained by combining the standard errors of the individual parameter variations under the assumption of no correlation between the effects of the different parameters is less than the global standard error derived from the whole set of simulations, indicating the presence of correlations between the different parameters. The parametric uncertainty reflects our uncertainty about the source parameters of future earthquakes.

The modeling uncertainty was estimated by measuring differences between the recorded and simulated response spectra of the 1985 Michoacan earthquake. The modeling uncertainty measures the discrepancy between the recorded and simulated ground motions that remains even when we know the source parameters of the earthquake, as was the case for the 1985 Michoacan earthquake. The overall uncertainty of the ground motion estimate is obtained by combining the global parametric uncertainty and the modeling uncertainty.

CONCLUSIONS

There is a large amount of variability in ground motion characteristics due to effects that are more complex than the simple parameterization of empirical ground motion models based on magnitude, distance and site category. New methods for analyzing the origins of this variability have provided important insight into the nature of strong ground motions, and indicate the directions in which further research may be able to reduce the uncertainty in the estimation of ground motions for engineering application. Specifically, the random effects approach has been applied to the strong motion data base to separately quantify two sources of variability: the variability in the average ground motions from one earthquake to the next, and the variability in ground motions from one site to another at the same closest distance from a given earthquake. For earthquakes of a given tectonic category larger than about magnitude 6, the event-to-event variability becomes very small and is insignificant compared with the intra-event variability. This finding indicates that while the average ground motions from one large earthquake are very similar to those of another, there are conditions that cause the ground motions to vary significantly from one location to another at the same distance from a given event. The factors that cause this variability are related to aspects of the earthquake source process, the propagation of seismic waves from the source region to the site region, and the site response that are not contained in the simple magnitude-distance-site category parameterization of standard attenuation relations. In these simple models, these other sources of variability are treated as randomness, whereas they potentially could be treated as resulting from specific effects which may be predictable.

In order to reduce the uncertainty in predicting the ground motions at a given site, we need to augment these ground motion prediction models to include more realistic representations of source, path and site effects. One approach to accounting more realistically for these effects in ground motion models is to include them in empirical models by using a larger number of predictive parameters related to source, path and site conditions. Examples of this approach are recently developed empirical models of hanging wall effects and near-fault rupture directivity effects.

Another approach is to use seismologically-based ground motion models that take account of the specific source, path and site conditions. These methods can be used to augment the recorded data used to generate empirical models, or to generate suites of ground motion estimates that can be used to develop independent ground motion models. Ground motion models based on synthetic seismograms can then be used to complement available empirical models. In some regions, the data base of strong motion recordings is too sparse to allow the development of empirical ground motion models, in which case ground motion models are based primarily on seismological models. Also, considerable progress has been made in understanding and predicting ground motion variability, especially at periods longer than about 1 second, through the modeling of rupture directivity and the effects of basins, basin edges, and buried folds and faults on ground motions. By incorporating these effects into ground motion models, in addition to the standard parameters of magnitude, distance and site category, it should be possible to reduce the uncertainty in the ground motion estimates for a specified site.

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