PEER LIFELINES PROGRAM

GOODNESS OF FIT IN SIMULATED NEAR-FAULT LONG PERIOD GROUND MOTIONS OF THE 1999 KOCAELI AND DUZCE, TURKEY EARTHQUAKES AND THE 1999 CHI-CHI, TAIWAN EARTHQUAKE

FINAL REPORT

April 5, 2002

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INTRODUCTION

The objective of this project is to validate procedures for generating near-fault ground motions by simulating the ground motions of past earthquakes and comparing the results with the recorded ground motions. The period range of interest in this project is specified to be 0.125 Hz to 1.43 Hz (8 seconds to 0.7 seconds period). In this project, we have validated our simulation procedures against recordings of three earthquakes: the 1999 Kocaeli and Duzce, Turkey earthquakes and the 1999 Chi-Chi, Taiwan earthquake.

Near-fault ground motions have special characteristics (Somerville et al., 1997) that need to be considered in selecting procedures for quantifying the goodness of fit. In particular, the fault-normal component is systematically larger than the fault parallel component at periods longer than about 0.5 seconds. In characterizing near-fault ground motions for design, it is often appropriate to specify the fault normal and fault components separately. Accordingly, in validating a near-fault ground motion simulation procedure, it is appropriate to generate separate fault normal and fault parallel components and validate them against the corresponding recorded components.

SIMULATION PROCEDURE

To simulate broadband time histories, the ground motions are computed separately in the short period and long period ranges, and then combined into a single broadband time history (Pitarka et al., 2000; Somerville et al., 1995; 1996). The use of different methods in these two period ranges is necessitated by the observation that ground motions have fundamentally different characteristics in these two period ranges. At long periods (longer than about 1 second), strong ground motions are deterministic in the sense that seismological models are capable of matching not only the spectral amplitudes but also the waveforms of recorded long period ground motions, once the rupture model of the earthquake and the seismic velocity structure of the region surrounding the earthquake are known. At short periods (shorter than about 1 second), strong ground motions become increasingly stochastic in nature. Seismological models are generally capable of matching the spectral amplitudes of the short period ground motions, but are generally not capable of matching the recorded waveforms. The transition from deterministic to stochastic behavior appears to be due to a transition from coherent source radiation and wave propagation conditions at long periods (over long dimensions) to incoherent source radiation and wave propagation conditions at short periods (over short dimensions). The two simulations are combined using matched filters at 0.8 Hz.

Low Frequency Part

The low frequency part of the ground motion (frequencies lower than 0.8 Hz) is calculated using composite source modeling. The earthquake source is modeled as a shear dislocation on an extended fault plane, whose radiation pattern is accurately represented. Wave propagation is represented rigorously by Green's functions computed using a frequency-wave number technique (Saikia, 1994) and 1D models of the velocity structure that contain the fault and the site. 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 (e.g. Hartzell and Heaton, 1983).

High Frequency Part

The high frequency part of the ground motion is calculated using composite source modeling and high frequency Green's functions. The stochastic approach used to calculate the Green's function (Boore, 1983) is based on the Brune (1970) omega-squared point source model. Based on this model the seismic moment for each fault element M_e is calculated using the following formula (Brune, 1970)

$$M_e = 16/7\ \Delta\sigma\ A\ L$$

where $\Delta\sigma$ is the stress drop, A is the area of the fault element and L is the characteristic dimension of the fault element, determined as the average between the fault element dimensions along the strike and dip. In all simulations we assumed a stress-drop of 100 bars whereas L varies between 2-4 km.

Two other important parameters of the stochastic source modeling are the corner frequency f_c and duration of the Green's function T_w.

$$f_c = (z\ 0.8\ \beta)/(\pi\ L)$$

where z = 2 (Bereznev and Atkinson 1997) and β is the shear-wave velocity.

$$T_w = c\ 10^{(0.31\ Mw\ -0.774)}$$

In this empirical formula M_w is the moment magnitude of the subevent and c is 1 for rock and 1.3 for soils.

In our simulations the rise time can be variable. The slip distribution on the fault is only used to calculate a weighting factor for each subevent required in the integration of the Green's functions over the fault. The weighting factor varies from 0 to 1 with the largest value corresponding to the fault element with the largest seismic moment release. This factor does not affect the assumed stress drop or the corner frequency determined for the fault elements.

Radiation Pattern and Local Site Effects

While at low frequencies the radiation pattern of waves radiated from the seismic source is readily observed, at high frequencies the pattern is not clear. In our simulations we used a frequency dependent source radiation pattern as modeled by Pitarka et al. (2000). According to this model the radiation pattern at frequencies lower than 0.8 Hz is modeled using theoretical radiation coefficients of body waves for a double couple point source. At the intermediate frequency range 0.8-1.7 Hz average radiation coefficients for body waves are applied (Boore and Boatwright, 1984). At frequencies higher than 1.7 Hz a constant average radiation coefficient calculated at that frequency is used.

Our method of modeling site effects allows for the use of two different procedures. The first procedure is based on a transfer function calculated using 1D or 3D local velocity models. The transfer function is used to correct the synthetic ground motion for local site effects.

In the second procedure, which was used for this study, a site-specific ground motion amplification factor is applied to the calculated response spectrum. In our simulations we first calculated synthetic accelerograms for rock site conditions using regional crustal models and a maximum frequency f_{max} of 7 Hz. The simulated response spectra at given sites were then modified for site effects based on the NEHRP site categories and corresponding amplification factors.

METHOD OF QUANTIFYING GOODNESS OF FIT

The objective of validation of a ground motion simulation procedure is to confirm that it is effective in reproducing the ground motion characteristics of recorded data. These characteristics are measured by ground motion parameters such as peak acceleration, peak velocity, response spectral acceleration, duration, and waveform correlation. The performance of any ground motion prediction method is quantified by measuring two quantities: the bias and the standard error (Abrahamson et al., 1990). The bias measures the difference between the recorded and simulated motions averaged over a set of strong motion recordings of a suite of earthquakes, and provides an indication of whether, on average, the simulation procedure is over-predicting, under-predicting, or even-predicting the recorded motions. The standard error measures the average difference between the simulated and recorded motions at a single recording station, and provides an indication of the uncertainty involved in predicting the ground motions at a single site. The average of all these errors, which include both over-prediction and under-prediction, is the bias. The simulated motions at a given site may have significant uncertainty (e.g. a factor of 1.5), reflecting limitations in the ability of the simulation procedure to predict the detailed characteristics of individual recordings, even though the bias (which averages this uncertainty over all recording sites) may be quite small, indicating that the simulation procedure neither overpredicts nor underpredicts the recorded data on average.

The bias and standard error of the simulation procedure in fitting the recorded ground motions is illustrated in the following figures, which quantify the goodness of fit in spectral acceleration between the recorded and simulated time histories. The top part of each figure shows the bias, i.e. the median value of the residuals (data minus simulation). We would like the bias to be not significant at the 90% confidence level. The bottom part of each figure shows the standard error of the scatter of the individual residuals about this median value. For example, a standard error of a factor of 1.5 (0.4 natural log units) means that at a specific station, the difference between the recorded and simulation ground motion at a particular response spectral period has a standard error of a factor of 1.5.

EARTHQUAKE RUPTURE MODELS

For all three earthquakes, we generated rupture models that describe the spatial and evolution of slip on the fault. The rupture model of the Duzce earthquake was funded by this project, and the rupture models of the Kocaeli and Chi-Chi earthquakes were funded by Ohsaki Research Institute, Inc, which generously made the results available to the PEER Lifelines Program. The gross source parameters of the three earthquakes are listed in Table 1. More detailed descriptions of the source parameters are given in the references in Table 1.

Table 1. Source Parameters of the Kocaeli, Duzce and Chi-Chi Earthquakes

Date	**Location**	**Length (km)**	**Width (km)**	**Moment (dyne.cm)**	**Mw**	**Mechanism**	**Reference**
17/8/1999	Kocaeli, Turkey	120	20	$2.3 . 10^{27}$	7.55	Strike-slip	Thio et al., 2001a
12/11/1999	Duzce, Turkey	52	24	$0.88. 10^{27}$	7.25	Strike-slip	Thio and Graves, 2002
21/9/1999	Chi-Chi, Taiwan	75	45	$3.37 .10^{27}$	7.65	Thrust	Thio et al., 2001b

STRONG MOTION RECORDING SITES USED IN VALIDATIONS

The strong motion stations used in the validations of the three earthquakes are shown in Figures 1, 2 and 3 and listed in Tables 2, 3 and 4 for the Kocaeli, Duzce and Chi-Chi earthquakes respectively. These tables list the NEHRP site category (BSSC, 2001) that is assigned to each station. For the Kocaeli and Duzce earthquakes, this information was provided by Rathje (EERI, 2000). For the Chi-Chi earthquake, this information was obtained from Lee et al. (2001).

Table 2. Strong motion recordings of the 1999 Kocaeli, Turkey earthquake used in validation

Longitude	**Latitude**	**Station Name**	**Site Category**
29.013	41.058	ist	B
29.360	41.823	arc	C
29.440	41.820	gbz	B
29.762	41.763	ypt	D
29.179	41.850	dzc	C
29.691	41.473	izn	D
29.131	41.183	brs	C

Table 3. Strong motion recordings of the 1999 Duzce, Turkey earthquake used in validation

Longitude	Latitude	Station Name	Site Category
31.182	40.463	mdr	B
30.876	40.743	375	B
30.855	40.703	531	A
31.015	40.755	58	A
30.872	40.744	59	B
30.792	40.720	61	B
30.820	40.723	62	B
31.610	40.747	bol	B

Table 4. Strong motion recordings of the 1999 Chi-Chi, Taiwan earthquake used in validation

Longitude	Latitude	Station Name	Site Category
120.854	24.468	TCU046	B
120.784	24.492	TCU039	C
120.761	24.416	TCU128	C
120.696	24.449	TCU036	D
120.773	24.348	TCU087	C
120.707	24.310	TCU103	C
120.766	24.277	TCU068	D
120.721	24.249	TCU102	D
120.652	24.260	TCU136	C
120.644	24.225	TCU060	D
120.739	24.198	TCU052	C
120.690	24.179	TCU049	D
120.676	24.148	TCU082	D
120.611	24.173	TCU057	C
120.720	24.091	TCU067	D
120.616	24.108	TCU063	D
120.691	24.059	TCU065	D
120.571	24.085	TCU109	D
120.678	23.983	TCU075	D
120.788	23.986	TCU071	D
120.849	24.041	TCU072	D
120.962	23.962	TCU074	D
120.613	23.980	TCU120	C
120.544	24.019	TCU123	D
120.596	23.922	TCU138	D
120.676	23.908	TCU076	D
120.857	23.904	TCU089	C
120.900	23.883	TCU084	B
120.894	23.840	TCU079	D
120.846	23.812	TCU078	D

120.580	23.857	TCU116	E
120.610	23.813	TCU122	D
120.606	23.757	CHY024	D
120.514	23.780	CHY025	E
120.562	23.686	CHY101	D
120.605	23.632	CHY028	D
120.552	23.582	CHY006	D
120.596	23.439	CHY041	D
120.544	23.521	CHY034	D
120.528	23.614	CHY029	C
120.544	23.465	CHY010	D

SEISMIC VELOCITY STRUCTURE MODELS

The seismic velocity structure models used in the ground motion simulations are listed in Table 5 for the Kocaeli and Duzce earthquakes, and in Table 6 for the Chi-Chi earthquake. The model for use with the Kocaeli and Duzce earthquakes was derived from Neugebauer et al. (1997), and the model for use with the Chi-Chi earthquake was derived from Iwata et al. (2000).

Table 5. Seismic velocity model for northwestern Turkey

Thickness	**V_P**	**V_S**	**density**	**Q_P**	**Q_S**
0.50	1.90	1.00	2.00	200.	100.
1.50	2.90	1.60	2.10	250.	200.
5.00	5.40	3.00	2.50	1000.	500.
10.00	6.16	3.50	2.78	1600.	800.
18.00	6.63	3.70	2.90	2000.	1000.
0.00	8.16	4.60	3.40	2500.	1250.

Table 6. Seismic velocity model for northwestern Taiwan

Thickness	**V_P**	**V_S**	**density**	**Q_P**	**Q_S**
1.00	2.88	1.55	2.00	200.	100.
1.00	3.15	1.70	2.05	400.	200.
1.79	4.37	2.50	2.30	500.	250.
4.30	5.13	2.85	2.48	500.	250.
5.00	5.90	3.30	2.60	550.	270.
4.00	6.21	3.61	2.70	600.	300.
8.00	6.41	3.71	2.75	700.	350.
5.00	6.83	3.95	2.80	800.	400.
5.00	7.29	4.21	3.00	1000.	500.
15.00	7.77	4.49	3.10	1000.	500.
0.00	8.05	4.68	3.10	1000.	500.

RESULTS

The goodness of fit measurements are shown in Figures 3 through 29. In general, the simulation procedure matches the recorded ground motions without significant bias across a broad range of periods from 0.01 to 10 seconds. For all three earthquakes, the simulation procedure tends to systematically overpredict the ground motions in the period range of 0.05 to 0.2 seconds. This may be due to inaccuracy in the representation of fmax in the stochastic simulation procedure.

The goodness of fit measurements for the Kocaeli earthquake for the average horizontal, fault normal, fault parallel, and vertical components are shown in Figures 4 through 7. There is little significant bias, and the standard error is 0.5 natural log units over a broad period range.

The goodness of fit measurements for the Duzce earthquake for the average horizontal, fault normal, fault parallel, and vertical components are shown in Figures 8 through 11. There is significant overprediction for periods longer than 4 seconds. At periods between 0.5 and 2 seconds, the fault normal component is overpredicted and the fault normal component is underpredicted. These discrepancies may be due to the location of most of the stations at the western end of the fault, which experienced low ground motion amplitudes due to backward directivity conditions. The standard error is 0.75 natural log units over the period range of 0.01 to 4 seconds.

For the Chi-Chi earthquake, there is a systematic underprediction of the recorded ground motions at the southernmost end of the fault, beginning as station CHY101 at latitude 23.7. This is illustrated in Figure 12, which shows the residuals (data – simulation) as a function of latitude for response spectral periods of 0.1, 1.0, and 3.0 seconds. For a period of 0.1 seconds, there is also a tendency for the simulations to overpredict the data at the northern end of the fault. These features of the Chi-Chi earthquake are attributed by Ma et al. (2001) to dynamic fault lubrication effects. Our ground motion simulation procedure is based on the assumption that the seismic radiation at all periods can be predicted from the rupture model of the earthquake, including the slip distribution on the fault, derived from strong motion and teleseismic data that have been lowpass filtered, typically at a period of about 2 seconds. This assumption may not hold for the Chi-Chi earthquake.

The goodness of fit measurements for all 41 selected recordings of the Chi-Chi earthquake for the average horizontal and vertical components are shown in Figure 13. There is little significant bias, but the standard error is about 1.1 natural log units, reflecting the underprediction of the southernmost seven stations. The distribution of residuals with latitude for the vertical component is shown in Figure 14, and the goodness of fit for all 41 stations is shown in Figure 15.

Figure 16 shows the residuals for the horizontal component for a set of 34 recordings of the Chi-Chi earthquake, excluding the seven southernmost stations. The goodness of fit measurements for these recordings for the average horizontal, fault normal, and fault parallel components are shown in Figures 17 through 19. There is little significant bias, and the standard error is reduced to about 0.75 natural log units. The random distribution of residuals with latitude shown in Figure 16 indicates that this still large degree of scatter is probably due to site effects, because the residuals vary over distances that are too short to be attributable to source effects. The distribution of residuals with latitude for the vertical component is shown in Figure 20, and the goodness of fit is shown in Figure 21.

In Figures 22 through 25, we show the goodness of fit for all three earthquakes, excluding the seven southernmost recordings of the Chi-Chi earthquake, for the average horizontal, fault normal, fault parallel, and vertical components. There is some significant overprediction in the period range of about 0.07 to 0.2 seconds as noted above, and slight overprediction at periods longer than 5 seconds, due to the Duzce earthquake. Otherwise, the simulations provide a good broadband fit to the recorded data in the period range of 0.01 to 10 seconds, with a standard error of about 0.7 natural log units. The horizontal and vertical component results are subdivided into soil recording sites in Figures 26 and 27, and rock recording sites in Figures 28 and 29. The slight overprediction at periods longer than 5 seconds is seen to be due just to the Duzce earthquake rock recordings.

CONCLUSIONS

The response spectra of the ground motion simulations for the 1999 Kocaeli and Duzce, Turkey earthquakes and the 1999 Chi-Chi, Taiwan earthquake provide a good broadband fit to the recorded data in the period range of 0.01 to 10 seconds, with a standard error of about 0.7 natural log units, as shown in Figures 22 through 25. There is some systematic overprediction in the period range of 0.07 to 0.2 seconds. The slight overprediction at periods longer than 5 seconds is due to the Duzce earthquake rock recordings.

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